Plataforma Solar de Almería

Ciemat P.S.A.

Annual Report 2005

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Introduction

At the time of writing, PSA activity is organized in three Units, two for research, and one, called **'PSA Management'** devoted to horizontal management of resources, training and technical support to the other two research units called the **'Solar Concentrating Systems Unit' (CSS)** and **'Environmental Applications of Solar Energy and Characterization of Solar Radiation' (EASE).**

The new CSS unit includes the activities previously under the 'Mid-Temperature Solar Thermal Energy' and 'High-Temperature Solar Thermal Energy' projects. It also takes on the activities performed in the 'very high concentration' Solar Furnace and DISTAL facilities which were previously part of the 'Training and Access Project'.

The CSS Unit continues to work on the direct steam generation technology (DSG), which aims to reduce the costs of solar thermal electricity by around 30%. The nucleus of its activity is the European INDITEP project, the main purpose of which is the detailed design of a 5-MWe DSG plant. The experience accumulated during the years of continued operation of the PSA DISS loop will be a decisive factor in the success of this project.

In 2005, activities were also directed at clarifying the last technological unknown in the DSG process: thermal storage. The DISTOR project, which is funded by the European Commission, officially began in February 2004 and lasts 45 months. Its main purpose is the development of a competitive thermal storage system suitable for solar plants with direct steam generation in the solar field, for which a storage system based on phase-change materials is currently under development.

The economic goal of the DISTOR project is a specific cost of 20 €/kWh storage system capacity, which would make its implementation in commercial solar thermal plants profitable.

The DISTOR project has 13 participants from five countries and is coordinated by DLR.

The CSS Unit work in Central Receiver technology focused on technological collaboration with the companies promoting the two commercial tower projects. The PS10 Project, which will be the first commercial solar thermal power plant in Spain, is due to be inaugurated toward the end of 2006. The second initiative, called SOLAR TRES, which employs molten salt as the receiver working fluid, is still in the promotion stage.

Our activity in the 'Environmental Applications of Solar Energy' has concentrated on detoxification and disinfection of water, and also seawater desalination.

The 'Associated European Solar Energy Laboratory' (SolLAB) was consolidated during 2005. The members of this virtual laboratory are the main European concentrated solar energy research institutes: the IMP-CNRS in Odeillo (France), the DLR Solar Energy Division (Germany), the Federal Technology Institute of Zurich (Switzerland) Renewable Energies Laboratory, and the CIEMAT itself. The agreement was signed in October 2004 and the coordinated tasks have already begun to bear fruit, especially in the fields of flux and temperature measurement and Ph.D. student training. The ‘Paul Scherrer Insititut’ of Switzerland has already signed up as a new ‘SolLAB’ member.

Furthermore, continued intensive collaboration with the University of Almería (UAL) has been consolidated with the creation of a mixed CIEMAT-UAL center for joint research in solar energy applications. The new laboratory building where this collaboration is physically located on the UAL campus, was partly financed by the ERDF Program, and was inaugurated in 2005.

Training and dissemination activities continue at a strong pace, as we are aware that we cannot ignore the facet of informing society about the existence of this renewable energies option. We therefore maintain educational agreements with universities and research centers around the world.

Important events this year were the visit of the Minister for the Environment, Cristina Narbona, and the ‘Terra Foundation’ ‘Sun and Peace Prize’ award.

And I do not wish to end this introduction without acknowledging the support received from the CIEMAT Directorate General and the fine work and professionalism of the entire PSA staff.

Diego Martínez Plaza
Director de la 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 Centro de Investigaciones Energéticas Medio Ambientales y Tecnológicas (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 Energy as an R&D division.

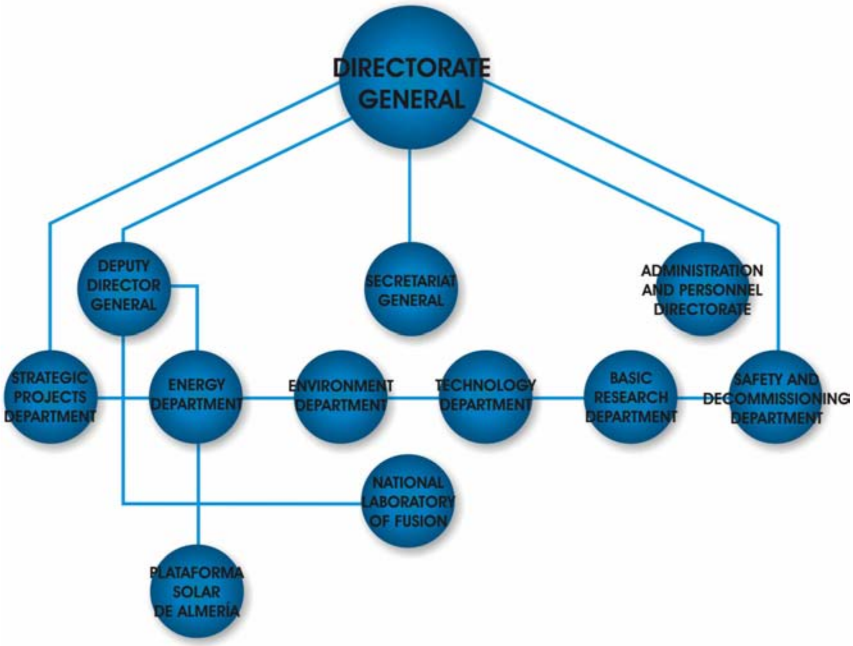


Figure 1. Integration of the PSA in the CIEMAT organizational structure

The objectives that inspire its research activity are the following:

- Contribute to a worldwide, sustainable, clean energy supply.
- Contribute to conservation of European energy resources, climate and environment.
- Promote market introduction of solar thermal technologies and derived solar chemical processes.
- Contribute to the development of a competitive Spanish solar thermal export industry

- Reinforce the cooperation between business and scientific institutions in the field of solar thermal technology research, development, demonstration and marketing.
- Foster cost-reducing technological innovations leading to increased market acceptance of solar thermal technologies.
- Assist industry in identifying market opportunities related to solar thermal technologies.

Figure 2. **Aerial view of the Plataforma Solar de Almería**

Organization and Functional Structure

In 2005, activities at the Plataforma Solar de Almería were structured around two research units, the Concentrating Solar Systems Unit and the Environmental Applications of Solar Energy and Characterization of the Solar Resource Unit. The first is devoted to the development of new and better ways of generating solar thermal power, and the second to exploring possibilities of solar chemistry, especially insofar as its potential for detoxification of industrial effluents, seawater desalination, and water disinfection. Supporting these R&D Units, are the corresponding PSA management and service areas, which, given the variety and complexity of the facilities, are of the greatest importance to daily work in all the lines of activity taking place here.

Within the Units, each R&D project is run by a project head and a technical staff on whose work the master lines of scientific activity and technological development at the PSA rely. They are largely independent in the execution of their budgets, the planning of their scientific objectives and the technical management of their resources. However, the two R&D Units share many PSA resources, services and infrastructures, so they must all be fluently communicated with the technical and administrative support units through the Director's Office, which sees that support capabilities, infrastructures and human resources are efficiently distributed. It is also the Director's Office which channels their demands to the various CIEMAT general support units located in Madrid.

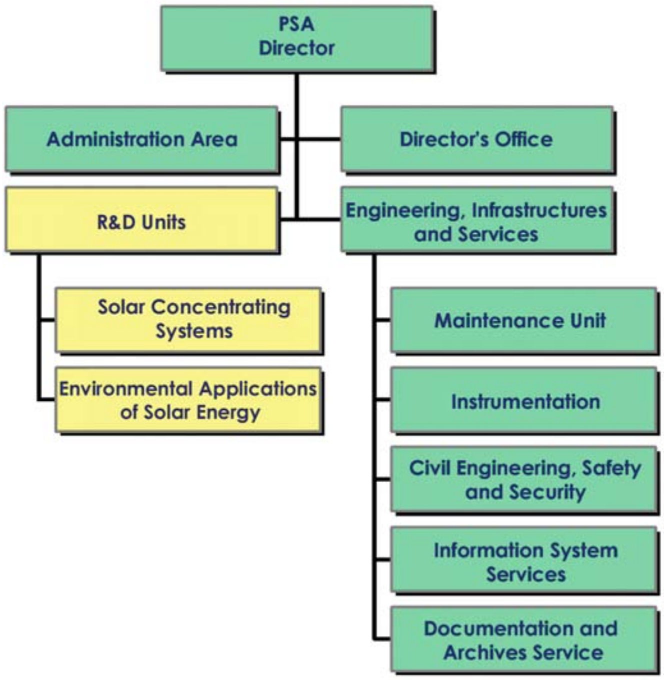


Figure 3. **PSA Organization Chart for 2005. Green indicates functions and services under the Director's Office.**

Human and Economic Resources

The scientific and technical commitments of the PSA and their associated workload are undertaken by a team of 98 persons who, as of December 2005, make up the permanent staff of the Plataforma Solar. Moreover, in addition to this permanent staff, there is a considerable flow of trainees and visiting researchers who are managed by the Director's Office.

Of the 98 persons that work daily at the PSA, auxiliary services, operation and maintenance contracts (32 persons) are an important part. Further auxiliary contracts are for 6 administrative and secretarial staff, 2 user information service technicians and 5 security guards. The O&M contracts are distributed among 9 facility operators, 5 operations watchers and 14 mechanical, electrical and electronic maintenance staff and 4 cleaners. The rest of the personnel are made up of the 51 persons on the CIEMAT-PSA staff, 20 of whom are located in the CIEMAT headquarters in Madrid. There is also a permanent DLR delegation of 12 responding to current commitments of the Spanish-German Agreement.

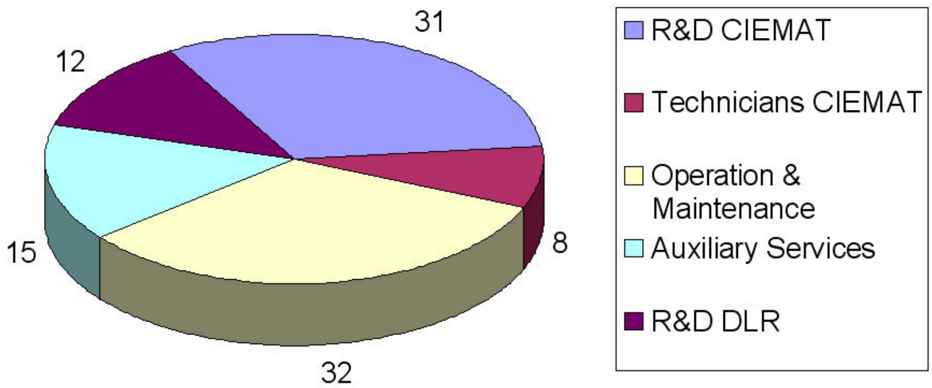


Figure 4. **Distribution of PSA permanent personnel as of December 2005.**

The upward trend in the PSA budget is clear, thanks in good measure to having raised additional revenues.

Successful pursuit of external revenues, mainly from the European Commission, has been an outstanding contribution of our constant partner 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 number of projects funded by the National R&D Plan, where there is a growing belief in renewable energies and in particular, the concentrating solar technologies, has also increased significantly.

The PSA budget was 5.34 million Euros in 2005 (not including the cost of R&D personnel). The CIEMAT contribution was increased to be able to undertake the activities approved for this year in the PSA Infrastructure Improvement Plan. This plan is devoted to major improvements necessary in the main infrastructure, buildings, heliostat fields, etc.

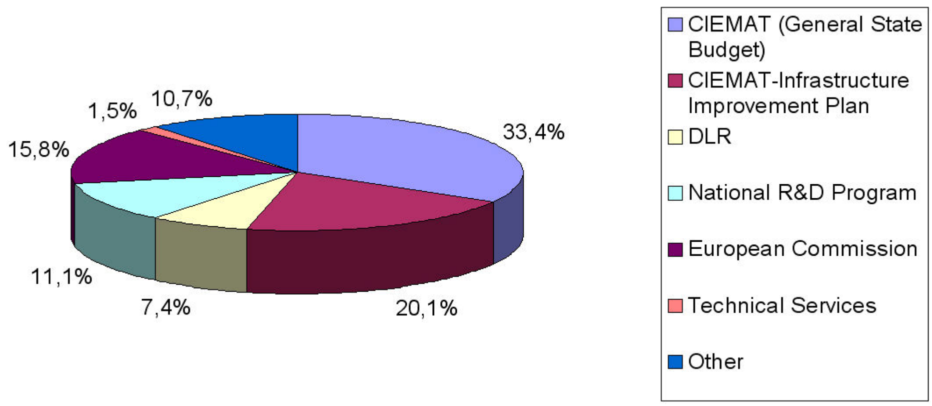


Figure 5. Distribution of PSA Income 2005

Scope of Collaboration

As mentioned above, the Spanish-German Cooperation Agreement with the DLR, commonly known as the CHA, has been maintained since 1987. At the present time, relations and commitments for scientific collaboration within this Agreement are regulated by its Annex IV, which includes a permanent DLR Delegation at the PSA from 2003 to 2005. A new Annex V covering the period 2006-2008 has recently been signed.

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, Switzerland, European Commission, South Africa, Israel, Algeria and Egypt).

2005 consolidated the recently formed Associated European Solar Energy Laboratory (SolLAB) activities. This virtual laboratory is 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 was signed in 2004 and the coordinated tasks have already begun to bear fruit, especially in the fields of flux and temperature measurement and training of Ph.D. students. The Swiss Paul Scherrer Institute has already become a new SolLAB member.

Training activities include an agreement with the University of Almería for joint management of research grants, as well as educational agreements for receiving students from universities all over Europe. The long-lasting collaboration with the UAL has been increased and consolidated with the creation of the CIEMAT-UAL Mixed Center for Research in Solar Energy 'CIESOL'. This year the CIESOL building was inaugurated on the University Campus in La Cañada, Almería. This building will be devoted to laboratories and rooms for joint meeting and training activities.

Figure 6. Edificio del Centro Mixto 'CIESOL' en el campus universitario de Almería

The scope of collaboration in the Concentrating Solar Systems Unit, continues to be excellent through PSA contacts with a wide range of national and international institutions. In projects related to parabolic-trough collector technology projects in 2005 with the Universities of Seville and Almería, research centers like INASMET, DLR, ZSW, and the Fraunhofer Institute for Solar Energy Systems of Germany and the Weizmann Institute of Science in Israel. In industry, there is intense contact with utilities such as IBERDROLA, electrical industry, such as SOLUCAR, GAMESA and the German FLABEG Solar International and engineering consulting firms such as the German FICHTNER and SBP, the Spanish INITEC and the French DEFY Systemes and EPSILON Ingenierie.

In the national scope of central receiver projects, collaboration continued in projects with such companies as SOLUCAR, SENER, IBERESE and SERLED, and universities, such as the University of Seville, Almería, the Polytechnic University of Catalonia and the UNED. Under the umbrella of the 6th Framework Programme's Energy Programme and the Spanish-German Agreement, there has been intense collaboration with DLR in several projects and 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).

The new lines of research in 'solar fuels and process heat' have given rise to new cooperative projects, among them the 'Instituto de Tecnología Cerámica de Castellón', the Venezuelan company 'Petróleos de Venezuela, S.A.', the Italian ENEA and the French CEA.

The Environmental Applications of Solar Energy and Characterization of the Solar Resource Unit has maintained and consolidated the extensive list of institutions with whom they have established relations in previous years. In fact, the list of current contractual relationships extends to all the possible spheres, from local (Univ. of Almería, DSM Deretil, Cajamar, Coexphal, Comunidad de Regantes Cuatro Vegas), national (Grupo Abengoa, Ecosystem, Aragonesas Agro, Emuasa, Indoor Air Quality, Fundación Inasmet, Autonomous University of Barcelona, Complutense University, and the Universities of Alcalá and La Laguna, the ICP-CSIC and the Hospital of San Carlos in Madrid), European (Weir-Entropie, Ao Sol, Hellenic Saltworks, Trailigaz, Janssen Pharmaceutica N.V., Ahlstrom Paper Group, IPM, Protection des Metaux, and universities: ETH, NTUA, INETI, EPFL, Claude Bernard Lyon 1, Poitiers, L'Aquila, etc.) and outside of the European Community where there are contracts with the Mexican Institute of Water Technology (Mexico), National Atomic Energy Commission (Argentina), National Univ. of Engineering (Perú), Tinep S.A. (Mexico), ENIG (Tunisia), Université de Fes (Morocco), Projema, S.A. (Morocco) y Photoenergy Center (Egypt).

Educational Activities

The principle governing the **Plataforma Solar de Almería's Training Program** is the creation of a generation of young researchers who can contribute to the deployment of solar thermal energy in all of its possible applications. Through this program, around thirty students of different nationalities are admitted every year who then contribute to the transfer of knowledge on solar thermal technology accumulated at the PSA during its twenty-five years of experiments to new generations of scientists. The main features of this training program are the following:

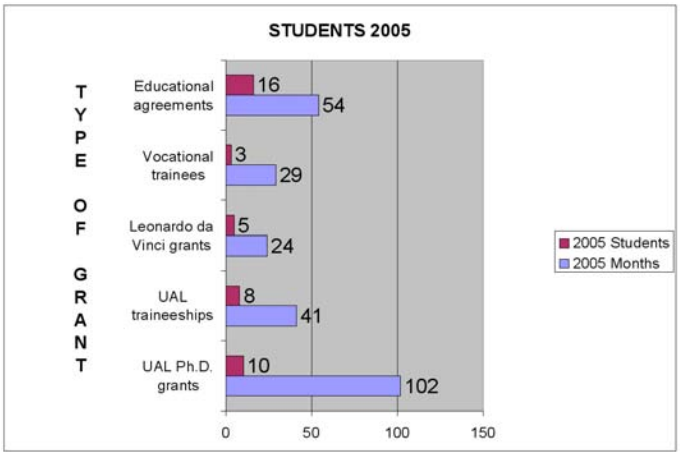


Figure 7. Student grants in 2005

- PhD research and training grants associated with the annual agreement with the University of Almería (UAL)
- EC 'Leonardo da Vinci' grants funding living expenses for European foreign students
- Miscellaneous specific educational agreements with other entities sending students to the PSA

The recent establishment of the European virtual laboratory 'SolLAB' has opened new possibilities for the scientific development of researchers in training at the PSA. One of the first joint activities initiated by SolLAB was annual seminars for Ph.D. students from the four institutions. On June 14-15, 2005, the first seminar was held the at DLR offices in Cologne.

Figure 8. PSA Participants in the Cologne seminar

Facilities and Infrastructures

General Description of the PSA

The PSA is located in southeastern Spain in the Tabernas Desert at 37°05'27.8" north and 2°21'19" west. It receives a direct annual insolation of over 1900 kWh/(m^2·year) and the average annual temperature is around 17°C.

The PSA's ability to offer researchers an experimental facility with climate 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 large scientific installations in the most advanced European countries, makes it a privileged site for evaluation, demonstration and transfer of solar technologies.

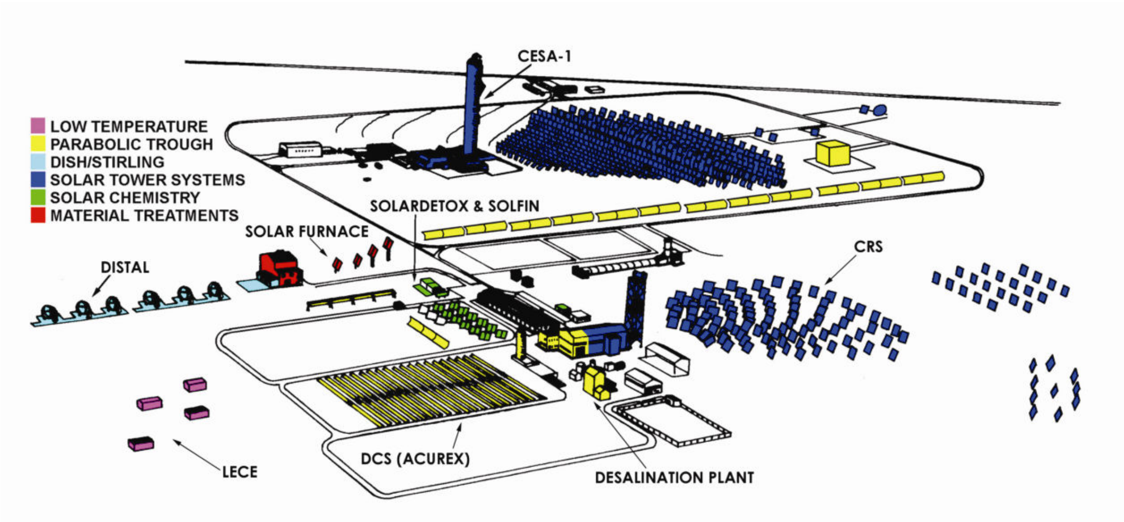


Figure 9. Location of the main PSA test facilities

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 MW_{th} respectively
- SSPS-DCS 1.2-MW_{th} parabolic-trough collector system, with associated thermal storage system and water desalination plant
- DISS 1.8-MW_{th} test loop, an excellent experimental system for two-phase flow research and direct steam generation for electricity production
- HTF test loop, a complete oil circuit for evaluation of new parabolic-trough collector components

- DISTAL dish/Stirling facility, 6 units.
- A 60-kW_t solar furnace for thermal materials treatments.
- A solar chemistry facility for solar detoxification applications consisting of a parabolic-trough loop with two-axis tracking and three CPC photoreactors for different types of trials.
- Laboratory for Energy Testing of Building Components[1] (LECE).
- 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.

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 a very flexible facility operated for testing subsystems and components such as heliostats, solar receivers, thermal storage, solarized gas turbines, control systems and concentrated solar radiation high flux measurement instrumentation. It is also used for other applications that require high photon concentrations on relatively large surfaces, such as in chemical or high-temperature processes, surface treatment of materials or astrophysics experiments.

Figure 10. The CESA-I facility seen from the East with heliostat rows focusing on the medium-height test level (60 m.)

Direct solar radiation is collected by the facility's 330-x-250-m south-facing field of 300 39.6-m^2-surface heliostats distributed in 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-

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

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 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 facet replacement and drive mechanism maintenance. To the north of the field are two additional areas used as test platforms 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/m^2, a peak flux of 3.3 MW/m^2 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 space shuttles during their reentry into the atmosphere in test pieces of the ceramic shield 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, 250-kW solarized turbine, and 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 520ºC 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 an electricity production demonstration plant, it 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$_{th}$ capacity range. The heliostat field is made up of 91 39.3-m^2 first generation Martin-Marietta units. A second field north of it has 20 52-m^2 and 65-m^2 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.

Figure 11. A CRS field heliostat reflecting the tower

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/m^2, total capacity of the field is 2.7 MW$_{th}$ and peak flux obtained is 2.5 MW/m^2. 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.

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

Figure 12. Front view of the 200-350-kW volumetric receiver test bed in the CRS tower

The test bed (Figure 12)consists of an 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 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 and place the PSA in a privileged worldwide 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 parabolic-trough

Figure 13. View of the DISS plant solar field in operation

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 suitable not only for the study and development of control schemes, but also for the study and optimization of the 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 circulates through the absorber tubes of a 665-m-long row of parabolic-trough collectors with 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 up to 100 bar pressure as needed (usually at 30, 60 or 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 equipped with all the instrumentation required for complete system monitoring.

Figure 14 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. 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 flexibility of system operation. The power block consists of water/steam separators, condensers, chemical dosing system, preheaters, deaerators 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.

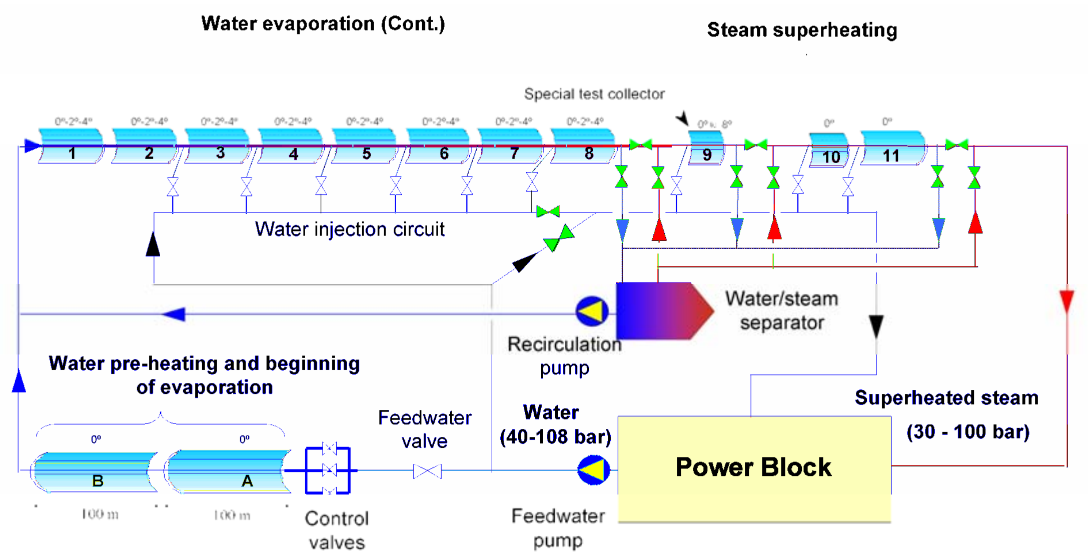


Figure 14. Simplified diagram of the PSA DISS plant

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 original facility consisted 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 400-kW maximum cooling.
- Centrifugal oil pump, with a flow rate of up to 8.3 liters per second
- 40-kW, 3-x-380 V electric oil heater.

Figure 15. General view of the HTF

In the HTF test loop, and in parallel to its initial solar collector, is the EUROtrough collector prototype which was installed later. 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, and it now forms part of the PSA parabolic-trough collector facilities. With the installation of the EUROtrough HTF loop, the system's collecting area has increased to 685 m^2.

A thermal storage system made up of four 5-m^3, 10-15-ton modules, two concrete and two ceramic, each with a 175-kWh storage capacity, have also been inserted in the test loop for evaluation (Figure 16). They are connected in such a way that they may be charged or discharged either together or separately.

Figure 16. Storage module tube bundles

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 from sunlight is 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.

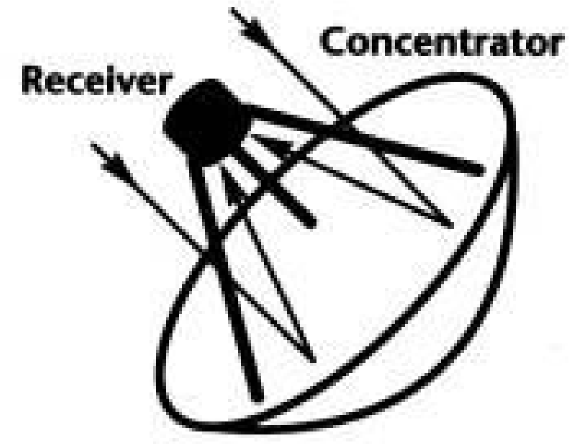


Figure 17. Schematic diagram of a parabolic dish with Stirling motor at the focus

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 18. 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.

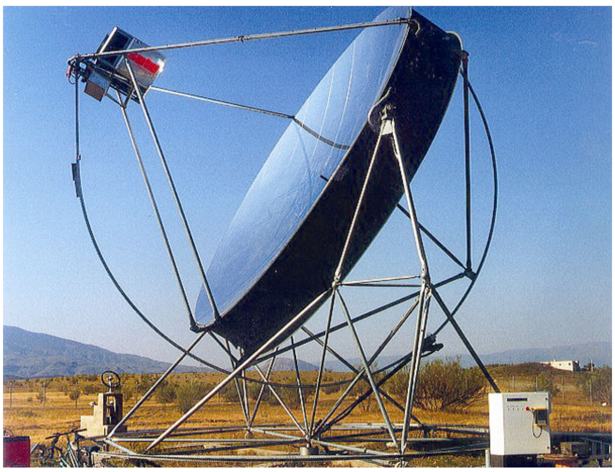


Figure 19. DISTAL II unit

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

Figure 20. Front and back views of the EUROdishes.

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.

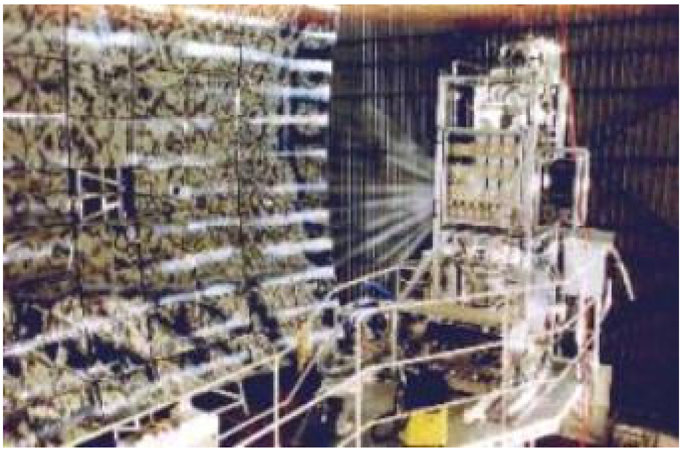


Figure 21. **Solar Furnace: Concentrator (left) and receiver in operation at the focus (right).**

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 22. **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].

Solar Chemistry Facilities

SOLAR PHOTOCHEMICAL FACILITIES

The first pilot plants with reactors for solar decontamination at the Plataforma Solar de Almería were developed at the beginning of the nineties (with support from the EU). The present configuration of the parabolic-trough collector photochemistry 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 rate 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, which can use diffuse radiation as well as direct, were installed. The CPC reflectors are made of anodized aluminum. At the PSA there are now several such plants. The oldest has three modules (1, Figure 23), each with a 3-m^2 surface tilted 37° from the horizontal, with a pump, tank and connecting piping for system operation. 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 (2) connected to a recirculation pump and a tank, increased the volume to 300 L. This col-

Figure 23. General view of the CPC Solar Photochemistry Facilities with the new collector in the foreground

lector 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 small twin prototypes (3) 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) in each reactor are mounted on a fixed platform also tilted 37º (local latitude). 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.

Due to developments in the context of the European CADOX Project (see R&D Projects, Environmental Applications of Solar Energy and Characterization of Solar Radiation), a new system consisting of a new CPC-type solar collector (4) (50-mm photoreactor diameter more suitable for photo-Fenton applications) with its corresponding tank and recirculation pump (75 L) coupled to a biological reactor has been installed (150 L based on biomass attached to inert matrix) and an ozonization system (50 L, with an ozone production system of up to 15 g O_3/h). All of monitored (pH, T, ORP, O_2, flow rate, H_2O_2, O_3) and computer-controlled (pH, T, flow rate). Small prototypes (5) have also been installed for disinfection applications under the European SOLWATER and AQUACAT Projects (see R&D projects, Environmental Applications of Solar Energy and Characterization of Solar Radiation).

There are also 3 ultraviolet solar radiation sensors available, one direct with solar tracking unit and 2 global in horizontal position and tilted 37ª (same angle as the CPCs) with regard to the earth's surface. All the data are sent to a computer that stores them for later evaluation of results.

SOLAR CHEMISTRY LABORATORY

The PSA Solar Chemistry Laboratory is a 75-m^2 building designed to hold all the conventional chemical laboratory equipment: workbenches, gas extractor fan hood, storeroom for small amounts of chemicals, central distribution of technical gases, UPS, safety systems (extinguishers, shower, eyewash, etc.) precision-scale workbench, ultrapure water system, ultrasonic bath, centrifugal vacuum distillation system, as well as many other systems normally used in a chemistry laboratory. In addition, it has the following analytical equipment 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 and automatic shredder. 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 Desalination Facilities

SOL-14 SOLAR THERMAL SEAWATER DESALINATION PLANT

This facility consists of the following subsystems:

- A 14-effect multi-effect desalination plant
- A CPC (compound parabolic concentrator) stationary solar collector field
- A thermal water storage system
- A double effect absorption heat pump (LiBr-H_2O)
- A water-tube gas boiler.

The system operates with water as the heat transfer fluid, which is heated as it goes through the solar collectors to the storage system. The hot water from this storage system provides the MED plant with process heat.

The solar field is composed of 252 stationary solar collectors (1.12 x Ao Sol CPC) with a total surface area of 500 m^2, arranged in four rows of 63 collectors. Due to the reverse return piping, the nominal total flow rate (14.97 m^3/h) is distributed uniformly among the four

Figure 24. SOL-14 stationary solar collector field (500 m²)

rows (3.74 m³/h) without need for any additional regulation. The collectors are arranged in groups of nine, each of which is connected in parallel in each row, which are in turn connected in parallel to the main header line to the storage tanks. Each group of nine collectors is arranged in the following manner: i) the collectors are lined up east-west to maximize solar energy collection, ii) each group is subdivided into three subgroups of three collectors, iii) the collectors in each subgroup are connected in parallel; iv) each subgroup is connected to the one after it in series. The maximum operating temperature is 100°C since the collectors are connected to the storage tanks in an open loop at atmospheric pressure.

The thermal storage system consists of two interconnected 24-m³ water tanks. This volume allows sufficient operating autonomy for the backup system to reach nominal operating conditions.

The fossil backup system is integrated by a propane gas water-tube boiler with a maximum production of 200 kg/h of saturated steam at a pressure of 10 bars. Each boiler ensures heat-pump (180°C, 10 bar) and MED plant operating conditions when there is no solar radiation. The gas is stored in a 2450-litre outdoor tank, allowing 143 hours of operating autonomy.

The desalination plant consists of a 14-effect multi-effect distillation unit, which is connected to the thermal storage system described above. For nominal production of 3 m³/h of distillate, plant consumption is 190 kW_t, with a performance factor (number of kg of distillate produced by each 2.326 kJ of thermal energy consumed) over 9. The salt concentration in the distillate is around 5 ppm. The nominal temperature gradient between the first and last effects is 40°C, with a maximum operating temperature of 70°C in the first effect. The vacuum system is made up of two hydroejectors fed by sea water at 3 bar. The

Dimensions:	2012 x 1108 x 107 mm
Apertura area	1.98 m²
Absorber	
Emissivity	0.10 - 0.15
Absorptivity	0.94 - 0.95
Weight (empty)	38 kg
Operating pressure..........	6 bar
Test pressure	12 bar
Optical efficiency............	0.70 - 0.71
Thermal loss factor	3.4 W/m²-K

Figure 25. Technical specifications of the 1.12x AoSol solar collector and detail of the piping in the solar collector field

vacuum system evacuates the unit at operation startup, compensates for small amounts of air and gas released with the feed water, and small losses that could occur in the various connections.

In 2005, a new prototype double-effect (LiBr – H_2O)absorption heat pump was installed developed specifically for connection to the multi-effect distillation plant at the PSA. This device increases the MED plant performance facto to about 20 due to the heat recovered from condensing low-exergy saturated steam produced in the last effect.

Figure 26. **Double effect absorption heat pump installed in the SOL-14 plant**

STATIONARY SOLAR COLLECTOR TEST PLATFORM

Figure 27. **View of the stationary solar collector test platform**

This facility was erected in 2002 for the purpose of offering additional services to the scientific research community, especially energy characterization of stationary solar collectors and their possible application in solar desalination processes.

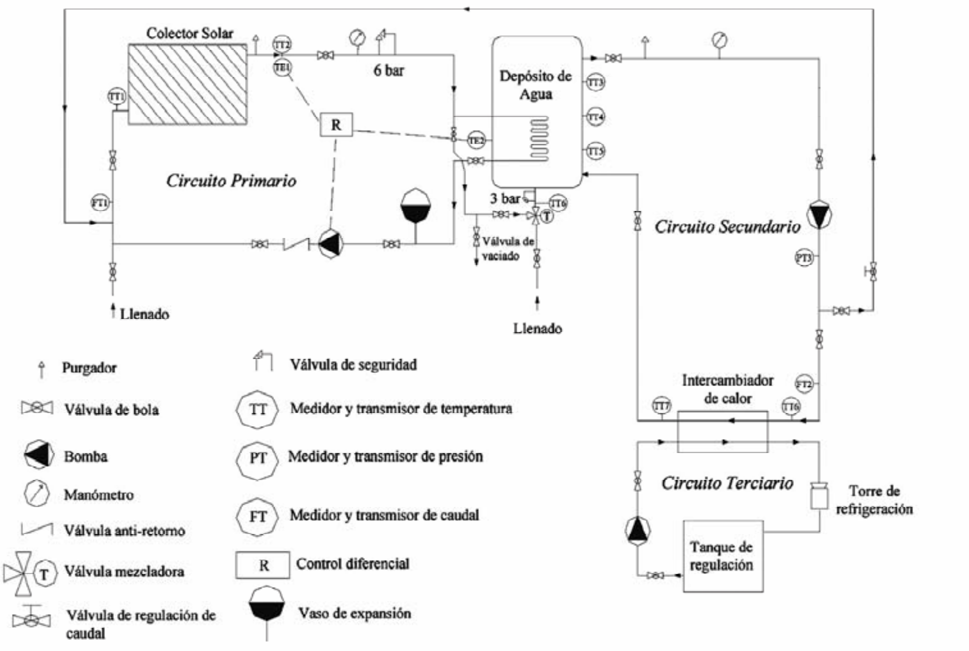


Figure 28. **General diagram of the stationary solar collector test platform**

Other Facilities

PSA METEOROLOGICAL STATION

The PSA has had a meteorological station since 1988, primarily for measuring integral solar radiation (global, direct and diffuse radiation), but also for other generic weather variables (temperature, wind speed and direction, relative humidity and atmospheric pressure, cumulative precipitation, etc.). The task of entirely remodeling this old station has recently been undertaken. Given the framework in which our facilities work, from the beginning this initiative was intended to comply with the strictest requirements of quality and accuracy in solar radiation measurement. As an overall indication of having reached this goal, the station has been a full member of the World Meteorological Organization's Baseline Surface Radiation Network, whose directives it follows, since October 2005.

In addition to measurement of the meteorological variables mentioned, its most outstanding feature is the measurement of the spectral distribution of solar radiation.

The new radiometric station's equipment may be classified in three basic groups:

1) ***Measurement instruments***. The PSA meteorological station instruments are in the highest range of solar radiation measurement. All the radiation sensors are ventilated and heated, and have a temperature measurement sensor. This equipment provides the best information on solar radiation and more general atmospheric variables, and can be used for filtering input data and validating spectral models. They are used for:
   - Measurement of the terrestrial radiation balance. Incoming and outgoing shortwave and long-wave radiation is measured at 30 m
   - Solar radiation characterization: components (direct and diffuse) and UV.
   - Vertical wind profile: wind speed and direction at 2, 10 and 30 m
   - Miscellaneous weather information: pluviometer, barometer and psychrometer

Figure 29. General view of the new PSA radiometric station

2) ***The Spectroradiometer*** is so different that it must be considered an independent installation. It is a prototype developed to CIEMAT specifications by *Instrument Systems*. This equipment, based on the SP320D, which incorporates a photomultiplier and a lead sulfur detector, records the spectral distribution of the solar radiation over its whole spectral range (from 200 to 2500 nm), compared to the majority of such equipment which works only for a part of the spectrum (generally visible or ultraviolet). The basic equipment is connected to a switch in such a way that it can work with three alternating probes, which are arranged in a solar tracker to record the global, direct and diffuse solar radiation, respectively. Although it is configurable, the equipment has been programmed to record a spectrum (with an approximate resolution of 2 nm in UV and visible and 10 nm in IR) in about 7 minutes, and changes measurement probes every 10 minutes. This way we have an hourly database with 2 spectra for each one of the solar radiation variables. Another important difference from the usual solar radiation spectral distribution measurement equipment is that it operates continuously from sunup to sundown.

3) ***The data acquisition system***. This system was specifically Developer in Visual C++ using IMP cards. Acquisition frequency is 1 s with 1-minute, hour and daily averaging. The data are stored in a relational database management system, described below, and a series of physical and other filters are applied during acquisition. It is worth mentioning that this data acquisition system is connected to a GPS which also acts as a high-precision time server.

4) ***The database***. The database was developed in Microsoft SQL Server 2000 and consulting tools were developed in ASP so it would work on the internet. The data base tables are dynamic, making it possible to remove or add sensors to the station without having to modify the table structure. The database size is designed to provide simultaneous access to 10 years of second data and averages of all the variables recorded. In 2005 the tools for its usage were completed and at the present time the information is available on the PSA website. In order to find out the demand for the information, it is necessary to log on for access.

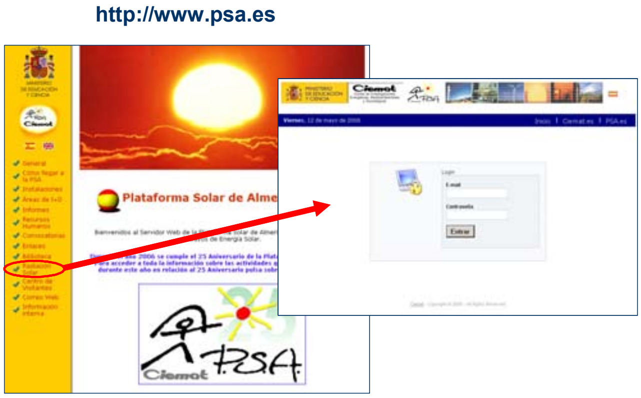


Figure 30. User login for access to solar radiation information.

THE SPECTRAL CALIBRATION LABORATORY

The need for a calibration laboratory arises from the way in which the Spectroradiometer is designed to operate. This equipment usually works only during specific measurement campaigns, in which case yearly recalibration is recommended. However, this equipment is in constant operation, so on-site calibration is necessary to:

- Minimize loss of data during calibration periods (around 1 month if the equipment must be sent to the manufacturer).
- Be able to increase calibration frequency as needed: every six months, quarterly, monthly or even weekly.

The calibration laboratory has been specially designed for calibration over the whole 200 to 2500 nm range.

Figure 31. Spectroradiometer probes for measuring global and diffuse radiation as installed in the solar tracker

Figure 32. Spectroradiometer detector with three-probe connector switch

Figure 33. **New Spectral Calibration Laboratory adjacent to the CESA-1 building**

Figure 34. **CEDER Radiometric Station in Soria**

RADIOMETRIC STATION AT CIEMAT - CEDER (SORIA).

This new station will provide better solar radiation information, and also serve as a comparison with PSA measurements. It is quite similar to the one at the PSA, but with simpler equipment in a shed on the roof. The sensors, arranged in a 2AP solar tracker, record global radiation and its two components.

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 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. LE high-precision time server CE 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 35. **Views of the LECE: Cells, reference buildings and solar chimney**

R&D Projects

Introduction

Research in the various groups at the PSA has continued to enjoy good health during 2005.

In the Solar Concentrating Systems Unit, activities continued in direct steam generation technology (DSG), which is expected to reduce the costs of solar thermal electricity production by around 30%. The nucleus of activity was the European INDITEP project which aims at detailed design of a 5-MWe DSG plant. The years of experience accumulated during the continual operation of the PSA DISS loop will be a decisive factor in the success of this project.

Furthermore, during 2005, activities to clear up the last remaining technological unknown in the DSG process, thermal storage, were begun. The main objective of the DISTOR

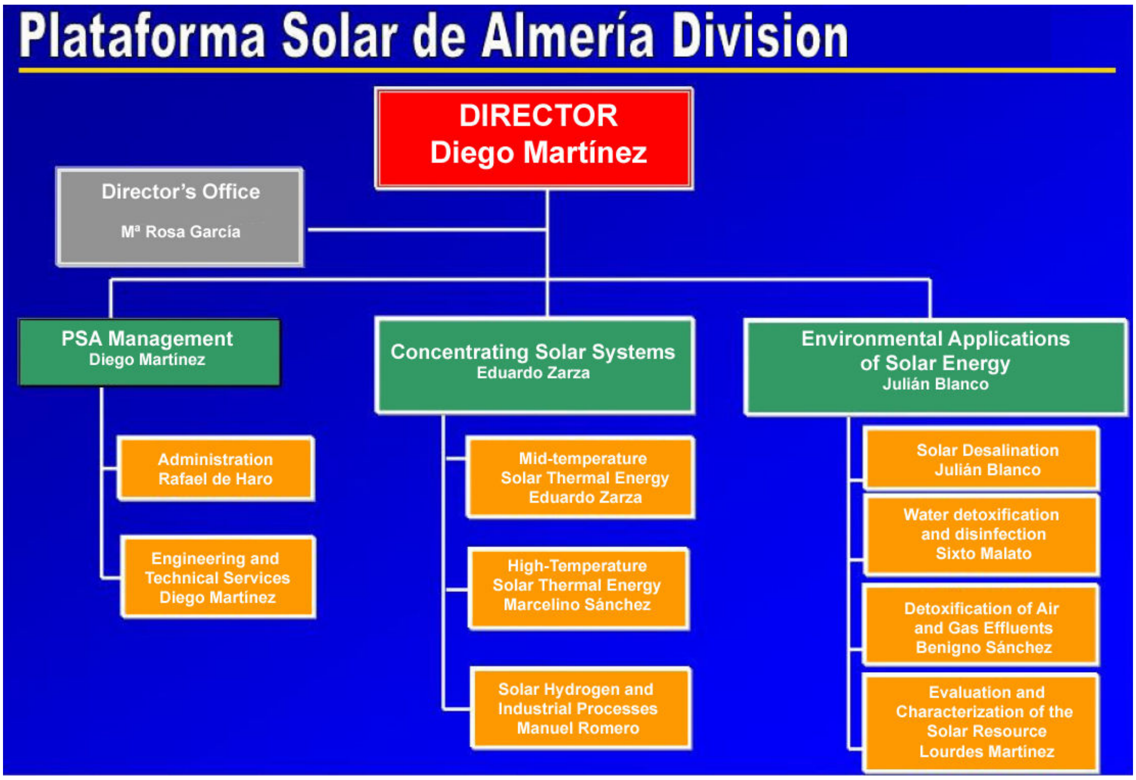


Figure 36. **PSA R&D Project Organization**

project, partly financed by the European Commission, is to develop a competitive thermal storage system adequate for solar plants with direct steam generation in the solar field. A storage system based on phase-change materials is under development for this purpose.

In central receiver technology, research activity has focused on technological collaboration with the companies building the first two commercial power tower plants, PS10, which is due to be inaugurated at the end of 2006 and will be the first solar thermal power plant in Spain, and SOLAR TRES, which is based on the use of molten salts as the working fluid, and is still in the promotion stage. Strategic collaboration has begun with SENER for the testing and validation of a receiver panel for this commercial plant.

Thermochemical hydrogen production also has a place in the group's activity. Phase 2 of the project undertaken with Petróleos de Venezuela, S.A. and the ETH of Zurich, was begun this year. A 500 kW receiver to validate scale up of the technology will be designed, fabricated and tested on the CRS tower.

2005 was an especially important year for the 'Environmental Applications of Solar Energy and Characterization of the Solar Resource' Unit, as the activities defined as its objective after the restructuring of CIEMAT at the beginning of 2004 became consolidated. The proof of this was the approval at the end of 2005 of a total of 5 European projects (European 6th Framework Program) plus another for excellence from the Autonomous Community of Madrid.

Growth of scientific and industrial interest in detoxification of waste water as an application of sunlight was outstanding in 2005. This was demonstrated by new industrial facility at the DSM-Deretil company in the framework of the CADOX project, based on the technology previously used in pilot plants.

In the field of solar disinfection, the SOLWATER and AQUACAT projects, which made it possible to develop a combined system (through generation of different oxidants) for the control of pathogenic elements present in drinking water tested successfully in Mexico, Peru, Argentina, Morocco, Tunisia and Egypt, were completed. Although the results were highly satisfactory, these systems are still in a preliminary stage of development. In seawater desalination, it is worth mentioning the culmination, after 4 years of development, of the AQUASOL project which provided the PSA with a highly innovative experimental facility and which, given its complexity and multitude of possibilities, is going to be a very useful tool for the design and practical implementation of this kind of systems based on the multi-effect distillation technology.

Solar Concentrating Systems Unit

INTRODUCTION

2005 was the Solar Concentrating System Unit's (SCSU) first year at the PSA, as at the beginning of the year the "High Temperature Solar Thermal Energy" and "Parabolic-Trough Collector Technology" R&D programs were merged to form the present SCSU. This was done as a result of CIEMAT restructuring toward the end of 2004 in order to optimize available resources and promote horizontal cooperation among the various departments, divisions and R&D groups at the CIEMAT.

The general goal of the SCSU is to promote and contribute to the development of solar concentrating systems, both for electricity generation and industrial process applications that require solar concentration, regardless of whether this need is for mid-temperature, high-temperature or high photon flows.

SCSU R&D activity is structured in three Groups: i) Mid-temperature, ii) High Concentration and iii) Solar Fuels and Solarization of Industrial Processes, which provides a transition between the previous situation with differentiated activities and personnel and the current situation with activity requiring attention to increased requests for consulting services from the newborn commercial sector and participation in research, development and demonstration projects. This situation suggests distributed management in the three Groups or areas of activity mentioned, but sharing personnel, experimental capabilities, etc., to optimize resources.

The new structure’s internal procedures enable an adequate flow of information and cooperation among its three Groups, so that R&D activity in each group does not become an exclusive work package, but rather encourages horizontal collaboration among them, making more efficient use of available Unit resources.

Solar radiation concentration is necessary for processes requiring high temperatures and/or high efficiencies. The shape of the concentrating system and its relationship to the receiver, where the concentrated radiation is transferred to the process of interest, is limited to a few technologies, all of which are present at the PSA: 1) linear-focusing parabolic-trough collectors which provide medium concentration (up to 50 times incident solar flux) and temperatures of up to 450°, with applications in industrial heat and electricity generation; 2) heliostat fields with central receiver tower, which achieve high concentrations (up to 1500-2000 times incident solar flux) and temperatures of up to 1100ºC, with applications in electricity generation and fuel production (such as methane reforming, etc.); 3) parabolic dishes, which achieve high concentrations (flux up to 2500-3000 times incident solar flux) and are usually applied to electricity generation (placing a Stirling motor and generator in the focal area); 4) finally, solar furnaces make it possible to work at the same concentrations as dishes (or more if a secondary concentrator is used, achieving flux of up to 10000 suns), but under near laboratory conditions.

In the Medium Concentration Group, activities are mainly related to the parabolic-trough collector technology (since this is the type of collector best suited to this temperature range), while activities in the High Concentration and Solar Fuels and Solarization of Industrial Processes Groups are related to the central receiver, dish/Stirling and solar furnace.

In pursuing the general goal mentioned above (promoting and contributing to the development of solar radiation concentrating systems), the activities common to all three groups include:

- Applied or technological research, such as the design, development, testing and evaluation of components and processes that represent or may represent improvements in the cost/benefit ratio for the developments of reference.
- Maintenance of quality and improvement in experimental capabilities, that allow us to continue being an international experimental reference in all types of solar concentrating technologies.
- Development and or use of analytical and design tools for plant and/or component predesign studies; feasibility studies; or optimization of the integration of the solar concentrating devices in more efficient electrical conversion system, both in thermodynamic cycles and direct conversion systems.
- Contribute to the development and consolidation of an industrial sector, by transferring technology, making feasibility studies and R&D roadmaps and defining action tending to eliminate the technological barriers that impede penetration of these technologies; communication of lessons learned in reports, publications in journals, contribution s in congresses, giving courses and seminars, etc.

In addition to these common goals and activities, each of the three groups has articulated its activity in 2005 around a few goals or priority fields of development:

Medium Concentration Group:

- Development of high pressure and temperature *Direct Steam Generation* in the parabolic-trough receiver tubes themselves in order to eliminate the oil now used as the working fluid in solar plants with this type of collector.
- Develop new parabolic-trough collector designs suitable for their application in industrial heating and cooling.
- Development of a thermal storage system using change-phase materials (latent heat storage).

High Concentration Group:

- Contribute to the design of a domestic molten-salt tube-receiver technology able to surpass the characteristics of the American Solar Two, taken as a reference and which may be implemented in the first commercial plant of this type, Solar Three.
- Development of the volumetric absorber technology, particularly the uncertainties still associated with them, such as their durability, optimization of the geometric design and thermophysical properties effective under high-flux/high-temperature conditions.
- Development of high-temperature, high solar concentration components and systems that are more efficient and cheaper, especially those with the most weight in the total plant cost (concentrator, receiver, thermal storage) and simplification of associated O&M through high levels of automation.
- Exploitation of the central receiver component testing, operation, control and evaluation capabilities and experience, by participating in third-party national and international development projects.

Solar Fuel and Industrial Process Solarization Group:

- Solar hydrogen production with various procedures.
- Study of physicochemical and thermochemical behavior of high-temperature materials, and
- Testing of photovoltaic cells and devices at high concentrations. This activity is done in collaboration with the High Concentration Group

The R&D activities carried out in the Solar Concentration Systems Unit are described further below separately for each one of the three Groups that make up the Unit.

Medium Concentration Unit

The Medium Concentration Group activities have the following general goals:

1. Development of new components and applications for concentrating solar systems that work in the range of temperatures between 150ºC and 45ºC, called the *mid-temperature range*.
2. Development of modeling and simulation tools for solar systems with parabolic-trough collectors, which are today the most widely used commercially in the temperature range indicated above, and
3. Promote the creation of a Spanish industrial nucleus to which the technology and knowledge acquired by the PSA in mid-temperature solar systems can be transferred, so that this industrial nucleus can drive commercial development, inside and outside of Spain, of mid-temperature concentrating solar systems.

Since the parabolic-trough collector technology, known by the initials PTC, is at present the best developed for solar radiation conversion into thermal energy in the mid-temperature range (150ºC-450ºC) or medium concentration (<100), current activities in the SCSU Medium Concentration Group are almost exclusively devoted to this technology. However, we also aware of a new technology which, although it is in its infancy from the commercial point of view, presents interesting characteristics for application in the same range of concentration and temperatures ad the parabolic-trough collectors. This is the Fresnel Linear Concentrators (FLC), of which up to now only a small number of prototypes have been installed.

The PTC are linear focusing, concentrating solar collectors which convert the direct solar radiation in thermal energy and are ideal for working with solar radiation concentrations of around 20 to 80 times. Due to concentration of the direct solar radiation incident on the collector aperture plane, it efficiently raises the temperature of the working fluid to above 400ºC. For this reason, the PTC are ideal for supplying industrial process heat between 150º and 400ºC. In view of the large number of processes that meet this condition, the commercial interest of the PTC is very important, since its commercial implantation could significantly contribute to meeting the Kyoto commitments for CO_2 emissions reduction as well as Spanish and European Union dependency on imported energy.

A PTC is basically made up of a parabolic-trough mirror that reflects direct solar radiation, concentrating it on a receiver tube placed in the line of focus of the parabolic mirror. This concentrated radiation causes the fluid that circulates inside the tube to heat up, transforming the solar radiation into thermal energy in the form of the sensible heat of the fluid. The photograph in Figure 37 below shows how a PTC works.

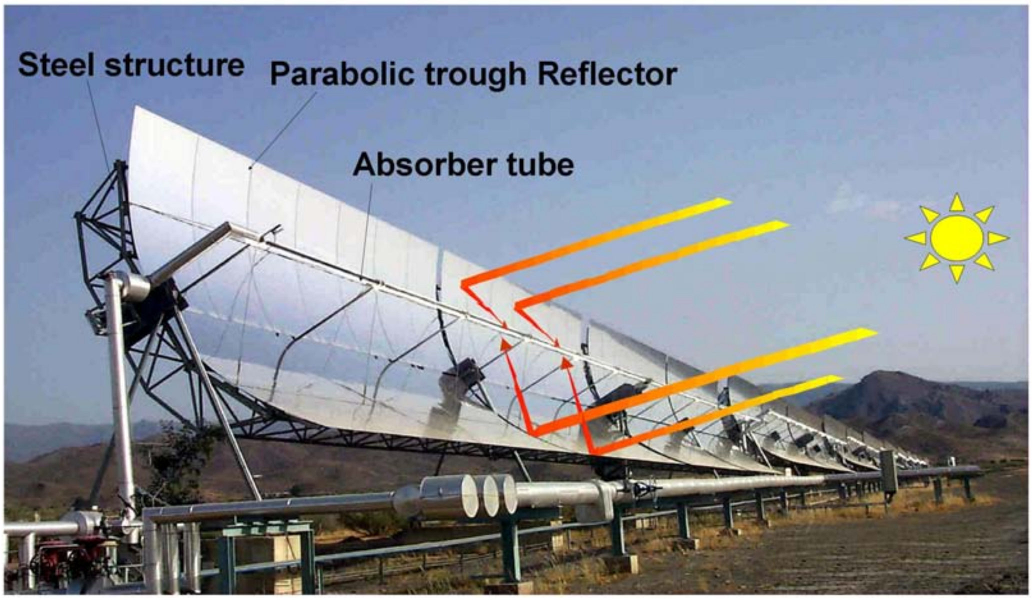


Figure 37. **Working principle of a parabolic-trough collector**

Medium Concentration Group activities are grouped into different projects that each have their own group of partners, budget and planning. The final results pursued by this set of projects is to promote its commercial implantation.

Among the activities carried out by the Medium Concentration Group at the PSA during 2005, those related to high-pressure, high-temperature direct steam generation in the PTC absorber tubes continued to occupy a position of major importance. This new technology, known by its initials DSG (Direct Steam Generation), continues to demonstrate its great interest for reducing the cost of the thermal energy supplied by this type of solar collector, since it makes the thermal oil and oil/water heat exchanger now employed in this type of solar facility unnecessary. A simultaneous feasibility study on the use of new working fluids for parabolic-trough collectors has also been done to explore new possibilities for cost reduction and increased efficiency.

In 2005, the strong contrast already demonstrated in 2004 between the technical and market maturity of the PTC plants for electricity generation (thanks to the valuable experience contributed by the SEGS plants in California) and the lack of development of other possible medium concentration or mid-temperature range solar energy applications that are also of interest, such as industrial process heat and industrial heating and cooling.

There continues to be a lack of solar collectors and industrial equipment on the market with suitable characteristics for this type of applications, which recommends a strong R&D drive to meet the same level of development they have for electricity generation. Spain, as in many other countries located in the so-called Solar Belt, has climate conditions that make these other mid-temperature solar system applications very attractive. This is why in 2005 at the PSA we had a certain amount of activity in this field and have continued working in the development of components for industrial heating and cooling and industrial process heat. We therefore continued to participate in Task 33/4 ("Solar Heat for Industrial Processes" or SHIP; www.iea-ship.org) of the International Energy Agency in order to take advantage of the experience and knowledge of solar thermal energy applied to industrial heat which other international entities possess. The area of work at the PSA related to mid-temperature solar systems has thus been enlarged as traditionally it concentrated exclusively on electricity generation (solar thermal power plants). However, the logical limitation of available resources has made the weight of activities related to solar radiation applied to solar heating and cooling and industrial process heat much less than the solar thermal power plant activities.

PSA activities in the Medium Concentration Group in 2005 were mainly related to the *INDITEP, DISTOR, FASOL* and *PREDINCER* projects. The activities and results achieved in these projects by the PSA in 2005 are described below.

INDITEP PROJECT

The INDITEP Project officially began on July 1, 2002 and ended on June 30, 2005. It received funding from the European Commission (Contract nº ENK5-CT-2001-00540) and the activities planned in it constitute the logical technical continuation of the DISS project activities (1996-2001). Once the technical feasibility of the Direct Steam Generation (DSG) process was demonstrated in the DISS project (Eck, et al, 2003), the next logical step was to optimize the process and its essential components, and at the same time, undertake the detailed design of the first commercial solar thermal power plant using direct steam generation in the solar field.

The INDITEP project was planned with our basic targets:

1) Detail design of a pre-commercial 5-MWe DSG plant
2) Optimization and advanced development of components to make the DSG technology more competitive (economic compact water/steam separator, etc.)
3) Characterization under real solar conditions of the most important components for DSG solar fields.
4) Socio-economic study of the DSG technology.

Most of the INDITEP project partners (IBERDROLA, ABENGOA, CIEMAT, DLR, Flabeg Solar, GAMESA, INITEC, SIEMENS and ZSW) also participated in the DISS project, which has ensured perfect continuation and connection between the activities of the two projects. The CIEMAT participation in the INDITEP project in 2005 concentrated on the following activities:

- Participation in detailed engineering of the pre-commercial 5-MWe DSG plant
- Operate and maintain the DISS plant in order to write operating and maintenance procedures for commercial DSG plants, and also evaluate new water/steam separators
- Study the behaviour under real working conditions of the new ball joints in the solar DSG collectors
- Develop new selective coatings able to resist temperatures of up to 550º.

PSA activities in each of these four areas are described below.

Detailed engineering of a pre-commercial 5-MW_e DSG plant:

Figure 38 shows a general simplified diagram of the pre-commercial DSG plant designed in the INDITEP project. The gross electric power is 5.47 MW, while the net electric power of the power block is 5.17 MW, with a net performance of 24.9%. The solar field is made up of seven parallel rows, each composed of ten 100-m ET-II collectors. In each row, the evaporating and superheating sections are separated by a water/steam separator. The total aperture area of the solar field is 38,385 m^2, with a peak thermal power of 15 MW (Zarza et al., 2004).

The main contribution of the PSA in 2005 to the detailed engineering of the 5 MW_e DSG plant was the technical specifications for instrumentation required in the solar field, and operating and control procedures, written in collaboration with IBERINCO, DLR and ZSW (Eickhoff *et al*., 2005). Since there has been no practical experience with a similar plant, the operating procedures contain all of the options learned in the PSA DISS experimental plant that seem commercially feasible, and there is no way to ensure which of the possible startup, shutdown and control options written in the INDITEP project for the pre-commercial 5-MW_e plant will be the best for larger commercial DSG plants, so the various options must be evaluated and optimized experimentally in the plant itself. These activities will take up the first 18 months of the 5-MW_e plant operation.

Tests defined for this period are the following:

1. Tests for verifying alarm limits and operation at programmed locations during solar field emergencies. Estimated duration: 1 month, included in the period of plant startup
2. Tests related to solar field startup and shutdown procedures to find out the advantages and disadvantages of the various options available from the viewpoint of large commercial DSG plants. Estimated duration: 4 months (at various times of the year.)
3. Tests related to process control parameters during routine operation. Estimated duration: 4.5 months minimum (tests at different times during the year.)
4. Evaluation of system thermal/electric performance under ambient conditions (summer/winter). Solar field process parameter optimization to increase final plant performance. Estimated duration (4.5 months minimum (tests at different times of the year).
5. Main solar field and power block component evaluation (water/steam separators, solar collectors, turbogenerator, etc.). Estimated duration: 4 months.

PSA DISS plant operation and evaluation of new components:

Another important fraction of participation of the PSA in the INDITEP Project in 2005 was devoted to testing in the experimental DISS plant to evaluate the new compact wa-

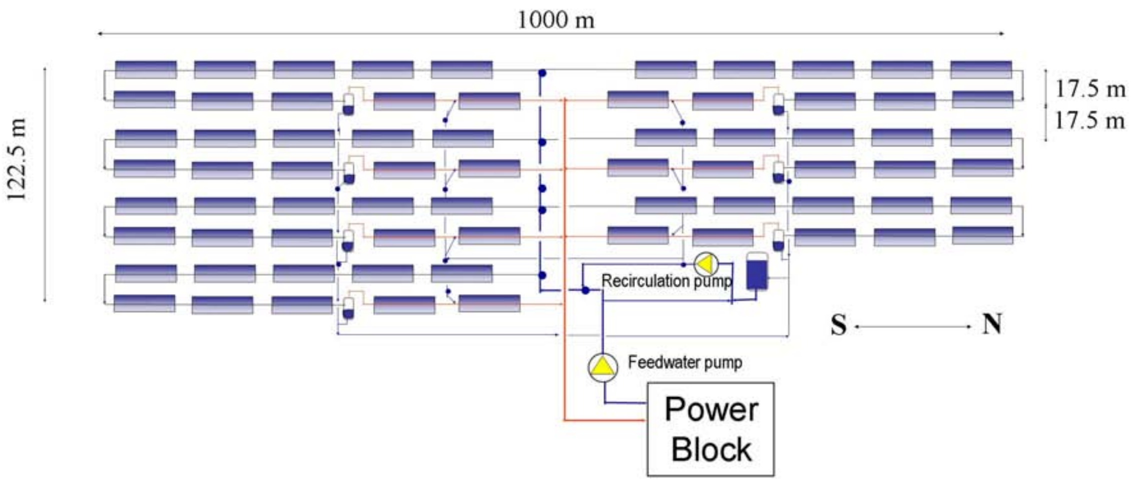


Figure 38. General diagram of the pre-commercial DSG plant designed in the INDITEP Project

ter/steam separators and continue testing different operating and control strategies.

In 2005, the DISS plant was operated for a total of 832 hours and three water/steam separator prototypes have been successfully installed, two cyclone separators in the same place and a third, plate separator in parallel. These separators were assembled in the interface installed by the DLR in the DISS loop in 2004.

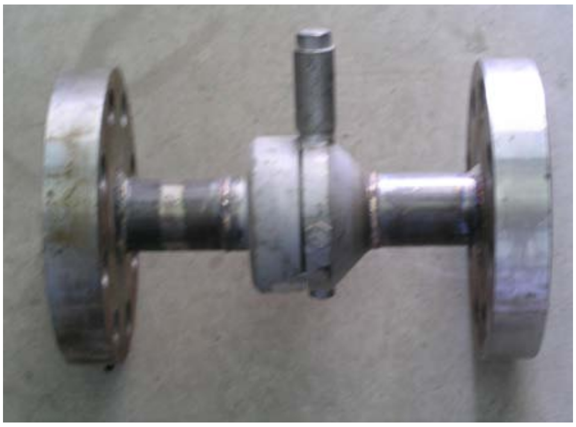
302 tests were completed in the DISS plant during 2005, distributed as below (tests not valid are not included):

Operating tests: 8
1st separator calibration, statistics and dynamics testing: 57
2nd separator designed by Frametone calibration, statistics and
dynamics testing:...87
DLR (plate) separator statistics and dynamics testing :...................................79
Control tests:...16
Ball joint testing at 30 and 70 bar: 55

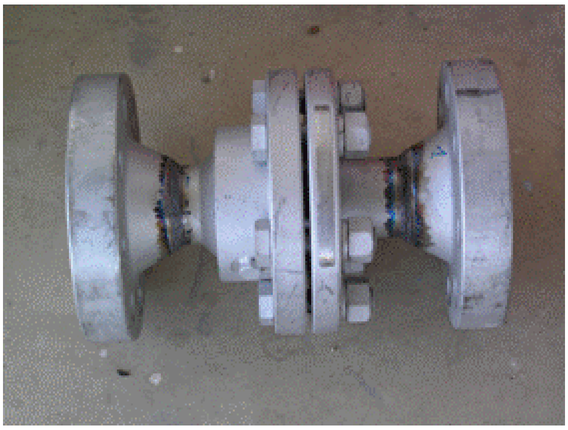
As demonstrated in the test list above, in 2005, 55 new ball joint tests were done at pressures of 30 and 70 bar. The tests carried out by the PSA with new ball joints have two aims:

- Evaluate the behavior of the new ball joints at 120 bar/400°C, so there are several commercial models available for DSG plants working under these pressure and temperature parameters in the solar field. The possibility of several manufacturers is important to avoid a monopoly leading to excessively high prices.
- See if it is possible for ball joints to allow the parameters of steam produced by the DSG solar fields to be increased to 100 bar/550°C, to improve performance in the power block. In this sense, the study carried out in the DISS project demonstrated that a regenerative Rankine cycle working with steam at 100 bar/550°C can increase solar/electric performance up to 23.2%. But ball joints suitable for these pressure and temperature parameters must be available for this to be possible.

Since the only ball joints for DSG solar fields for 100 bar/400°C experimentally evaluated to date under real solar conditions are manufactured by the American Advanced Thermal Systems (ATS) company, in 2005, two models by a different manufacturer, the HYSPAN company. The two models tested are for 120 bar/400°C and °00 bar/550°C. The tests done in 2005 were with steam produced in the DISS solar field and had a maximum pressure of 70 bar. The figure below shows the two models of ball joints that were tested in 2005. It can be observed that the flanges necessary for the ball joints to install them in the test bench that we have at the PSA for this type of experiments. It is planned that once the 30 and 70 bar tests have been completed, they be tested at higher pressures of up to 550°C at the ENDESA *Litoral de Almería* power plant in Carboneras, Almería. For various technical reasons, it was not possible to complete all of the tests planned in 2005, so they will continue



HYSPAN 120bar/400°C ball joints



HYSPAN 100bar/550°C ball joints

Figure 39. The two HYSPAN ball joint designs for DSG plants.

into 2006.

Some improvements were also made to the DISS plant in 2004. An example of these improvements is the installation of a new absorber tube and change in position of three more. Improvement in local open loop local controls was also continued in collaboration with the Electronics Technical Office installed in the DISS plant collectors. One new version of this control was installed in the two ET-II collectors that were added to the DISS plant at the beginning of the INDITEP project and are now under observation and evaluation.

As advanced in the 2004 Annual Report, in 2005, the PSA worked on integrating our local solar tracking control into an overall plant architecture suitable for the current technological situation. In this direction, some steps were taken in meetings with companies in the sector, but industry does not seem to be taking a serious interest in this subject, so it is still open.

- **Development of new Solgel coatings:**

In 2005, in the framework of the INDITEP project, the PSA has been working on developing antireflective glass coatings and selective high-temperature absorbers. The activity in these two fields is summarized below.

a) Antireflective glass coatings

In the last few years, antireflective coatings have been found with very good optical (τ_{solar}>0.97) and mechanical properties for coating the glass of the absorber tubes. In 2005 the outdoor durability of these coatings was studied in a QUV weathering chamber which alternates cycles of condensation, temperature and UV radiation.

It has been experimentally proven that there is a strong hydrophobic influence on the outdoor durability of the film. To augment this property in the material, different concentrations of methyltriethoxysilane (MTEOS), the methyl radical of which is non-hydrolizable were added, conferring strong hydrophobicity to the antireflective film, which completely repels water. The following figure shows the transmittance in the solar spectrum of the materials prepared.

Incorporation of MTEOS in the solution as a precursor of polymeric silica with triton produces a slight decrease in the solar transmittance, which becomes more severe the higher the MTEOS content.

Figure 40 below shows the behavior of different materials in the weathering chamber. The antireflective coatings prepared without MTEOS show a decrease in transmittance of almost 5%, while those prepared with 10% MTEOS, the drop is less than 1.5%, after 2000 hours of testing, which corresponds to about 5 years outdoor exposure. Next year, different materials are going to be tested to try and increase the hydrophobicity of the antireflective film and improve its outdoor durability.

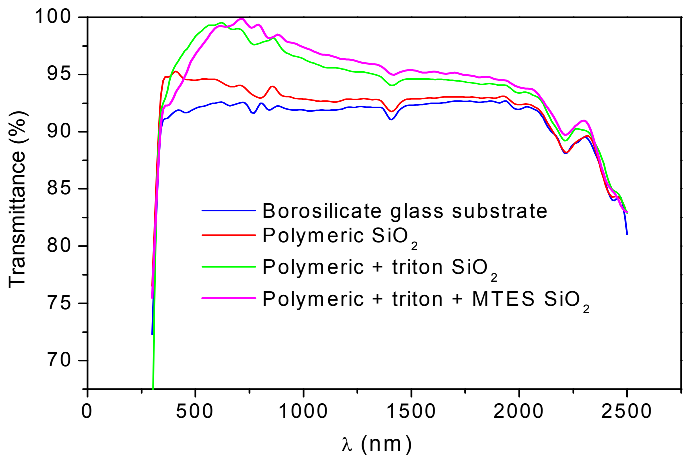


Figure 40. Solar transmittance of the different antireflective materials prepared with borosilicate glass.

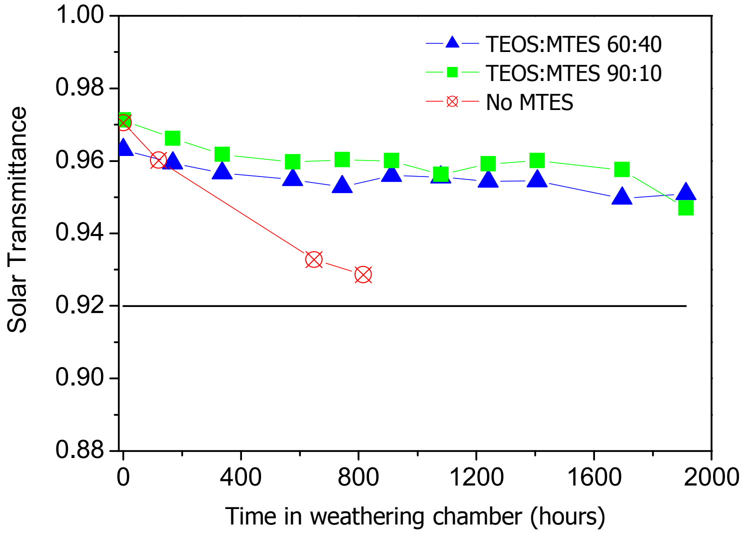


Figure 41. **Variation in solar transmittance of the various AR coatings in the weathering chamber**

b) Selective high-temperature absorbers.

In 2005, we concentrated our efforts on finding a selective high-temperature (550ºC-600ºC) stainless steel pipe coating stable in air. At high temperatures, in the selective absorbers the mechanism that fails is mainly thermal oxidation of the infrared reflector and diffusion of chemicals among the various coatings of the absorber.

In 2005, a fine coating of platinum was used as an IR reflector to avoid oxidation in air and an alumina/platinum cermet anti-diffusion barrier to make the IR reflector stable in air at 550ºC.

Two different materials were employed as absorbent coatings, one dual coating made of two alumina/platinum cermets with different metal content, and one $Mn_xCo_yCu_zO_4$ spinel.

The optical properties of the cermet absorber completely developed at the PSA, with the antireflective silica coating are α=0.95 and ε_{500C}=0.14. The individual coatings were sintered at 600ºC with no degradation of the optical properties. The thermal durability of this absorber is under study at 550ºC in air, with promising results.

To reduce the cost of the absorber and the number absorbent coatings, the possibility of substituting the alumina/platinum cermet with an spinel is being studied. Spinels are

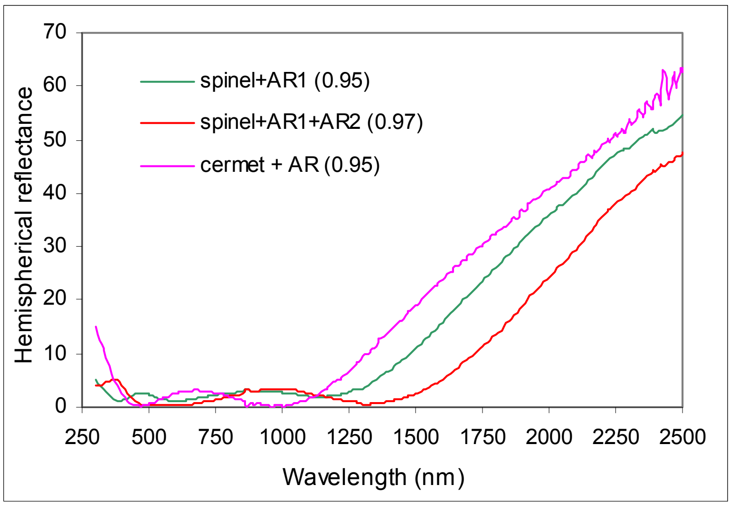


Figure 42. **Hemispherical reflectance of three selective high-temperature absorbers developed at the CIEMAT**

highly thermally stable materials so they are good candidates for high-temperature applications. The initial results are good and solar absorptance of up to 0.97 with thermal emissivity higher than with the cermet absorber coating have been achieved. The following figure shows the absorbent edge of the spinels, which have much higher wavelengths than the cermet, implying greater emissivity.

Emissivity of the absorbers with spinel and one or two antireflective coatings at 500°C is 0.18 and 0.26 respectively. Next year, the thicknesses of the spinel and antireflective coatings will be optimized to increase solar absorbency and reduce thermal emissivity.

DISTOR PROJECT

The DISTOR Project is a European R&D Project with financial assistance from the European Commission (Contract N°. SES6-CT-2004-503526). This 45-month project officially began in February 2004. It is coordinated by the German DLR and has a large number of participants: CIEMAT-PSA, Sistemas de Calor, INASMET and IBERINCO (Spain), DEFY Systemes and EPSILON Ingénierie (France), SGL Technologies GmbH and FLAGSOL GmbH (Germany), Sanlucar Solar Solucar, S.A. (Spain), ZSW (Germany), Weizmann Institute of Science (Israel), and the Central Laboratory of Solar Energy and New Energy Sources (Bulgaria).

The main purpose of the DISTOR project is to develop competitive storage suitable for direct steam generation solar plants. Since most of the thermal energy in the steam is released when it condenses, and this process takes place at a constant temperature, the best storage system for this type of solar plant would be based on a medium that absorbs heat at a constant temperature. This leads to a need for thermal storage based on latent heat using phase-change materials, which is what the DISTOR project is developing. Mixtures of sodium nitrate and potassium prepared with another material providing acceptable thermal conductivity to promote charging and discharging in the storage system are being studied. The economic goal of the DISTOR project is a specific cost of 20€/kWh storage system capacity, since this figure would make it profitable.

Thermal storage systems in the 150°-400°C range currently available are based on materials that increase in temperature (sensible heat) and therefore are not valid for solar systems with direct steam generation. This is precisely the need for developing a storage system specific to solar fields with direct steam generation, since without it, continuous generation of electricity with solar systems of this type is not possible.

The participation of the PSA in the DISTOR project concentrates on two specific areas:

1. Technical specifications the storage system to be developed must meet
2. Installation in the PSA DISS experimental plant and evaluation under real solar conditions of a first 200 kWh-capacity prototype of the new storage system.

As the technical specifications were completed in 2004, our participation in the DISTOR project in 2005 concentrated on preparing the prototype's installation in the DISS experimental plant scheduled for the end of 2006, specifically, reviewing the prototype's interface with the DISS plant, which is the only experimental plant with direct steam generation in the solar collectors in operation today, as proposed at the beginning of the project. This was necessary because the information obtained from PSA activities in another European R&D project (the INDITEP project) made it clear that the interface initially proposed would not be suitable. Figure 43 shows the interface first proposed.

In the schematic shown in Figure 43, pump P-23 is a key element, since it will have to operate under a high pressure water flow rate (approx. 80 bar) and near-saturation temperature, so the available NPSH would be very low. Such a pump is infrequent in commercial applications, making it prohibitively expensive (>75,000€). Furthermore, this pump would probably be very inefficient (<25%), so a new interface design was necessary.

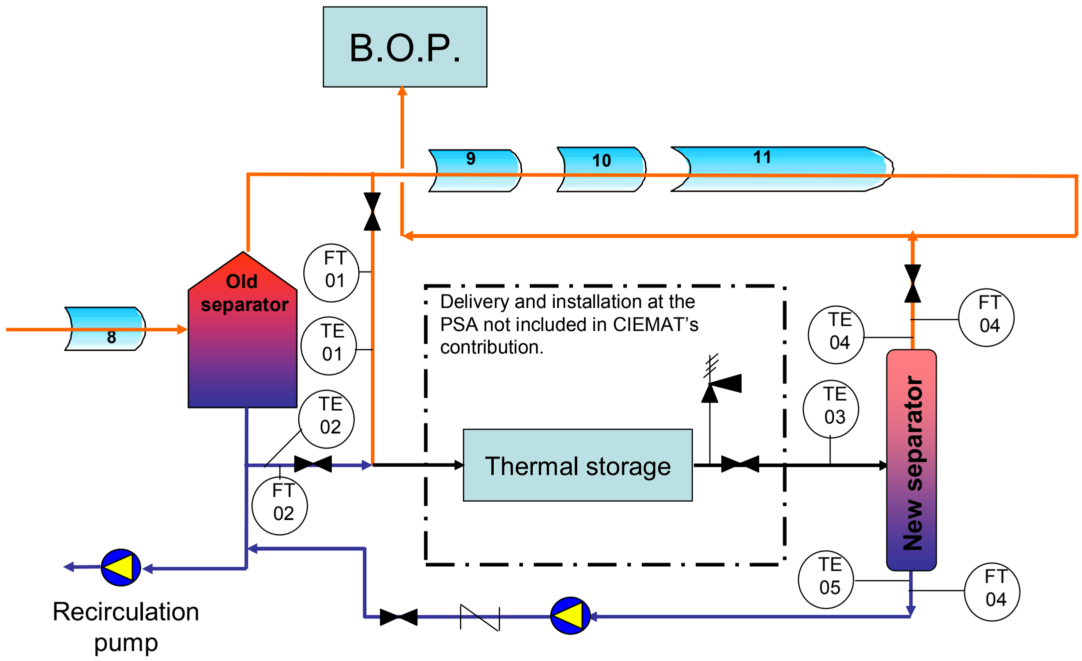


Figure 43. **Schematic diagram of the interface initially proposed for connecting the storage module to the PSA DISS experimental plant.**

After considering various options, the interface shown in Figure 44 seemed the most suitable, since the two water pumps required are already installed in the DISS plant. This makes it cost considerably less than the first proposal. The use of the flash tank already existing in the DISS plant also makes pressure compensation possible using economical perforated plates.

In 2005, the PSA also worked on the conceptual design of the data acquisition and control system necessary to monitor storage module testing. Although at the beginning of the project, it was planned to implement new measurement channels in the DISS data acquisition and control system, this option was discarded to avoid possible perturbation of DISS plant operation, and a data acquisition and control system specific to the storage module, but directly communicated to the DISS plant, will be installed instead.

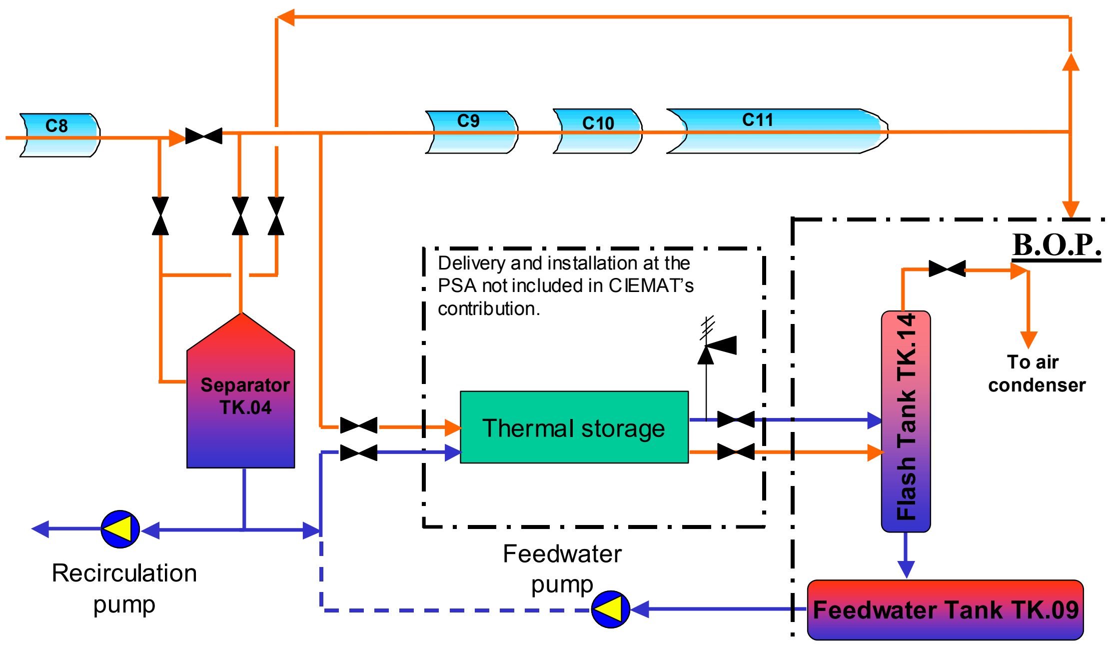


Figure 44. **Schematic diagram of the new storage module interface proposed for the PSA DISS experimental plant**

FASOL PROJECT

The purpose of the FASOL Project is to develop a new medium-size parabolic-trough collector suitable for small-to-medium solar thermal energy applications at temperatures up 300ºC. The activity carried out in this project was closely related to our participation in International Energy Agency **Task 33/IV (Solar heating for industrial processes)** (www.iea-ship.org), with which we have been collaborating since it began in 2003.

Knowing that information is one of the main requirements for extending solar thermal energy into the area of industrial processes in Spain, the Medium Concentration Group organized a Workshop in the first quarter of 2005 in the framework of the 9th GENERA (Energy and Environment International Trade Fair) in Madrid. 70 persons attended the course, including representatives of industry interested in energy savings and efficiency as well as the solar thermal industry and members of national and international solar energy R&D centers. Two articles were also written on the potential of solar thermal energy and keys to its industrial application. One was published in a widely distributed engineering journal and the other was presented at the National Renewable Energies Congress, CONEERR 2005 (Rojas, Cañadas, 2005).

On a scientific-technical level, our collaboration with Task 33/IV is mainly within Subtask C, "Development of new collectors and components" and D, "System integration and demonstration plants".

In Subtask C, we continued working on the design and development of a collector for industrial process heat known as the FASOL project. Experience acquired in 2004 demonstrated that the parabolic-trough reflector is one of the still unsolved technological specifications, both with regard to the parabolic shape of its support structure and weather resistance of its reflective materials.

In mid-2005, a company in Almería, Castaño Bolea e Hijos, made a new parabolic-trough concentrator similar to the two previous prototypes (reinforced composite material on a metal structure with a 2.6-m-wide aperture) but with a new methodology appropriate for treatment and curing of the composite material. The optical quality of the parab-

Figure 45. **First page of the announcement of the workshop in industrial applications of solar thermal energy**

ola of this third prototype was evaluated at the PSA by photogrammetry and, although the results were better than with the two previous prototypes, it became clear that for adequate optical quality of the parabolic-trough collectors, the manufacturer must be highly specialized in the handling and treatment of composites.

In view of the general flexibility of plastics, the possibility of their use as a reflective surface support instead of the thin glass usually used for this was explored in the FASOL project. Two mirrors, one with a methacrylate and the other a polystyrene support, and in both cases, an aluminum reflective foil, were tested. They were exposed to outdoor conditions at the PSA for eight months, during which time the spectral reflectivity was measured periodically and different cleaning treatments were tried out. While the methacrylate mirror was returned to its nominal reflectivity with a simple cleaning method, degradation of the polystyrene mirror had already made it unacceptable for its application in parabolic-trough collectors after the first two months of exposure.

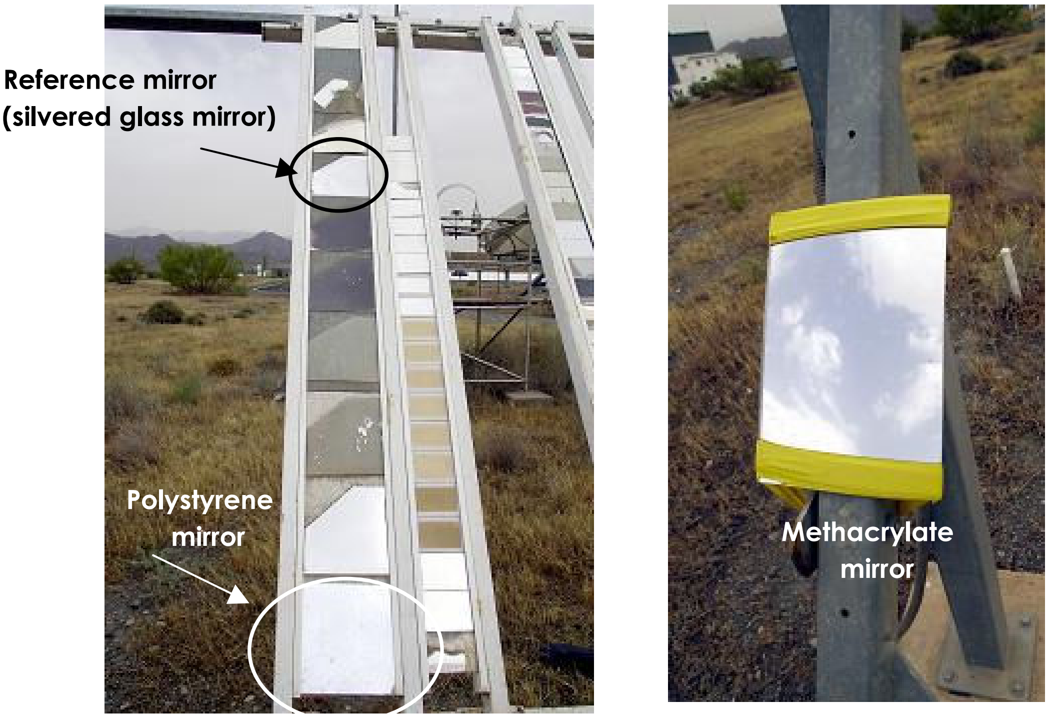


Figure 46. **Outdoor test bed for reflective materials**

In 2005, the new optimized collector concept for industrial process heat evolved, in the first place, toward a smaller design (no more than 1.50 m aperture) so it can be installed on rooftops and terraces and, in the second place, toward less conventional designs, such as a glass cover in the aperture plane (protecting the parabolic reflector from the ambient) to provide a larger number of reasonably-priced materials options. A mathematical model has been designed to reproduce the optical and geometrical performance of these designs with different combinations of materials. This optical-geometrical efficiency model, along with the thermal efficiency model already developed previously, will make it possible to find out what combination of materials and collector design has the best cost/efficiency relationship.

PREDINCER PROJECT

The PREDICNCER Project is a coordinated R&D Project with funding from the Ministry of Education and Science under its CICYT program (Project ID: DPI2002-04375-C03). The project began in 2002 and ended in November 2005. In the framework of the project, the CIEMAT collaborated with the University of Almería Robotics, Electronics and Automatics Department Research Group and the University of Seville Systems Engineering and Automatics Department (project coordinator), to study different bounded-uncertainty process models, and develop and evaluate predictive control algorithms applicable to solar parabolic-trough collector fields for them.

The project goals undertaken were:

- Development of modeling techniques and identification of bounded-uncertainty models
- Development of formulas that include the uncertainty in the predictive controller design stage
- Analysis of the robustness of the formulas and their modification to ensure robustness.
- Computational studies and implantation of the algorithms
- Identification of the reference test plants, and
- Validation of the controllers developed in the DISS plant

For existing DISS and Acurex PSA parabolic-trough plants (PTC), we have analyzed First-Principle (mass balance, energy and momentum) non-linear model structures using the Dymola software tool and the object-oriented language, Modelica (Figure 47), simplified non-linear First-Principle models with bilinear simplification, with which we have been able to develop controllers employing the feedback linearization technique to reject disturbances (Figure 48), and linear models around a work point found both by simplifying First-Principle models where the bounded uncertainties of the parameters (physical magnitudes) are estimated taking into account the system operating ranges, and using parametric identification of I/O data, where low-order dynamic models are found with additive uncertainties like:

$$\sum_{i=0}^{n_a} a_i y(t) = \sum_{i=0}^{n_b} b_j u(t-d-j) + e(t)$$

These models are being used to apply robust model predictive control techniques (robust MPC) (Figure 49). The MPC controller takes the uncertainty or discrepancies between model and plant into account in the design, considering the worst possible outlet case calculated by the model. Then an algorithm minimizing the maximum target function pos-

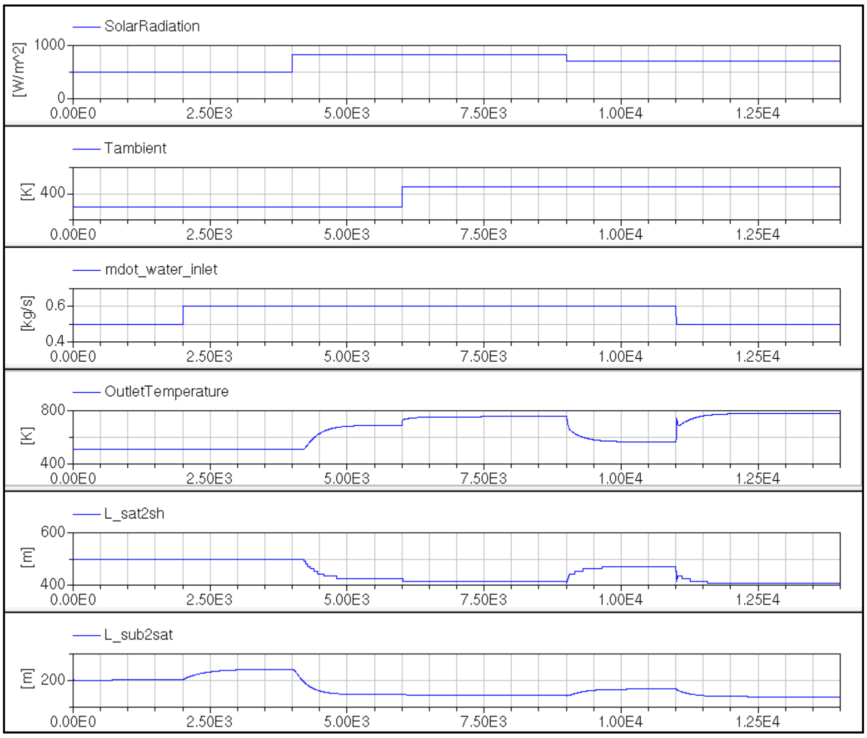


Figure 47. Results of DISS loop simulation developed with the Modelica/Dymola tool with the progress of outlet steam temperature and the length of the saturated/superheated steam interface when there are steps in solar radiation, ambient temperature and Feedwater flow rate.

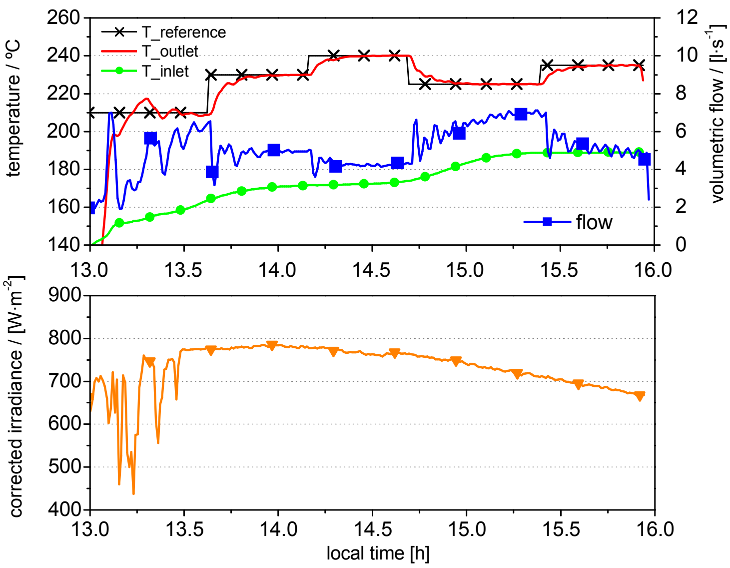


Figure 48. **Results in the Acurex solar plant. Application of feedback linearization control designed from the non-linear (bilinear) simplified model. Disturbances in radiation and inlet fluid temperature.**

sible in the classic MPC is implemented for all uncertainties (min-max predictive control), that is, the optimum controller action sequence, *u*, is calculated as:

$$u^* = \arg \min_{u \in U} \max_{\theta \in \Theta} J(u, \theta)$$

where *U* is the set of permissible action sequences, θ is the uncertainty and Θ is the set of values considered for the uncertainty.

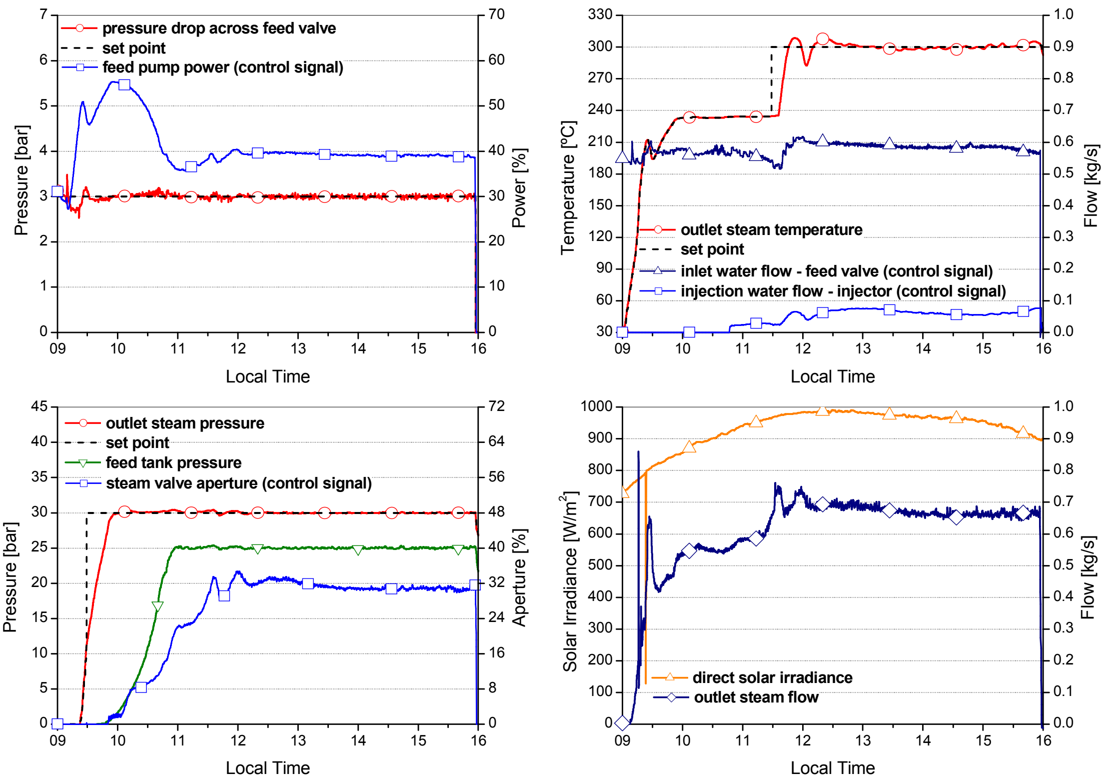


Figure 49. **Results in the DISS plant: Application of control schemes designed from linear models around a work point. System response with outlet steam pressure and temperature control under instable direct radiation**

In addition to applying these control techniques, the behavior of this type of solar system during disturbances has also been improved. The use of automatic command generators has also increased plant automation, the number of operating hours planned and, thereby, the final efficiency of these solar systems, for which an increase in production of more than 2-3% is estimated.

Concerning computational studies, our work on the implementation of an OPC (*OLE for Process Control*) data server in the PSA DISS plant should be pointed out. The OPC protocol can make different computer tools compatible, allowing real-time communication of the DISS plant control application and data acquisition (Symphony/INFI90 de Elsag-Bailey/ABB) with the modeling and simulation environments we use to develop and implement the controllers and models (Modelica/Dymola or Matlab/Simulink).

The project (2002-2005) produced 7 articles in scientific publications and 17 communications to national and international congresses.

OTHER ACTIVITIES IN 2005

In addition to their work in the INDITEP, FAROL, DISTOR and PREDINCER projects, the PSA Medium Concentration Group also worked in other areas, among them, the tests carried out in the PSA HTF loop, such as the WANDA and OPAL projects, mainly directed at collaboration with the DLR and financed by the German BMU, are worth mentioning. In 2005, DLR performed 36 charge tests and 33 discharge tests in the PSA HTF loop with the concrete thermal storage system in the WANDA project. The system was operated for 12 days to test and adjust the automatic storage system inlet temperature control using automatic valves installed in the oil pipes.

Other types of tests performed in the HTF loop have been the adjustment of off-sets in the EUROTROUGH collector local solar tracking control installed in this loop, thermal loss tests and infrared absorber tube temperature measurement.

Nineteen thermal performance tests, 6 photogrammetry tests and 6 incident flux measurement tests on the collector absorber were also performed in the EUROTROUGH collector using direct sensors (German "Parascan II" project).

In 2005, the HTF test loop was also used to evaluate new components developed by Spanish industry. This test loop was operated for a total of 763 hours in 2005.

The PSA also participated in the ANDASOL-1 project, although due to the delay in starting construction, participation in 2005 was less than planned and was limited to technical and scientific advisory services to the companies responsible for detailed engineering and plant construction in matters related to the solar field.

In the field of Direct Steam Generation, steps toward construction of the 5-MW_e pre-commercial plant designed in the INDITEP project were begun. Contact was made with possible partners, an unavoidable step if the DGS technology is to be used commercially in large thermal power plants. The construction of large commercial DGS plants is impossible if a pre-commercial-scale plant has not first verified everything related to control and operation of the DSG solar field. The results and experience acquired at the PSA in the experimental DISS loop provides a promising basis that makes us optimistic in so far as the feasibility of the DSG project for large commercial plants, but does not allow us to eliminate the reluctance that possible investors may have due to lack of previous experience in a large enough plant to ensure proper functioning of large DSG plants. This is the goal pursued with the design of a 5-MW_e DSG plant in the framework of the European INDITEP project. The main problem that arose in 2005 in attempting to build this 5-MW_e DSG plant is the lack of adequate public subsidies, since national or regional demonstration project programs were not intended for projects like this one.

Furthermore, as in 2004, we also continued to meet the requests of a large number of companies interested in the parabolic-trough solar thermal power plant technology who came to the PSA for consulting and information. The legal framework defined in Spain for solar thermal power plants by Royal Decrees 436/2004 (BOE of 27/03/2004) and 2351/2004 (BOE of 24/12/2004) has meant an important leverage for Spanish industrial activity in this field. The premium set for electricity produced in solar concentrating plants in any of its three variants (parabolic-trough, central receiver or dish/Stirling), along with the possibility of an annual 12-15% hybridization with gas, has strengthened the interest in the investment and industrial sectors in the solar concentrating technologies. These attractive conditions have led numerous companies to the PSA in 2005 in search of consultation and collaboration. Unfortunately, the logical limitation of available human resources in the PSA Medium Concentration Group and previously acquired commitments in projects already underway have made it impossible to take care of all of the requests for collaboration received in 2005 as well as we would have liked, but a great effort was made to provide the maximum information and advice possible to companies that have requested it of us.

High Concentration Group

The two things that should be mentioned in 2005 because of their importance as an activity in itself and the advancement of the general goals of the High-Concentration Solar Thermal Energy Group (HCSTE), were a consequence of the new framework of incentives for solar thermal power production (RD 436/2004):

- The great advance in the construction of the PS10 plant, the civil engineering work of which was almost completed at the end of 2005, and
- The reactivation of the Solar TRES project, for which CIEMAT undertook validation of the salt receiver technology shared by SENER and CIEMAT.

The power tower, or central receiver system (CRS) technology, consists of a large field of heliostats or mirrors that track the position of the Sun at all times (elevation and azimuth) and direct the reflected rays onto the focus placed at the top of a tower. As it is a fixed focal point, off-axis optics are used, so its analysis and energy-optical optimization are complicated. The orders of solar concentration are from 200 to 1000 and rated plant capacity from 10 to 50 MW, usually less than in parabolic-trough concentrating plants. They can use a wide variety of thermal fluids, such as saturated steam, superheated steam, molten salt, atmospheric or pressurized air, and operate in temperature ranges between 300°C and 1000°C. It is a technology in which the PSA has a long tradition of research and two absolutely privileged facilities, the CESA-1 and CRS with very flexible test beds for testing and validation of components and subsystems.

Their high incident radiation flux (typically between 200 and 1000 kW/m²) enables them to work at high temperatures and be integrated in more efficient scaled cycles, from Rankine cycles with saturated steam to Brayton cycles with gas turbines, are easily hybridized in a wide variety of options, and with thermal storage, have the potential for generating electricity with high capacity factors, so that today, systems above 4500 equivalent hours per year are possible.

Central receiver systems, after a scale-up and demonstration stage, are today at the gates of commercial operation. To date, more than 10 experimental facilities have been tested worldwide. They have usually been small 0.5 to 10 MW systems and the majority were operated in the eighties. That experience demonstrated the technical feasibility of the concept and its ability to operate with large thermal storage systems, as well as to test various receiver concepts which are differentiated by the type of heat transfer fluid employed, such as molten salt, saturated steam or air-cooled volumetric receiver. The most extensive experience has taken place in several 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 since then have improved components and procedures, so that today, predictions place system solar-to-electric conversion efficiency at 23% at design point and 20% annual. In spite of everything, the great central receiver system challenge still pending is a first generation of commercial grid-connected plants operating under market conditions.

The high capital cost is still an obstacle for the making full commercial use of their potential [Romero, Buck y Pacheco, 2002]. The first commercial applications that are about to be born still present installed power costs of 2500 to 9000€/kW (depending on the size of storage) and costs of electricity produced are around 0.16-0.20€/kWh under certain favorable boundary conditions. A reduction in the cost of the technology is therefore essential to enlarge the number of commercial applications and potential sites. Aware of this problem, the PSA, in addition to participating in the first CRS commercial demonstration projects, has a permanent line of system and components R&D aimed at reducing costs and improving their efficiency.

Royal Decree 436/2004 of March 12th (BOE nº 75, March 27, 2004) which lays out the methodology for updating and systematizing the legal and economic framework, includes most of the ambitions and demands of the scientific, technological and industrial sector interested in promoting the development and commercial implantation of solar thermal power in Spain. With the approval of an incentive tariff schedule for solar thermal power which in practice recognizes a sale price for electricity generated in solar plants three times higher than the market price, the basis is set for activating the sector and unblocking a series of projects that have been planned since 1998 with active participation of the PSA. Interest of business and engineering firms in the central receiver tower and dish/Stirling technologies has been revitalized, and as a result, the PSA is in their sights as the technological tractor and pole of diffusion of knowledge and experience in the subject.

Furthermore, in August, 2005, the Renewable Energies Promotion Plan for 2005-2010 was published to revitalize the slow development of the first plan for 2000-2010, and which, in view of the enormous movement in applications for solar thermal power plant technologies permits, has increased the power limit to be covered by Royal Decree 436/2004 from 200 MW to 500 MW installed in 2010.

A tangible result of this regulating framework in the central receiver technologies has been the reactivation of the two plant projects mentioned above, the 11-MW PS10 led by the SOLUCAR company and the 17-MWe SOLAR TRES plant promoted by the SENER company. Both plants will have a decisive influence in the next few years in demonstrating the commercial maturity of these systems.

The civil engineering work for the SOLUCAR PS10 plant was almost completed by the end of 2005 and its connection to the grid is planned for Fall 2006. This is the most important central receiver technology development event in the world. Although the activity of the High Concentration Group in 2005 on the PS10 was slight, the implications of the materialization of PS10 have changed our priorities insofar as technological development. Thus volumetric receiver technology has been relegated to a secondary priority, since it is not being used in the PS10 receiver, and has reactivated interest in the optimization of tube receivers.

Moreover, the 17-MW_e Solar Three commercial central receiver demonstration plant project, which employs a molten salt receiver developed by SENER and CIEMAT, was again undertaken in 2005. After a period of lethargy due to circumstances beyond the control of CIEMAT, SENER and CIEMAT decided to go ahead and undertake development of the receiver, in spite of the absence of outside technological offers, and initiate its validation with the construction, testing and evaluation of a 4-MWth prototype. The resulting receiver technology will be co-owned by SENER and CIEMAT, and after its validation in 2006, will be used in the Solar Three Plant.

This momentum of technological deployment has conciliated the participation of the PSA High Solar Concentration Group (HSCG) in both demonstration projects (PS10 and Solar Three), with the performance of other R&D activities in specific projects, almost all of them financed by public R&D programs, with the exception of salt receiver panel development for which financing is shared by SENER and CIEMAT. So three types of HSCG R&D activity can be distinguished:

A) Participation in demonstration projects (such as PS10 and Solar Three);

B) Technological Development of Components and Systems

C) Improvement of experimental capacity and quality procedures

Specifically, the High Concentration Group participated in the following projects in 2005:

A) PARTICIPATION IN DEMONSTRATION PROJECTS:

1) Project: "PS10: 10 MW Solar Thermal Power Plant for Southern Spain"; Ref. NNE5-1999-00356. Announcement: 1999/C 77/13. Financed by: EC- DG XVII (ENERGIE Program). Head researcher: Rafael Osuna (SOLUCAR). Participating entities: CIEMAT, SOLUCAR (Spain), DLR, Fichtner (Germany). Duration: July 2001/Juy 2004 (CIEMAT participation extended to plant operation startup).

2) Project "SOLAR TRES: Molten Salt Solar Thermal Power 15 MW_e Demonstration Plant"; Ref. NNE5/369/2001. EC- DG XVII (ENERGIE Program). GHERSA, SENER, CIEMAT (Spain), Saint Gobain (France), Boeing (USA), Alstom (Czech Republic). (December 2002/December 2007). Head researcher CIEMAT: M. Sánchez.

"Development of receiver for a molten-salt solar thermal power plant" Collaboration Agreement between CIEMAT and SENER Ingeniería y Sistemas S.A. for developing the design technologies, defining operating and control strategies to guarantee and lengthen the life of a molten salt receiver to be employed in solar thermal power plants (Duration: Nov. 17, 2005 / Dec. 31, 2007). Head researcher CIEMAT: Félix M. Téllez.

B) TECHNOLOGICAL DEVELOPMENT OF COMPONENTS AND SYSTEMS:

1) Project: "ECOSTAR: European Concentrated Solar Thermal Roadmap". Ref. 502578. Announcement: Energy1- Sustainable Energy Systems – 6th FP. Financing entity: EC DG Research). Participating entities: CIEMAT (Spain), DLR, VGB (Germany), CNRS (France), WIS (Israel), IVTAN (Russia), ETH (Switzerland). Coordinator: R. Pitz-Paal (DLR). Head researcher CIEMAT: M. Romero. (Duration: December 2003/April 2005).

2) Project: "HICONPV: High Concentration PV Power System". Ref. 502626. Announcement: Energy1- Sustainable Energy Systems – 6º PM. Financing entity: CE DG Investigación). Participating entities: Solúcar Energía (Coordinator), DLR, Fraunhofer ISE, PSE, CIEMAT, RWE, Ben Gurion University, EDF, University of Malta. Head researcher CIEMAT: Jesús Fernández Reche (Duration: December 2003/December 2006).

3) AVANSOL Project: "Advanced volumetric absorbers for high solar concentrating technologies". Its purpose is to answer two questions in central receiver solar thermal Technologies: 1) Durability of the volumetric absorber under real operating conditions and 2) Optimum choice of material and porous absorber geometry. Coordinator: Solucar; Participating entities: Fundación INASMET, University of Seville and CIEMAT. Ref. PROFIT, CIT-120000-2005-49, CIT-120000-2005-49. Head researcher CIEMAT: Félix M. Téllez; (Duration: October 30, 2005 –October 30, 2007)

C) IMPROVEMENT OF EXPERIMENTAL CAPABILITY AND QUALITY PROCEDURES:

1) Project: "Development of Solar Thermal Plant Control Systems and Tools". Specific collaboration agreement between CIEMAT and the University of Almería. Head researcher: Manuel Romero (CIEMAT) and Manuel Berenguel (UAL). (Duration: November 2003 to December 2006).

2) Project: "MEPSOCON: Concentrated solar power measurement in central receiver power plants". Ref. DPI2003-03788. Announcement: National R&D Plan 2002, Indus-

trial Production Program. Ministry of Science and Technology. Head researcher: Jesús Ballestrín (CIEMAT). Participating entities: CIEMAT. (Duration: December 2003 to December 2006.)

A) PARTICIPATION IN DEMONSTRATION PROJECTS

CIEMAT-PSA activity in demonstration projects consisted of accompaniment, transfer and advising in design of components and plants, based on accumulated PSA experience in component development and testing as well as analysis and design. In 2005, significant support was given development of a molten salt technology for the Solar Three plant, for which SENER and CIEMAT have undertaken with their own funding validation of the receiver tube technology and development of a 4-MWth prototype.

Project PS10

The PS10 Project started in 1999 has come a long way to date and awakens many expectations in the solar community as the first commercial solar tower initiative inside and outside of our country. For the PSA, the PS10 Project is of enormous importance because it is an obligatory reference that focuses central receiver technologies research and development and channels feedback from industry. In this case, the SOLUCAR company and a public research center such as CIEMAT, have defined joint strategies for developing heliostats, advanced concentrators, solar receivers, software codes and tools, as well as thermal storage, generating several different projects that have been funded by the Ministry of Education and Science's PROFIT program.

The main purpose of the PS10 (Planta Solar 10) project is the design, construction and commercial operation of a solar thermal power tower plant and heliostat field with a gross rated power of 11 MW_e. This plant is being built in the municipal limits of Sanlucar la Mayor in the province of Seville, and is scheduled for inauguration in the last quarter of 2006. The plant is promoted by ABENGOA, through its operating company SANLUCAR SOLAR, and the project coordinator SOLUCAR. The project has received a five-million-Euro subsidy from the European Commission and 1.2 million Euros from the Andalusian Regional Government. CIEMAT, DLR and Fichtner Solar also participate as partners in the European project.

In the beginning, the project was based on the Phoebus scheme, which used atmospheric-pressure air as the thermal fluid and a volumetric solar receiver. In 2003, the technical project had to be completely revised, because the base-line annual production requirements set by the promoter of 3000€/kW and annual production of 24 GWh, could not be reached with the air technology in a first small-sized commercial plant. Based on these limitations, the basic plant scheme was modified into what is now a saturated steam solar receiver. The system makes use of a field of Sanlucar-120 glass-metal heliostats, saturated steam cavity receiver and turbine, and thermal storage in steam.

It has a total of 624 121-m^2 heliostats developed by SOLUCAR and a 100-m tower. A cavity solar receiver, selected to reduce radiation and convection losses, achieves a thermal efficiency of 92%. The absorber panel is made of independent flexible tubes to absorb thermal expansion and mechanical deformation without risk of breakage or leakage. The receiver produces saturated steam at 40 bar and 250°C, feeding a boiler that increases the system thermal inertia.

The power block works with saturated steam at 250°C and a nominal conversion to electricity of 30.7%. The system thermal efficiency at design point is estimated at 21.7% and average annual efficiency is 16.3%. In this sense, the challenges of finding a simpler and more economical technology, and improving efficiency, have been achieved.

For cloudy periods, or solar transients, the plant incorporates a 15-MWh saturated steam storage system which provides 50 minutes of operation at 50% turbine load.

Figure 50. PS10 Plant under construction with a heliostat focused on the receiver zone at the end of 2005

The PSA collaboration with SOLUCAR in project redefinition, was basically in review of the new solar receiver designed by the TECNICAL company, definition of a direct flux measurement system inside the cavity, validation of the heliostat field optimization procedure (by comparison of the SOLVER and STC codes), and in evaluation of the Sanlucar-120 heliostat.

All in all, the PS10 Project is only a first step which uses low-risk technological options (low temperature, and small plant size), where the logical progression to further plants, some of them already well-defined, is to larger sizes (such as the upcoming PS-20) and higher operating temperatures (superheated steam) which will reduce specific investment and power production costs. In this sense, a plan for a double cavity receiver (one for saturated and the other for superheated steam) towers was assessed under the PROFIT project called SOLPRO. The SOLPRO proposal is being kept in reserve by SOLUCAR for future water/steam plants.

SOLAR TRES Project

The purpose of the Solar Tres Project is to build and operate a 17-MW commercial-scale demonstration solar power plant using heliostat field, tower, and molten-salt (40% potassium nitrate and 60% sodium nitrate) for heat transfer and energy storage in Spain.

The Solar TRES project began in 1999, almost at the same time the American Solar Two project, which concluded that the technology was ready for commercial operation, ended. So two of the main participants in Solar Two, Boeing and Bechtel Corp. agreed with the Spanish GHERSA company to develop the commercial central receiver technology using molten salt as the heat transfer and storage fluid. The initial consortium of European and American companies received a 5M€ subsidy from the European Commission (December 2002), although startup of the project was delayed until the new regulations for such plants was clarified (2004), and because of strategy changes of some of the partners. Finally, in 2005, the team was consolidated with entirely European companies (SENER, Siemens, GHERSA, Saint Gobain and CIEMAT) led by SENER. For these reasons, the initial completion date of mid 2007 will have to be extended.

The project accumulates previous experience in the Solar Two project, but also includes design innovations resulting from the work by SENER and CIEMAT, along with the technical conditions imposed on solar thermal energy by Spanish legislation. The Solar Tres design faces the challenge of solving some problems, basically related to certain components, found in Solar Two. This challenge motivated an agreement between SENER and CIEMAT for the development and evaluation of a new heliostat concept and a prototype molten-salt receiver with better thermal performance able to operate with large amounts of fluid without compromising its durability (at least 25 years). This agreement, undertaken as component “validation” (heliostat and receiver) for the Solar Tres plant, is a technological development project in and of itself (SENER-CIEMAT).

The plant will have a total heliostat field area of 142.31 hectares, receiver thermal power of 120 MW_t, and 15 hours of storage. The plant capacity is 17 MWe which will provide 96,400 MWh_e per year. It also includes a share of natural gas as permitted by current Spanish legislation (RD 436/04). Power generated will be delivered entirely to the grid.

Table 1. Technical specifications of the Solar Tres plant

Number of heliostats	2480
Reflective area of the solar field	285 200 m²
Land area occupied by the heliostat field	142.31 Ha
Total area occupied by the plant	160 Ha
Tower height	120 m
Receiver thermal power	120 MW_{th}
Turbine power	17 MW_e
Thermal storage capacity	15 hr
Gas Burner capacity	16 MW_{th}
Estimated annual power production	96 400 MWh_e
CO_2 emissions saved over best conventional alternative	23 000 tons/yr
CO_2 emissions saved over a coal plant	85 000 tons/yr

Solar Tres is approximately three times the size of Solar Two, employs 115,6-m² heliostats, a receiver with higher thermal power, and achieves better plant efficiency.

The larger-capacity thermal storage system can work for 15 hours with a load of 8130 t of molten salt, with submerged tank heaters. The efficient, low-risk system, uses high-temperature 565°C molten salt with a loss of only 1-2°C a day, and low-temperature molten salt storage at 285°C, 45°C above its melting point.

The 120-MW_t cylindrical receiver system, designed to minimize the thermal effort and resist cracking from intergranular corrosion, has a high thermal performance and is able to work with large flows at low heat loss.

Furthermore, improvement in the physical arrangement of the plant with closed circuit circulation of molten salt has reduced the number of valves, eliminated unnecessary piping and allows safe drainage avoiding solidification of salt.

The thermal storage system has a larger capacity and can work for 15 hours with an 8,130-t load of molten salt. This efficient system involves less risk than other high-temperature systems. The molten salt is at a maximum temperature of 565°C, losing only 1 to 2°C per day. And at low temperature, the salt is stored at 45°C above its melting point, that is, at 285°C.

The various advances in design have improved conversion efficiency over Solar Two. Although the turbine power is only slightly higher, the enlarged heliostat field and thermal storage system make it possible to operate the plant 24 hours a day during the summer and achieve an annual solar capacity of around 64% (around 5600 equivalent hours) and

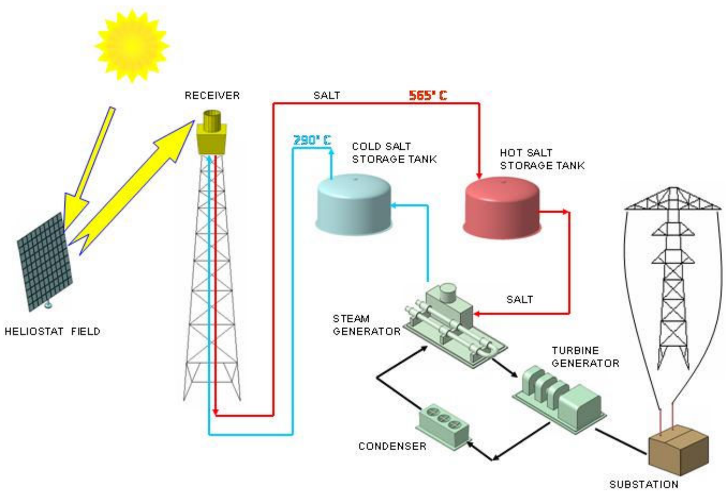


Figure 51. Schematic Diagram of the Solar Tres plant

even up to 71% (including 15% production from fossil fuels).

At the end of 2005, the Solar Three Project was in the stage of technical verification (heliostats, receivers, molten sat system, etc.) at the Plataforma Solar de Almería facilities and is completing promotion and final site definition, as well as final cost estimation. At the same time, management of public financial aid has been undertaken (the engineering project and technology verification already has a subsidy of 5M€ from the EC R&D Framework Program, although the construction of the plant has no financial aid at all at this time) and bank financing based on "project finance" mechanisms.

Salt Receiver Panel

During 2004-2005, Boeing withdrew its offer for Solar Tres receiver construction, compromising project continuation due to the absence of an alternative commercial offer. In this situation, SENER decided to take on the Solar Tres salt receiver engineering and development on its own. Nevertheless, to reduce the risk involved, it requested that CIEMAT share in the design and validation of a tube salt receiver, including, design, construction and testing of a receiver panel prior to fabrication of the Solar Tres receiver, which is made up of a set of 16 panels.

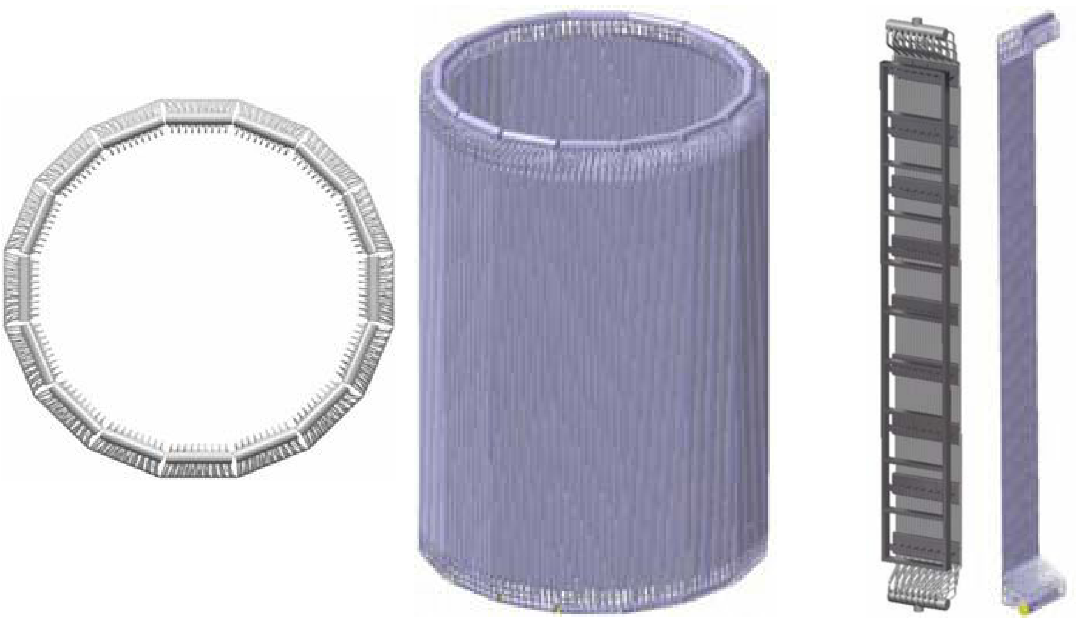


Figure 52. Solar Tres receiver diagram.

In the second half of 2005, SENER and CIEMAT signed a collaboration agreement to validate the receiver technology (with SENER-CIEMAT technology), and to define the operating and control strategies necessary to ensure and prolong the molten-salt receiver lifetime for application in solar thermal power plants (beginning with Solar Tres).

The budget for this agreement was valued at around 6M€, of which 1.5M€ are for equipment, shared by the two institutions(65% SENER, 35% CIEMAT). The equipment will make up almost the entire system except for the turbine and generator, including: 4-MWt receiver subsystem, 20-ton molten salt storage tank, 1-MWh evaporator, air condenser, electrical heat tracing system, piping, 400-sensor measurement and control system.

The development of the prototype is understood as an indispensable step in reducing risks associated with the first own development of a technology that could be implemented in the first solar thermal power plants under very demanding operating conditions (with solar flux of up to 1000 kW/m^2, salt temperatures of 565°C and important temperature differences between different zones on the receiver panel).

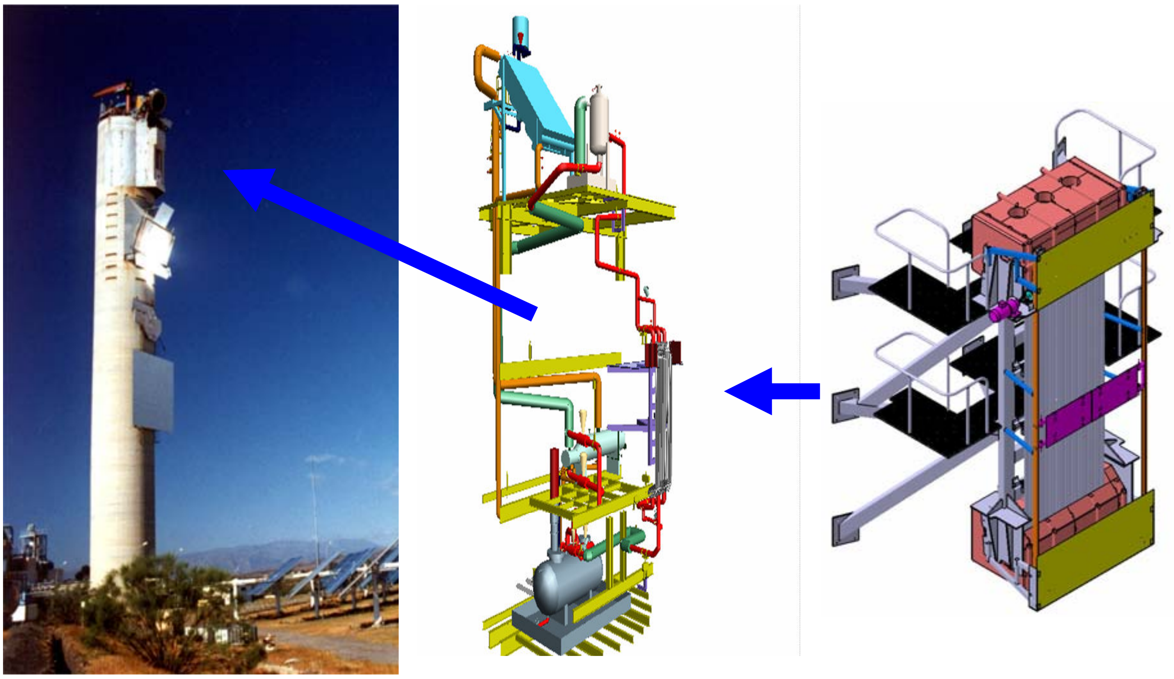


Figure 53. **Detail of the system and panel receiver to be installed at the 70-m level of the CESA-1 tower**

In 2005, the basic design for the experimental system to be installed at the 70-m level of the PSA CESA-1 tower was undertaken and component acquisition began (Salt pump, evaporator, etc.). Installation of the set of components is planned for the first quarter of 2006 and the first verification tests and commissioning are scheduled for July 2006. The general program is designed to asses the feasibility of the receiver design and efficiency by the end of October 2006, when fabrication for the Solar Tres receiver would begin.

The installation of the panel at the PSA will test control strategies and verify the durability and maintenance of the absorbent tube treatment, etc. The duration of the SENER-CIEMAT Agreement has therefore been extended to December 2007.

B) DEVELOPMENT OF CENTRAL RECEIVER SYSTEMS AND COMPONENTS

This line of research is the most consolidated, since it has inherited the goals and resources of the former Central Receiver Systems Project. This group of projects includes feasibility studies and participation in integral demonstration projects that mean the active contribution of the PSA to technology transfer and commercial implementation of solar high-concentration systems. This does not exclude participation in projects for integrating new innovative schemes, development of specific components, such as the solar receiver, the solar concentrator, control systems and perfecting design and simulation tools.

ECOSTAR project:

The purpose of this short project (December 2003 to April 2005) is to roadmap for solar concentrating power generation technology. Work was coordinated by DLR (German Aerospace Center) with the participation of the main European concentrating solar technology research and development centers (CIEMT, ETH, IVTAN, WIS, CNRS), and advised by the European Power Producers Association (VGB). The study specific concentrated on determining those technical innovations with the greatest impact on penetration of solar thermal power systems.

The methodology for analysis selected seven typologies of reference plant (SEGS) parabolic-trough, parabolic trough with direct steam generation, power tower with water/steam receiver, power tower with molten salts, power tower with air-cooled volumetric receiver, hybrid power tower with pressurized volumetric receiver and dish/Stirling systems). The comparison was done for a 50-MW_e plant adapted to each of the technologies and a levelized electricity cost (LEC) was the parameter compared. During 2005 the conclusions of the study were published and presented in several forums and congresses.

Many of the systems included in the study are being assessed for implementation in Spain with the economic reference the 21c€/kWh for electricity produced with solar thermal power. For the most mature technology, the PTC with oil as the heat transfer fluid (and for which there are plans for construction of several 50-MW_e plants with molten-salt thermal storage), ECOSTAR estimates 17-18c€/kWh. Other technologies assessed with smaller plants of about 15 MW_e in the same place the cost is significantly higher, varying between 19 and 28c€/kW. Scale-up of these plants to sizes of 50 MWe in the same place lead to electricity cost estimations of 15 to 20c€/kWh.

As the costs estimated for the different systems are rather similar, within the margin of doubt on current costs, and since the maturity of the technologies evaluated is not homogeneous, it is impossible for ECOSTAR to recommend priorities of some technologies over others. Nevertheless, the sensitivity analyses performed make it possible to estimate the relative impact of implanting different innovations in the various technologies. The generic conclusions establish three levels of priority for implementing innovations. The table below shows central receiver system research priorities.

Table 2. R&D priorities in CRT, according to ECOSTAR (ΔLEC = Potential electricity cost reduction)

Technology	Priority A	ΔLEC	Priority B	ΔLEC	Priority C	ΔLEC
TRC + molten salt	Increase size to 50 MW Larger heliostat; structure	3-11% 7-11%	Advanced mirrors	2-6%	Advanced storage	0-1%
TRC + Water/Steam	Increase size to 50 MW Larger heliostat; structure	6-11% 7-11%	Superheated steam Advanced storage	6-10% 5-7%	Advanced mirrors	2-6%
TRC + Air + Steam turbine	Increase size to 50 MW Larger heliostat; structure	8-14% 7-11%	Advanced storage Better receiver performance	4-9% 3-7%	Advanced mirrors	2-6%
TRC + Air + Gas Turbine	Larger heliostat; structure Include thermal storage	7-11% 7-10%	Increase size to 50 MW	3-9%	Advanced mirrors Better receiver performance	2-6% 1-2%

Several generic conclusions may be arrived at from this study:

- Series production of modular components and scale-up to larger-sized plants will lead to a significant cost reduction (estimated at 30% of the current cost), and efforts in technological innovation could lead to a considerable additional reduction in costs.
- All of the technologies evaluated in the study have a significant potential for lowering cost through mid-term implementation of innovations such as those analyzed in the ECOSTAR project (See Figure 54)
- Mid-term research should prioritize improvement of modular components such as concentrators (heliostats), or receivers.
- In mid-to-long term, research should focus on less modular components, such as thermal storage or optimum integration in larger and more efficient thermodynamic production cycles.
- The development of these technologies requires a boost that can come either from extending conditions for financial assitanc4e such as outlined in Spain, to other countries, especially those with high solar potential. The southern Mediter-

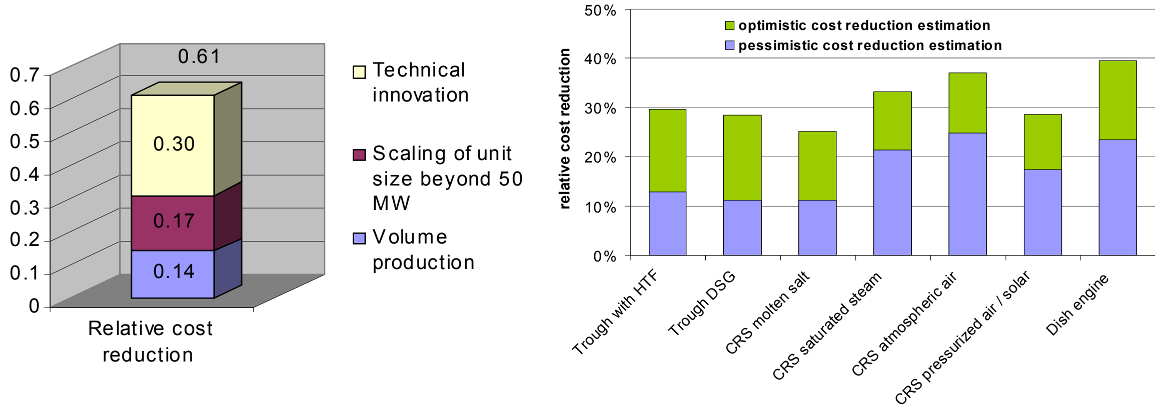


Figure 54. Influence of technological innovation on cost reduction for different solar thermal power systems (Results of the ECOSTAR) project

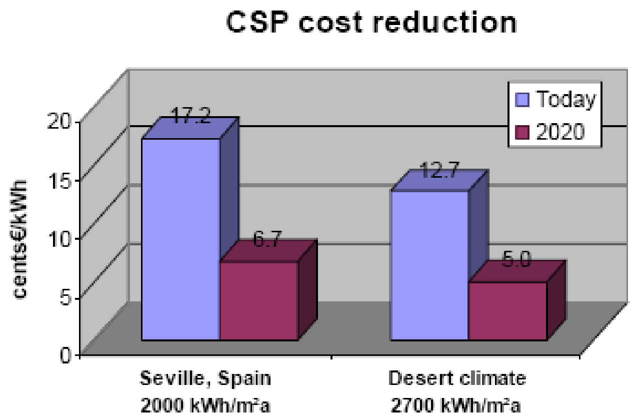


Figure 55. Estimated LEC found in the ECOSTAR Project for two different time scenarios (today and 2020) and two resource levels (2000 for southern Europe, 2500-2700 for North African deserts).

ranean Basin offers significant potential for cost reduction because they have a 20-30% higher solar resource.

New power production schemes: The HICON-PV project

Integration of thermal energy collected in the solar receiver in more efficient power production schemes is one of the permanent lines of research at the PSA. This approach is carried out both through a search for options or thermal power production schemes based on more advanced thermodynamic cycles and incorporation of power production systems by direct conversion (photovoltaic, MHD, thermal ionic, etc.).

The HICON-PV project (High CONcentration PV Power System) is a project financed by the European Commission under the Sixth Framework Program the purpose of which is the development, fabrication and testing of a concentrating photovoltaic device able to work with solar radiation fluxes of up to 1000 kW/m^2, as a way to develop a concentrating technology that can reach a cost per unit of 1€/Wp (one Europ per peak watt) in 2015. The project began in December 2003 and is planned to end in December 2006. The participants are Solúcar Energía (coordinator), DLR, Fraunhofer ISE, PSA-CIEMAT, RWE, Ben Gurion University, EDF and University of Malta

The HICON-PV Project proposal is based on the use of GaAs multi-junction cells that support high solar flux and reach efficiencies of up to 35% (solar-to-electric conversion). With current silicon technology the cells are limited to concentrations of less than 500 kW/m^2 and efficiencies that barely surpass 20%.

The CIEMAT tasks in this project include selection of suitable solar concentrating systems for high photovoltaic concentration and their adaptation to the strict radiation flux and temperature distribution requirements on the photovoltaic module (in collaboration with DLR); testing and evaluation of photovoltaic modules in the PSA solar furnace and the development of test standards, procedures and evaluation of concentrating photovoltaic devices.

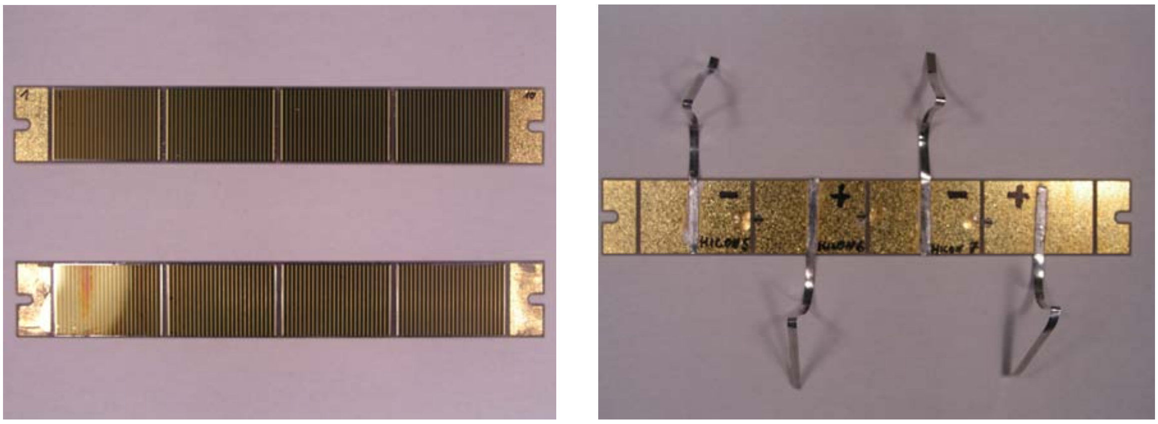


Figure 56. Cells and Monolithic Integrated Modules (MIMs) tested in the PSA Solar Furnace in 2005

In 2004, PSA project activity concentrated on the Solar Furnace with all the instrumentation necessary for testing the cells developed by Fraunhofer ISE, besides simulation and optical optimization of different types of solar concentrators (parabolic, Fresnel or tower). In 2005, all the new components installed in 2004 were commissioned and tested and different cells monolithic integrated modules (MIMs) were characterized, as well as the thermal behavior of the cooler for the photovoltaic modules proposed by PSE.

As flux on the MIM surface may not vary over 10%, after solar flux characterization testing in the solar furnace and modeling and testing of secondary concentrating devices or flux homogenizers, a secondary concentrator/homogenizer was designed so that solar flux incident on the cells would have the required flatness.

Volumetric Receivers: AVANSOL

The receiver is the authentic nucleus of any power tower system, because it is the most technologically complex element, and the need for the absorber to have minimum losses and in very strict concentrated flux conditions. Among the various options for thermal flux and heat exchange configurations, the PSA has been focusing its research since 1986 on the development of air-cooled volumetric solar receivers, the absorber being an illuminated matrix or porous medium (metal screen or ceramic monolith), through which the cooling gas flows.

After development experience with about thirty different-sized volumetric receiver prototypes (between 50 kW_t and 3000 kW_t at the absorber outlet), the main conclusions are their reliability, environmentally-friendly use of air as the heat transfer fluid, and high availability, high thermal system efficiency due to high working temperatures (between 700 and 1000°C), great cost reduction potential from modular designs

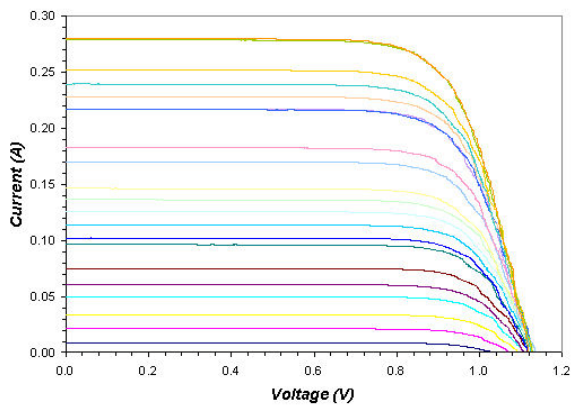


Figure 57. I-V Curves at different concentrations for one of the cells tested in the PSA Solar Furnace 2005

that can be manufactured in series and availability of proven high-temperature thermal storage solutions, e.g., rock beds.

All of these developments have had three basic purposes: 1) Demonstrate their high-flux, high-temperature, and in some cases, medium-pressure (~10 bar) operating capacity; 2) Improve thermal efficiencies (a function of the working temperature) of solar radiation conversion; 3) Simultaneously with the above two purposes, low-cost designs (through modular designs and choice of materials).

Nevertheless, in spite of the advances in this technology, there are still a series of pending questions that are crucial to the development and industrial application of the air technology in central receiver systems, mainly:

- The durability of materials and designs tested and/or used must still be proven under high solar flux/high-temperatures
- Specific receiver costs must be further reduced

Approach to the second challenge requires combining the election of absorber materials with easily mass produced structural designs and adequate porous geometries having high effective solar absorbencies.

This was the motivation for the AVANSOL project proposal, accepted in the PROFIT program and scheduled for October 2005 to October 2007 with the following participants.

Este planteamiento motivó la propuesta del proyecto AVANSOL, aceptado en el programa PROFIT, con duración de Octubre de 2005 a Octubre de 2007 y los siguientes participantes:

<u>SOLUCAR:</u> Project Coordinator, also the company coordinating international volumetric receiver development projects, such as SOLAIR (3 MW_{th}). As the company promoting the first commercial central receiver plant, it continues to be interested in the volumetric receiver technology as an option for future plants, to the extent that some uncertainties prior to the project are clarified.

<u>CIEMAT:</u> 3 CIEMAT groups participate in AVANSOL:

- *PSA*, which probably has the longest experience in the world in testing and evaluation of volumetric receivers, is in charge of the technical coordination of the Project.
- *Power Plant Structural Materials Division*, which contributes its experience in characterizing deterioration (corrosion / rust) of metals, etc., and
- *Fusion Materials Division*, which contributes its experience in ceramics for extreme conditions (temperature, radioactivity, etc.)

<u>INASMET:</u> This company has wide experience in developing porous ceramic structures (Alumina, SiC, etc.) and characterization (mechanical, etc., of ceramics)

<u>University of Seville:</u> The USE manufactures "bio-mimetic" structures that can replicate any porous biological structure in ceramics, such as SiC.

The Project has taken on the challenges of:

Developing methodologies that enable the durability of both ceramic and metal volumetric absorbers to be estimated, perfecting accelerated aging techniques and deriving relationships between aging and durability under conditions such as solar flux and high temperatures.

Review options for durable materials and geometric structures that can be manufactured in series and are easily scalable and therefore have a high cost reduction potential.

The Project is due to last from October 2005 to October 2007. In 2005, preparation of the laboratory techniques for optical and thermal characterization of small samples (as the

Figure 58. **Examples of porous structures for solar volumetric receivers**

first step in selection), and experimental capabilities for thermal cycle testing, solar flux cycling (using a parabolic dish and a device for intermittently positioning the samples in the focal zone) and aging in a weather chamber.

Heliostats and solar concentrators

Heliostat improvement and cost reduction continues to be one of the crucial points for economic feasibility of central receiver solar thermal power plants, since they represent between 30% and 40% of the total plant cost. The tracking device (motor, gears, etc.) is responsible for 40% to 50% of the heliostat cost, since high precision solar-tracking and high mechanical resistance (due to wind loads and large reflective surfaces) are required.

In 2005, the CIEMAT validated the optical and tracking quality of the SENER heliostat prototype designed for the Solar Tres plant under a subcontract. It was done in two campaigns to quantify the functional characteristics of the prototype, both for aiming at a fixed target throughout the day and its optical quality, that is, ability to concentrate the solar radiation. These tests followed the Testing and Evaluation Protocol previously designed by the PSA for this purpose.

Development of Advanced Control Systems

There is a fruitful line of collaboration with the University of Almería (UAL) in the development of control systems based on a scientific cooperation agreement signed in 2002. Under this agreement, significant development work has been done in cooperation with the Automation, 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 the integration of control, data acquisition and evaluation environments for solar tower receivers.

a) **b)**

Figure 59. **(a). Sener heliostat (2005). Area: 115.6 m²; Geometry: spherical; Alignment: on-axis; Focal distance (for testing at the PSA): 472.85 m.; (b) CESA-1 tower image analysis target (PSA)**

In 2004, a significant advance was made in the design of control systems for the CESA and CRS fields. It should be emphasized that for the development of the software for these control systems, technologies are being used that not only offer a local solution to the PSA heliostat field control problem, but are scalable and adaptable to commercial solar tower plants. Specifically, distributed objects technologies are being used, in which the real-time determinism of the software components is ensured through the use of Real-Time Operating Systems (RTOS). In this project, CORBA® is being used on RTOS LynxOS® software for heliostat control system development. Insofar as the integration of controls, acquisition and solar receiver test result evaluation environments, a Control System for the Receiver Block, Storage and Air Circuit has been designed and developed based on LabView®. This system will be perfectly integrated with the Heliostat Field Control System as well as other computers in the CIEMAT telematic network (in the PSA subnetwork and the CIEMAT-Moncloa subnetwork, to provide an environment for real-time analysis of the experiments performed at the PSA.

In 2005, the algorithms developed were implemented. Coding and verification of these algorithms in critical real-time environments (LynxOS/RT-CORBA) required a long time to do.

At present, the central control system is being tested in the CESA-1 heliostat field. This new system, once any errors which may appear have been corrected, is expected to replace the μVAX control application that has been working for over twenty years in this heliostat field by the beginning of 2007. This system will enable many experiments to be designed which could not be done to date on the old control platform.

C) IMPROVEMENT OF EXPERIMENTAL CAPABILITIES AND QUALITY PROCEDURES:

This section includes activities considered fundamental for a center of excellence in testing and measurement of solar concentrating systems such as the PSA. In particular, the search for more reliable concentrated solar flux measurement methods and instruments and preparation and testing of materials subjected to high flux, are essential for the next generations of plants. Although these activities are usually permanent in any scientific facility of reference in solar concentration, most of the time they go by unnoticed as they are hidden within component development projects or systems testing. They are therefore characterized by their markedly horizontal profile. There are, however, projects funded by the National R&D Plan that focus specifically on the development of these techniques and processes. In 2004, such activities were under the MEPSOCON and SOLARPRO projects.

Instrumentation and Measurement (MEPSOCON Project)

Many factors affect the measurement of concentrated solar radiation, making it necessary to improve its precision. This uncertainty is propagated in the design of the final solar plant and eventually, its price. This is why it is necessary for the various causes of distortion of incident power measurement to be analyzed so this uncertainty can be significantly reduced. The definition of a calibration procedure for the sensors (calorimeters) used in measuring highly concentrated solar radiation as well as the design of a new calorimeter to mitigate the differences already 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 is funded by the National R&D Program through its Design and Industrial Production Program, began on December 1, 2003 and is due to end on November 30, 2006. MEPSOCON and the development of radiometers and calorimeters is the object of collaboration with the National Autonomous University of Mexico's Center for Research in Energy. Among other goals is the design, construction and characterization of a cavity calorimeter for the measurement of concentrated radiation flux in solar concentrating systems.

The characterization methods employed have the Gardon radiometer as the reference, for which a specific calibration procedure has been defined, using a dual cylindrical-cavity graphite black body, following the NIST procedures (Nacional Institute of Standards and Technology). Once the Gardon radiometer calibration procedures had been designed, a systematic error was detected (Type B uncertainty), in its use for measuring solar radiation. This uncertainty is dependent on the radiometer coating. If the coating is Zynolyte paint, the radiometer overestimates the measurement by 3.6%, and if the coating is colloidal graphite, it overestimates it by 27.9%. These systematic errors are because at the calibration temperature (850ºC) the spectral radiation of a black body is significantly different from the spectral distribution of solar radiation, which, according to the Wien´s displacement law is at 2580 nm. A systematic error is therefore observed in the power absorbed by the coatings under the two different spectral distributions. This systematic error has been acknowledged by the Vatell Corp., with whom an article on these findings, of great importance for widespread use of these radiometers in solar applications, has been coauthored. In order to use these sensors for the measurement of solar radiation, a correction of the calibration constants must be made, using an adimensional factor of 0.965 for Zynolyte and 0.782 for colloidal graphite.

The three main tasks set in the beginning have been undertaken during the two years the project has lasted, and, as they were planned for three years, their development has been unequal up to now, although the goals set are still scheduled to be achieved.

In 2005, the construction of a radiometry laboratory now in the commissioning phase (see Figure 60 below). This new laboratory was built with ERDF funding (B2C937097144C9BF Laboratory for Radiometric Calibration for the Plataforma Solar de Almería).

The laboratory is equipped with scientific-technical instrumentation also financed by ERDF (16A99EDA0ECDA337 Equipment for the Radiometric Calibration Laboratory) and the MEPSOCON project itself. Among these instruments, the acquisition of black bodies, pyrometers, high-precision electromagnetic flow meters and water pump with special features.

The current radiometric calibration procedures for Gardon radiometers (radiometric and calorimetric) were analyzed in the laboratory, and the error quantified in each case. The uncertainties involved in transferring the sensors calibrated in laboratory to solar radiation conditions were analyzed, and it was found that calibration has to be corrected when measuring under solar radiation conditions. To quantify this correction, we found the spectral absorptivity curves (spectrophotometer) for the black radiometer coatings (mainly Zynolyte and colloidal graphite) and the spectral reflectivity curves (spectrophotometer) of the heliostat mirrors, and the differences in absorptance of these coatings under black body conditions (Planck's Law) and solar radiation (spectroradiometer).

The systematic errors quantified (see Table 5) in measuring the concentrated solar power with Gardon radiometers calibrated using a black body at 850ºC are:

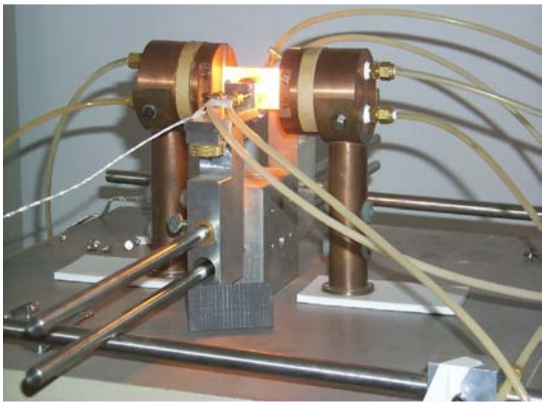


Figure 60. New radiometry laboratory set up at the PSA

Table 3. Systematic error in measuring solar power

Coating	Systematic error
Zynolyte	+ 3.6 %
Colloidal graphite	+ 27.9 %

By working in the solar context of the Plataforma Solar de Almería's Solar Furnace, it was possible to validate the laboratory calibration procedures described above and verify experimentally the systematic errors committed in measurement of high solar irradiance. These results were recognized by the VATELL company, manufacturer of the Gardon sensors which will co-author a publication on the subject.

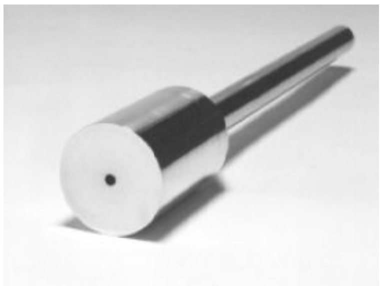


Figure 61. **Cavity radiometer**

The acquisition of a Kendall absolute cavity radiometer in the range of 50-5000 kW/m² and ± 1% precision is worth mentioning. This sensor has that advantage of being self-calibrating and making irradiance measurements regardless of the type of radiation (UV, visible or IR). This sensor is intended to be a national primary standard for high irradiance.

Gardon sensor thermal behavior was simulated with the FLUENT finite elements code to find out the influence that working in an outdoor scenario such as during the evaluation of solar receivers has on irradiance measurement. The conclusion is that perturbation in the solar irradiance measurement due to convective or thermal phenomena is less than ±1%.

This project is in turn related to other projects or groups that require quality certification of high solar flux measurement, such as:

1. The European HICONPV, for which concentrated solar flux characterization testing was done during which the photovoltaic cell had to be subjected to concentration for its own characterization testing
2. On the other hand, it is in the framework of the European SOLLAB consortium (Alliance of European Solar Concentration Laboratories) where it actively participates in the "Flux and Temperature Measurement Group" with other members from each country. Among the goals of this group is the definition of European solar irradiance measurement standards (http://www.promes.cnrs.fr/ACTIONS/Sollab/presentation.htm).

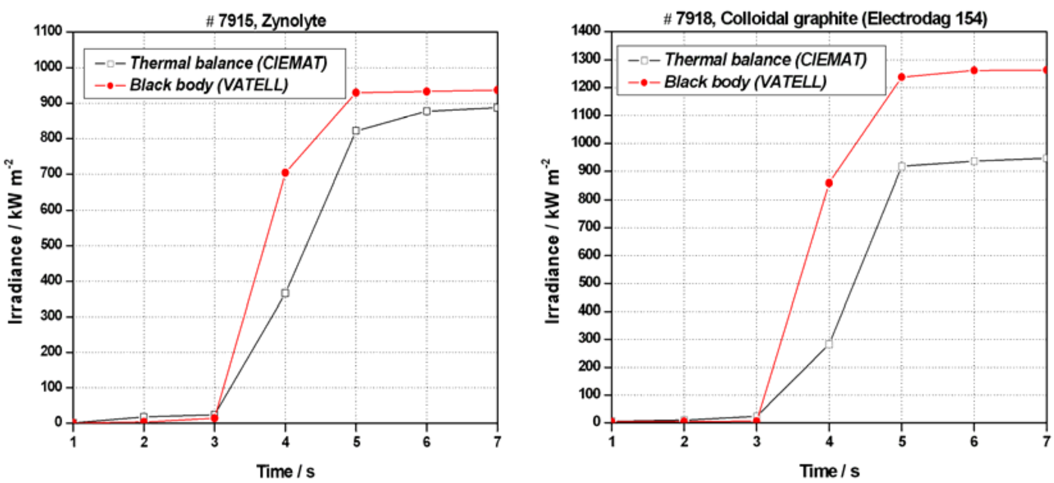


Figure 62. **Solar irradiance measured with the Gardon sensor: calorimetric and radiometric measurements**

Improvement of facility capabilities

In 2005, apart from maintenance of experimental capabilities in the two heliostat fields (CESA-1 and CRS) and on various levels of the CESA-1 tower with experiments underway (such as the KOSMOSOL Project, continuation of SOLAIR, or 3-MWt ceramic volumetric receiver on the 80-m level of the CESA-1 tower, the PDVSA project on the CRS tower), a laboratory for optical and thermal characterization of CRT absorber elements has been commissioned. In 2005, this laboratory acquired a 4000-W lamp, a motorized optical best bed for characterizing reflectivity and angular transmissivity of absorbers and reflectors using laser and photodiode light sources.

Figure 63. New spectrophotometer for optical characterization

Furthermore, as mentioned above, aging testing capabilities for thermal cycle and concentrated solar radiation exposure were perfected. Kiln linings have been acquired and a DISTAL 1-type parabolic disc is being prepared at the PSA as a test device.

The activity mentioned under the section on control is also in and of itself an installation improvement, as the algorithms and device in the control room are updated. At the end of 2005, the new heliostat field control system being made at the PSA was already well advanced.

Apart from the replacement or installation of new generic sensors (such as the meteorological), other improvements have also been made:

- Repair of 6 CRS heliostat structures
- Acquisition of 80 high-reflectivity mirrors for repair of CRS heliostat facets.
- These repairs and repair of mechanical breakdowns, angular position gages and electric batteries have improved CRS heliostat field availability from 52% to 92%.

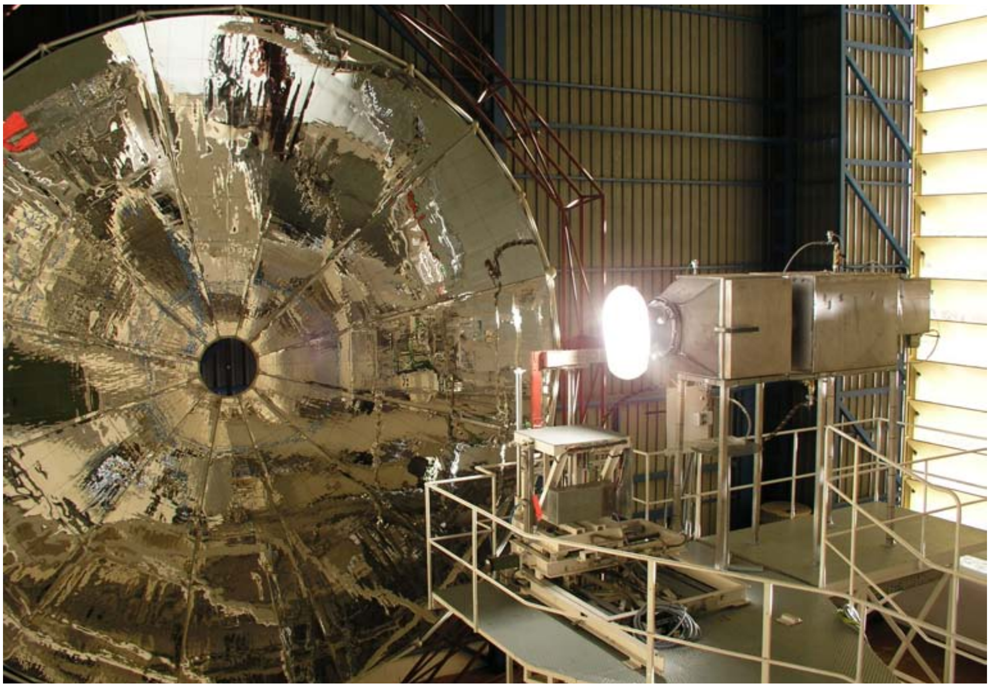


Figure 64. Volumetric receiver processing plant in operation in the PSA Solar Furnace

- A first draft of the technical specifications for renovating the CRS and DCS low voltage room.
- High-pressure heliostat and collector washing equipment with two nozzles for simultaneous washing has been purchased. This machinery replaces one that had been in use for 22 years and broke down frequently, interrupting the mirror-washing schedule.
- A new safety valve was installed in the TSA plant to replace a leaky one that did not allow pressure to be controlled properly.
- A vacuum pump has been acquired and installed for the facet-shaping bench. Facet repair and replacement that is going to be carried out in the coming years to provide the heliostat fields with 100% availability will require fabrication and shaping of new facets that will be done in the PSA facilities, reducing their cost.
- A remote-control two-axis rotary platform has been acquired for installing the heliostat laser-canting equipment.
- To replace CASA heliostat mechanisms for the CESA-1 plant, an order was placed with SENER for the design, fabrication and supply of 5 heliostat mechanisms, completely adaptable to the CASA heliostat structures and pedestals in the PSA CESA-1 field.

Solar Fuels and Industrial Processes Group

The production of different electric energy vectors permitting seasonal storage and transport of solar energy, as well as its integration in industrial processes that have to be adapted for solarizing the endothermal stages, are emerging activities in the Solar Concentrating Systems Unit.

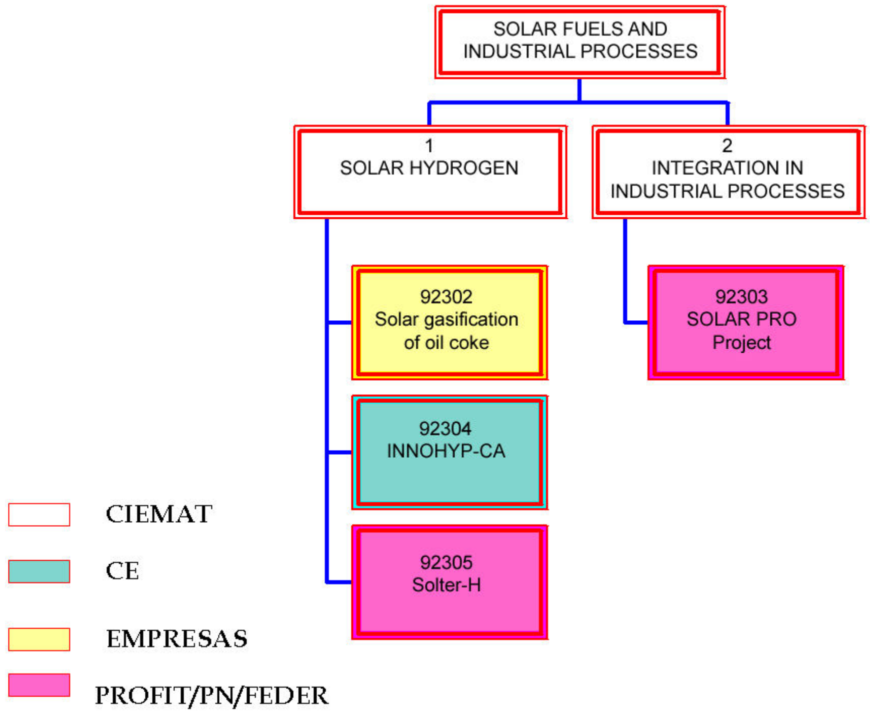


Figure 65. **Structure and content of the lines of research in solar hydrogen and integration in industrial processes. Colors show sources of funding**

Solar gasification of petroleum coke project

Complete replacement of fossil fuels is a long-term goal that requires the development of new Technologies. It is strategically desirable as an intermediate stage to consider mid-term goals oriented toward the development of hybrid solar/thermal endothermic processes in which fossil fuels are used exclusively as chemical reagents and the solar energy is the process heat source. An major example of a hybrid process, and certainly one which will probably cause the most impact, is solar gasification of petroleum coke. The results are cleaner fuels with an energy content improved by the solar energy: its calorific value is increased above that of the main raw material by the solar contribution in an amount equal to the enthalpy exchange in the reaction. The petroleum coke-solar energy combination creates a link between today's oil-based technology and the solar chemistry technology of tomorrow.

Petroleum coke gasification is a complex process, but the overall chemical conversion may be represented by the simplified net reaction:

$$C_1H_xO_y + (1-y)H_2O = \left(\frac{x}{2} + 1 - y\right)H_2 + CO$$

Where x and y are the elemental molar relationships of H/C and O/C in petroleum coke, respectively. The chemical obtained is syngas, the quality of which depends on x and y.

The solar gasification of petroleum coke project is in collaboration between Petróleos de Venezuela (PDVSA), the Swiss Federal Institute of Technology Zurich (ETH) and the CIEMAT, and its main goal is to develop a clean solar petroleum coke, and heavy oil in general, gasification technology. In its first stage, the project has concentrated on characterizing the process for three types of petroleum coke from a heavy crude oil operation in Faja del Orinoco in Venezuela: Flexicoke, and Delayed Coke from Petrozuata and Amuay. The chemistry kinetics tests performed in laboratory reactors with kinetic control have confirmed the high quality of the syngas produced at temperatures over 1300K, where the composition of the gas is practically reduced to CO and H_2. The gas obtained is very clean, since there are no combustion gases and all of the coke is used as chemical reagent. Kinetic constants and the corresponding kinetic model have also been found and a model has been developed using the Fluent® code for transfer of matter and energy in the reactor, which analyzes the fluid dynamic behavior of particles of 1 to 100 microns.

An exergy analysis based on the Second Law of Thermodynamics examined two technically feasible pathways for obtaining energy from the gasification chemicals and established a basis on which to compare them with electricity generation in conventional power plants. The two pathways are: 1) syngas produced by solar gasification with petroleum coke vapor is used as a fuel in a combined Brayton-Rankine cycle with 55% perform-

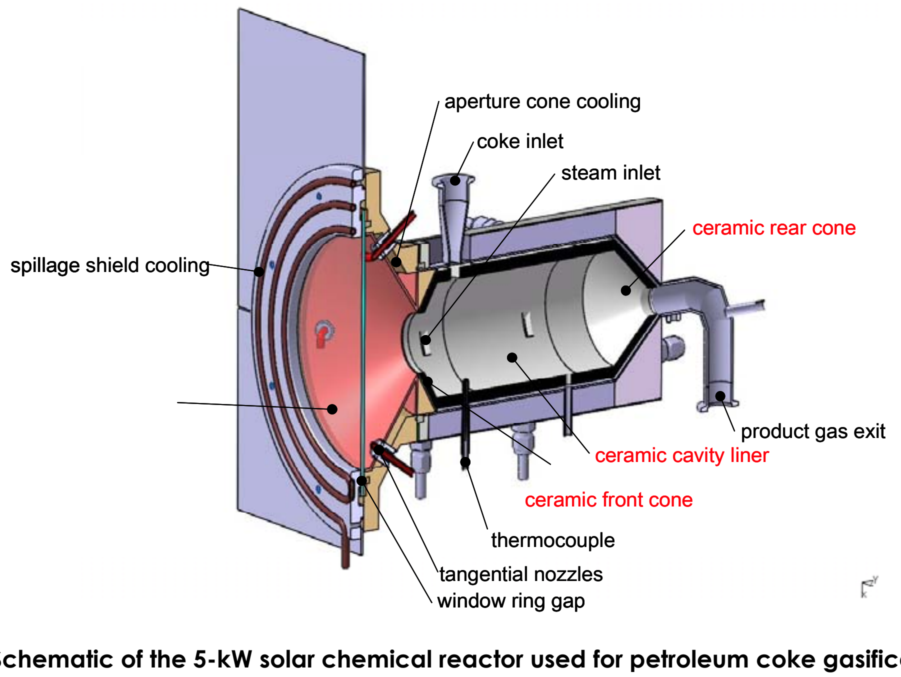


Figure 66. Schematic of the 5-kW solar chemical reactor used for petroleum coke gasification (PDVSA, ETH, CIEMAT collaboration project)

ance; and 2) the syngas produced by solar gasification with steam is reprocessed until H_2 with the displacement reaction, followed by separation of H_2/CO_2, and the H_2 is used to feed a fuel cell with 65% performance. The exergy analysis shows that the two paths can double the specific electricity output (6.6 kWh/kg of coke), and thereby reduce specific CO_2 emissions to half compared to a Rankine cycle fed by fuel with 35% performance.

In 2004, Phase 1 of the project, consisting of the design and construction of an experimental 5-kW reactor tested in the solar furnace, was completed. The reactor tested produced top quality syngas from petroleum coke at an operating temperature of 1300-1800K, with 87% conversion and residence times of 1 s. CIEMAT, apart from participating in testing of the 5-kW reactor in the PSI solar furnace in Switzerland, also performed a laboratory test campaign with scale model heated by an electrical resistance in which new methods of feeding the coke in slurries were tried.

In 2005, Phase 2 of the Project, consisting of concept scale-up to a 500-kW pilot plant that will later be tested in the CRS tower at the Plataforma Solar de Almería, was begun.

Roadmap for thermochemical hydrogen production (INNOHYP Project)

CO_2-emission-free thermochemical hydrogen production is currently undergoing renewed interest, after two decades of ostracism and lack of interest. The high concentration solar technology has the capabilities and properties required for large-scale solarized hydrogen production, using high temperatures and thermochemical cycles.

The INNOHYP-CA project (Innovative high temperature routes for Hydrogen Production – Coordinated Action) is a Concerted Action funded by the European Commission in its 6th Framework Progam, the object of which is to review the state-of-the-art of innovative CO_2-emission-free mass thermal production of hydrogen. The project is being coordinated by the French Commissariat for Atomic Energy (CEA) and the collaboration of seven other participants (ENEA in Italy, DLR in Germany, the University of Sheffield in the United Kingdom, Empresarios Agrupados and CIEMAT in Spain, CSIRO in Australia and the EC Joint Research Centre in the Netherlands). The study concentrates on classical thermochemical water disassociation such as UT-3 SI, Westinghouse and metal oxide cycles such as the ZnO cycle, mixed ferrites and others, such as high-temperature electrolysis. Fossil-fuel decarbonization processes, such as is also being analyzed, thermal methane cracking, solar methane reforming and solar gasification of carbonaceous materials. The INNOHYP project also reflects on the technological challenges to be solved and propose the scope of future research and development, as well as a bridge to other roadmapping projects (Hyways Project), and as liaison with technological platforms and international collaboration forums such as the International Energy Agency and the IPHE (Internacional Partnership on Hydrogen Economy).

The project began in September 2004 and is scheduled to last two years. In 2005, a report on the state-of-the-art of the various processes was prepared that will make it possible to begin the corresponding comparative roadmap in 2006.

Metal oxide hydrogen production (Solter-H Project)

Of the multitude of endothermal processes of interest for their solarization, those based on metal oxides are especially attractive. The Solter-H Project is funded by Spanish Ministry of Education and Science PROFIT program, in which the Hynergreen Company and CIEMAT also participate. In this project. The purpose of this project, which reviews the state-of-the-art of different thermochemical cycles, is to select a process for later development by the partners, first on a laboratory scale and later upscaling to several kW in a solar furnace or solar dish.

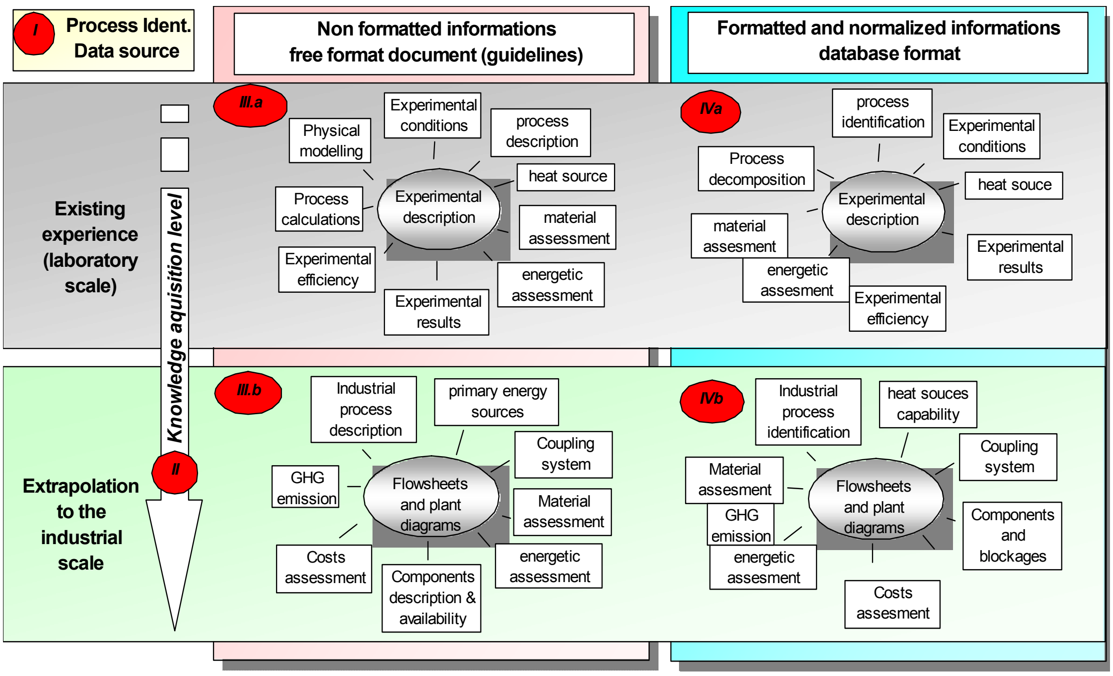
Both the available bibliography and operating data existing for General Atomics and UT-3 cycles seem to be excessively complex, both with regard to the number of reactions involved and the technological development required to solve some basic problems. This, along with inherent power-plant operating problems would make operation extremely complicated, since heliostat field control would have to be integrated with several receivers, basic separation operations, purification, etc. This interaction among the various field components would be even more critical in the presence of transients or even during startup and shutdown. However, hybrid cycles such as the Westinghouse cycle, although less efficient and with two clearly differentiated reactions, could be a feasible alternative for a solar plant. Fruit of this conclusion was a joint proposal to the EC 6th Framework Program presented with the CEA and DLR, however, this proposal unfortunately did not receive funding. Nevertheless, this process has been retained as subject to possible development in future international cooperation.

In the scope of national projects, collaboration between Hynergreen and CIEMAT considered development of a process that could adapt the knowledge of both in solar concentrating technology and volumetric solar absorbers seemed more feasible. In this sense, mixed ferrites have more attractive characteristics for possible solarization. The absence of reliable data is, however, one of the strongest limitations for beginning solarization of this process. The Solter-H project is intended to develop the steps necessary for a technical and economic feasibility study analyzing the use of mixed ferrites in solar reactors, by testing different doped ferrites, first in laboratory and then in small solar concentrators.

Solar PRO: DEVELOPMENT OF HIGH-TEMPERATURE INDUSTRIAL PROCESS HEAT SYSTEMS USING CONCENTRATED SOLAR RADIATION

Energy is the basis of industrialized civilization. Continually decreasing reserves, the need to limit emissions into the atmosphere, progressive growth in demand and energy dependence on foreign powers have driven important efforts in energy savings and leveraged the use of renewable energy sources, since they are considered a determining factor in meeting the community regulations on limiting acid emissions into the atmosphere and international agreements signed by Spain in environmental matters, such as the Kyoto protocol.

Solar thermal energy is the renewable energy which, because of its characteristics, must take on a relevant role in industry, since it is possible to directly, or indirectly transferring its energy to an absorbent material, provide the thermal energy necessary for many



(Source: CEA)

Figure 67. Methodology designed in the INNOHYP project for the analysis of state-of-the art mass thermochemical hydrogen production.

industrial processes, supplying solar process heat at different temperature levels.

It is obvious that the industrial processes that usually require a major energy contribution are those that are produced at high temperatures. However, it must be kept in mind that for the future implantation of solar thermal concentrating technology in high-temperature industrial processes, a strong research effort is necessary. This is especially true for this type of applications, which requires the detailed study of technical and economic feasibility for each process, including the design of process-specific chambers or reactors, depending on process characteristics and technical and production requirements, as well as testing and characterization of the reactors, processes and products, so the technological feasibility in each particular case can be demonstrated, and design and production parameters adjusted to them.

The demonstrated experience of the PSA in various solar concentrating technologies in national and international projects for materials treatment and generation of solar heat at different temperatures, makes it possible for us to take on innovative projects, such as SolarPRO.

The purpose of SolarPRO is to demonstrate the technological feasibility of the use of solar thermal energy as an energy supply system in industrial processes other than electricity generation for which the common denominator is high temperature. SolarPRO combines the experience and knowledge acquired in many central receiver technology projects with know-in materials treatment in the solar furnace since its inauguration in 1991.

For this, the PSA as project coordinator, is collaborating with research groups highly specialized in the processes to be studied:

- Instituto de Tecnología Cerámica (Castellón) (ITC). Technology center with knowledge of industrial ceramics manufacturing processes
- Polytechnic University of Catalonia (UPC) Dept. of Fluid Mechanics. Knowledge of ground polluted by heavy metals.
- University of Seville (USE) Dept. of Mechanical and Materials Engineering. Knowledge of metal sintering.

Table 4. Processes initially selected for study

Typical industrial ceramics processes		
Drying of 'raw' pieces	100ºC < T < 200ºC	Drying and baking chamber con volumetric receiver
'Third firing' for certain kinas of decoration	800ºC < T < 900ºC	Drying and baking chamber con volumetric receiver
Baking of ceramic tiles	850ºC < T < 1100ºC	Drying and baking chamber con volumetric receiver
Powder metallurgical processes		
Metal sintering	T~ 1000ºC	Processing in controlled atmosphere chamber
Waste treatment		
Processes for eliminating heavy metals from polluted soils.	T< 630ºC	Solar rotary furnace

The main project goals are:

1) Demonstrate the technological feasibility of the concept.

2) Acquire enough data and experience to optimize design and operating procedures

3) Identify possible new processes that could be supplied with energy from solar process heat.

4) Come to conclusions that assist in proposing later system scale-up.

The main milestones reached in 2005 were the development and testing of an experimental laboratory-scale device for producing high-quality ceramic compounds using concentrated solar energy at processing temperatures over 1300ºC, installation and commissioning of a processing plant based on the volumetric receiver technology in which processing temperatures of up to 1000°C have been reached, and development of a specific data acquisition system to control process variables at all times. Furthermore, an additional chamber was built for treatment of materials in controlled atmosphere and a rotary furnace reactor for thermal desorption of soil polluted by heavy metals which will be installed and characterized in the solar furnace next year.

Environmental Applications of Solar Energy and Solar Radiation Characterization

INTRODUCTION

The program of work and activities in the Environmental "Applications of Solar Energy and Solar Radiation Characterization" Unit are currently organized around the following 5 main lines of research:

a) Solar detoxification of liquid effluents
b) Solar disinfection of drinking water
c) Solar gas detoxification
d) Solar seawater desalination
e) Characterization and measurement of solar radiation

Figure 68 shows the Unit's structure with the main lines of research carried in 2005 in the context of the various projects underway, the most relevant activities of which are briefly described below.

2005 was an especially significant year for the "Applications of Solar Energy and Solar Radiation Characterization" Unit, because of the consolidation of its activities which were defined as its goal when CIEMAT was restructured at the beginning of 2004. This is demonstrated by the approval at the end of 2005 of five European projects (EC 6th Framework Programme) plus another in the Madrid Regional Government's Excellency Program. These projects, which obviously are not reported here because they were started so recently, will be carried out in 2006:

1) Photozyme Nanoparticle Applications for Water Purification, Textile Finishing, Photodynamic Biomineralization and Biomaterials Coating (PHOTONANOTECH)
2) Innovative and/or Integrated Technologies for Treating Industrial Wastewater

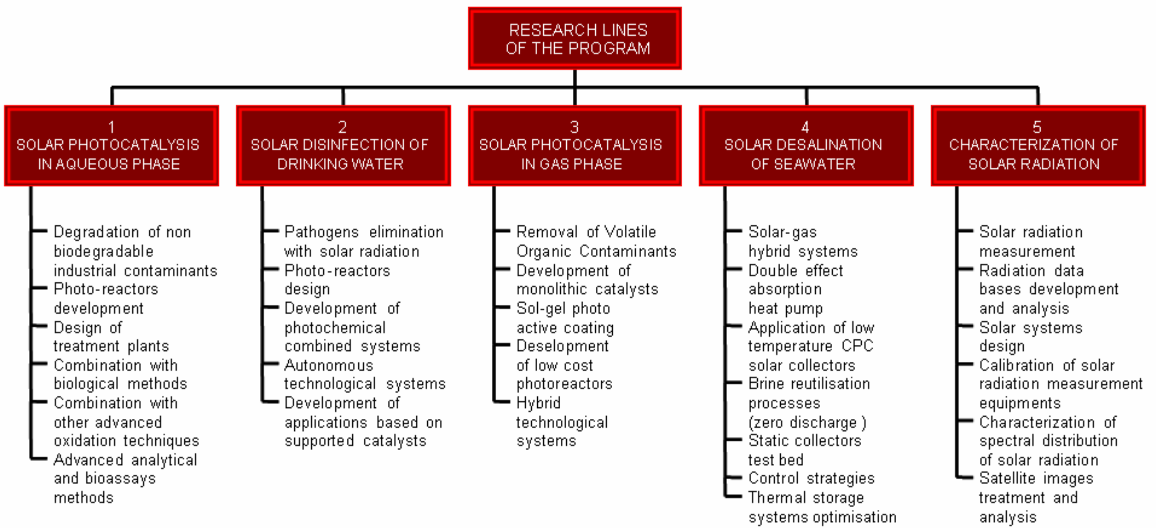


Figure 68. Environmental Applications of Solar Energy and Solar Radiation Characterization Unit Structure, by subject, line of research and knowledge group

(INNOWATECH)

3) Innovative Solar Disinfection of Drinking Water for Use in Developing Countries or in Emergency Situations (SODISWATER)
4) Mechanic Power Generation based on Solar Heat Engines (POWERSOL)
5) Seawater Desalination by Innovative Solar-Powered Membrane-Distillation System (MEDESOL)
6) Development of New Systems For Eliminating Toxic and Corrosive Gases Generated by Wastewater Treatment Plants (DETOX-H2S)

These projects, which are within the scope of most of the Unit's lines of research, will enable both in-depth technological development and an increase in the number of research groups with whom we closely cooperate.

Concerning activities in 2005, the continually growing scientific and industrial interest in this application of solar radiation to the field of detoxification. This is demonstrated by the erection of a new industrial facility based on technology used in other previous plants by the DSM-Deretil company in the framework of the CADOX project [Blanco y Malato, 2005c, 2005d], the many contacts for development of other similar facilities and the intense activity for the diffusion of these techniques and technologies [Blanco y Malato, 2005b, 2005c, 2005d; Malato y Blanco, 2005g, 2005h, 2005i].

In the field of solar disinfection, the SOLWATER and AQUACAT projects, in which a combined system employing the generation of various oxidants for the control of pathogens in drinking water was developed and successfully tested in Mexico, Peru, Argentina, Morocco, Tunisia and Egypt, were concluded. Although the results were highly satisfactory, these technological systems are still under preliminary development.

Gas detoxification activities also received a strong boost in 2005, enabling definitive consolidation of this research group. The studies performed in this field have drawn growing interest from certain companies because of the possibilities for eliminating foul odors and gas pollution in general, especially for problematic gas generated at urban wastewater treatment plants.

No doubt the area that has grown the most in 2005 is solar desalination. The water shortage problem, which is becoming more severe, as much in our own country as in many other countries around the world, along with a clear synergy between this problem and the availability of high levels of solar radiation, make the perspectives and possibilities for research and development of these technologies more and more promising. In this sense, it is worth mentioning the culmination, after four years of development, of the AQUASOL project, which has provided the PSA with an innovative experimental solar desalination facility, which, given its complexity and multitude of possibilities, is going to be a very useful tool for the design and practical implementation of this type of MED multi-effect distillation system [Blanco y Alarcón, 2005e]. Furthermore, the future execution of the MEDESOL and POWERSOL projects (mentioned above) include a very large part of the available technological spectrum for which the incorporation of solar energy for desalination of brackish or sea water makes sense. The strategy pursued in each of these initiatives, as well as the scientific and technological developments of each project, will provide the PSA with a unique set of solar desalination experimental installations making the PSA a reference for this technology and its applications.

Finally, , in the area of solar radiation measurement and characterization, completion of the new PSA meteorological station and startup of its web data access service, which has been implemented following "Baseline Surface Radiation Network" directives should also be mentioned. This access is available to the public at the address, http://meteo.psa.es/, simply by prior registration. A second outstanding aspect related to this activity is the current growth of interest in both solar thermal and photovoltaic solar technologies for solar power plants. This has also motivated an ever-greater demand by many companies for studies on the solar potential at specific sites, using both surface measurements and satellite image analysis.

In conclusion, it may be said that there has been clearly constant growth in the Unit's activities during recent years, demonstrating the scientific quality and prestige achieved by the group and the definitive deployment of these technologies as possible real answers to the global water and power problems looming on the horizon.

SOLAR DETOXIFICATION OF LIQUID EFFLUENTS

Combined Photocatalysis-Ozonation Treatment (Fotozon Project)

This project studies elimination of recalcitrant pollutants in water using Advanced Oxidation Processes (AOPs). This original project combines Photocatalysis and Ozonation, for which a strong synergy, significantly increasing the detoxification capability of either methodology alone, was observed in preliminary experiments [Malato and Blanco, 2005e].

The general project goals are:

1) Study the photocatalytic synergies (homogeneous and heterogeneous) + ozonation. Find the optimum operating parameters.
2) Find the conditions for detoxification. Combination of the technology proposed with a biological treatment. Application to the detoxification of waste water
3) Preparation of TiO_2 photocatalysts that improve their response to sunlight
4) Perform pilot plant experiments making use of sunlight. Real-scale validation of lab experiments. Application to solar treatment of industrial waste water effluents
5) Design or pre-design of a wastewater treatment plant [Augugliaro et al., 2005]

The Plataforma Solar de Almería mostly participates in the second and third years of this 3-year project (2003-2005). In fact, in 2004, ozonation experiments in water with 5 different compounds (Alachlor, Atrazine, Clorfenvinphos, Diuron, Isoproturon) were carried out in an ozonation pilot plant built for the purpose (see PSA Annual Report 2004). All of the compounds were successfully degraded, however, the disappearance of total organic carbon (TOC) is another matter: Figure 69 shows the progress of TOC during the reaction. It may be observed that after 1000 minutes of reaction, TOC is 47.9 mg/L (initial TOC in the solution was 64.8 mg/L) which means that only 26% of the initial TOC was eliminated. With these results it seems clear that ozonation is not a good method for total mineralization of nonbiodegradable compounds. Nevertheless, these results do not present a serious disadvantage, since one of the goals of this project is to study compatibility of ozonation and a biological treatment [Farré et al., 2005].

Figure 69 also contains data concerning inorganic ions formed during the reaction, since the initial compounds contain heteroatoms such as Cl, N and P, and therefore, formation of Cl^-, NH_4^+, PO_4^{3-} and NO_3^- during the reaction is to be expected. The final amount of chlorine detected was 20 mg L^{-1}, which is 7.43% of the maximum amount expected for total mineralization. As only 26% of TOC was degraded, it is clear that the process is more effective for dechlorination than for min-

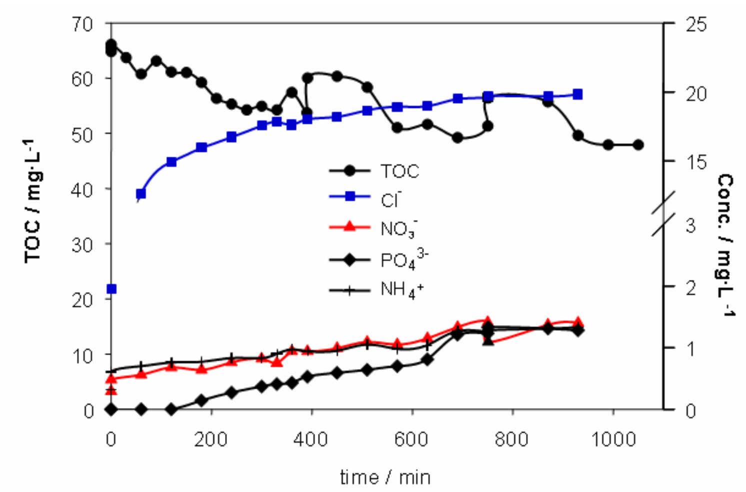


Figure 69. TOC concentration in Cl^-, NO^{3-}, PO_4^{3-} and NH_4^+ over time during ozonation of a mixture of pesticides. Volume treated: 50.1 L; O_2 flow rate: 200 L h^{-1}; $[O_3]_{gas}$: 26.8 g m^{-3}.

eralization. The total amount of ozone consumed in the reaction was 7.8 g (9.2 g O_3 consumed per gram of TOC degraded). Therefore, the mixture of compounds treated with ozone achieved low TOC degradation and high ozone consumption. However, partial mineralization of the solution for potential secondary treatment in a biological reactor could be enough.

In a detailed study of the possibility of combining chemical and biological treatments, the Zahn-Wellens biodegradability test was performed on samples taken during ozonation. The 5 compounds described above are toxic and nonbiodegradable and the Zahn-Wellens test applied to the original solution of the mixture of 5 compounds did not show any degradation of TOC after 28 days. Therefore, all of the samples used in the test were taken after complete disappearance of the initial compounds. Figure 70 shows the data from these tests.

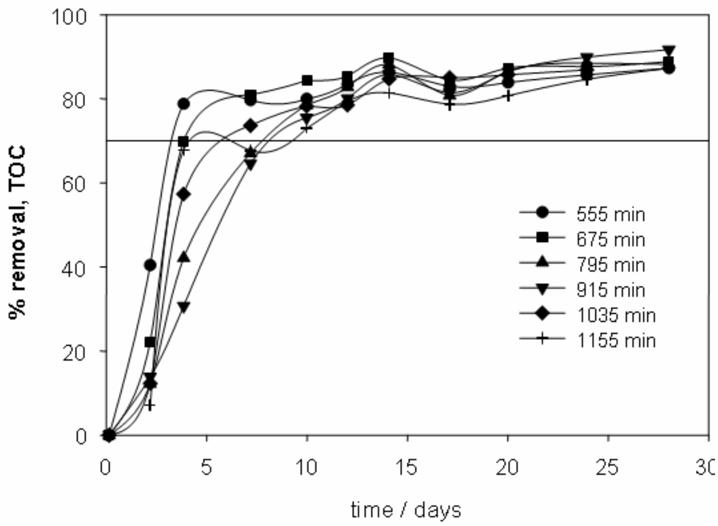


Figure 70. Zahn-Wellens Test of simples taken in the experiment shown in Figure 69 after 555, 675, 759, 915, 1035 and 1155 minutes of ozonation

It is important to mention that at 70% TOC degradation, the solution is considered biodegradable. It may be observed that after 28 days of biotreatment, the solutions are biodegradable. The reason why the test was performed on samples taken after 555 minutes of reaction is because of the possibility of generating toxic or nonbiodegradable degradation intermediates. According to the results of this experiment, that possibility can be discarded. It may therefore be concluded that partial mineralization by ozonation of the solution of 5 compounds produces a solution that is potentially suitable for biological treatment.

ELIMINATION OF PERSISTENT CONTAMINANTS BY ADVANCED OXIDATION (FOTODETOX PROJECT). http://www.psa.es/webesp/projects/fotodetox/index.html

This Project, financed by the Spanish RD&I Plan, began in 2004 and is coordinated by the PSA Environmental Applications of Solar Energy and Solar Radiation Characterization Group with participants of the Univ. of Almería Chemical Engineering Dept. and the Polytechnic Univ. of Valencia Textile and Paper Engineering Dept. Its main goals are:

1) Study of the biodegradability of water polluted by pesticides and partially treated by photocatalysis using specific cultures of single bacteria strains (selected from among those commonly used in WTPs). Find out which are the most active bacteria strains for its biodegradation.
2) Develop a predictive model for the biodegradability of water partially treated by photocatalysis.
3) Study the biodegradability (by real active sludge from WTPs) of water polluted by pesticides and partially treated by photocatalysis.
4) Develop a bioreactor specially adapted to this type of water partially treated by photocatalysis [Ballesteros y col., 2005].
5) Pre-design of a solar photocatalytic water treatment plant for pretreatment of water containing persistent pollutants and make them compatible to the input requirements of a municipal WTP.

During the first year (see PSA Annual Report 2004), the main pesticides used in intensive agriculture as applied in the province of Almería were studied in depth. Analytical techniques necessary to evaluate their degradation were perfected and the non-biodegradability of those selected was verified. The feasibility of TiO_2 photocatalysis in the solar pilot plant was also studied for each pesticide [Oller et al., 2005b].

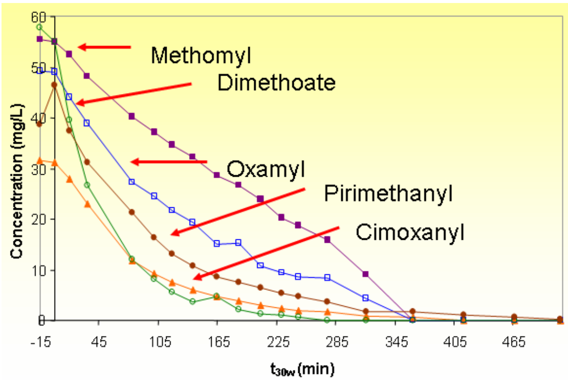


Figure 71. Photocatalytic degradation (TiO_2) of each pesticide in the mixture

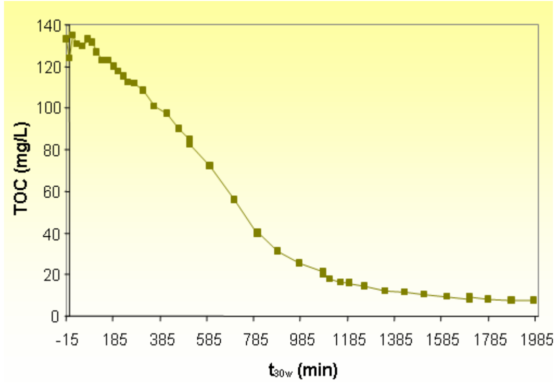


Figure 72. Total organic carbon in the mixture

In 2005, a feasibility study of TiO_2 photocatalysis of pesticide mixtures (Methomyl, Cymoxanyl, Oxamyl, Dimethoate Pyrimethanil) was carried out and a study of each of them with photo-Fenton is now underway. Degradation of each of these pollutants is analyzed by HPLC-UV, the measurement corresponding to the mixture at any given time. Figure 72 shows how the pesticides disappear completely after about 420 minutes. Pyrimethanil is a bit more resistant to degradation. These results agree with those of experiments with the single pesticides described in the PSA 2004 Annual Report. Moreover, monitoring of TOC demonstrates incomplete mineralization after about 33 hours of photocatalytic treatment with a residual TOC of about 7 mg/L. As there are compounds in the mixture containing nitrogen, sulfur and phosphorous in their structures, they were also analyzed for their release as nitrate, ammonia, sulfate and phosphate. It may be observed that the nitrogen balance is not completely closed, although total nitrogen concentration present in the form of nitrate and ammonia is very near expected. The sulfur and phosphorous balances are completely closed, and all the sulfur and phosphorous has been oxidized into sulfate and phosphate.

Only cymoxanyl and oxamyl have been studied up to now with photo-Fenton (Figure 73 and Figure 74). Temperatures were kept at 30°C and pH was between 2.5 and 3 with 20 mg/L of Fe^{2+}. Degradation of cymoxanyl was complete (noticeably faster than with TiO_2). Mineralization was incomplete (residual TOC similar to TiO_2). The nitrogen balance was incomplete. Degradation of oxamyl was complete (also noticeably faster than with TiO_2). Mineralization was better than with TiO_2, reaching a TOC of around 2 mg/L.). The nitrogen balance was similar to that of cymoxanyl.

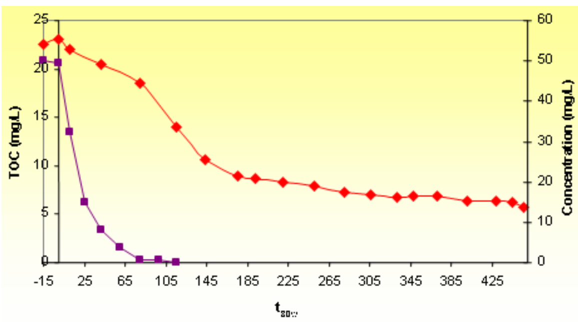


Figure 73. Cymoxanyl degradation by photo-Fenton

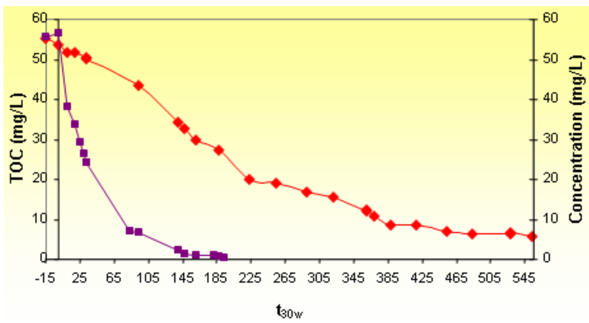


Figure 74. Oxamyl degradation by photo-Fenton

Treatment of water containing persistent organic pollutants by a combination of advanced oxidation and biological processes (CADOX Project). http://www.psa.es/webeng/projects/cadox/index.html

Following the project goals, as defined in the 2003PSA Annual Report, the first tasks in the Project were designed to find the main parameters for degradation of target compounds by oxidation (TiO_2, photo-Fenton and ozone). It was demonstrated that all of the compounds subject to this work can be successfully treated by photo-Fenton, TiO_2 and ozone. In 2004, two prototypes were erected (one at the PSA and the other at INETI, in Portugal) during the project, and their main characteristics were described in the 2004 PSA Annual Report. The purpose of the work [Hincapié et al., 2005a, 2005b] with these prototypes in 2005 was to find the basic parameters necessary to design and build the demonstration plant which is the final project goal. This plant was finished at the end of 2005.

The main conclusions arrived at from the experiments performed with the prototypes were:

1. The reactivity of the compounds treated by both advanced oxidation processes tested (photo-Fenton and TiO_2) were very similar.
2. With atrazine and the pesticides in the phenylurea family, there was always some TOC left at the end of the treatment, due to the stability of the triazine ring and urea that forms during photocatalytic degradation.
3. TiO_2 photocatalysis takes longer than photo-Fenton for similar mineralization.
4. Evolution of pH during treatment by TiO_2 depends on how much chlorination there is of the molecules treated (hydrochloric acid generated lowers the pH) and the organic nitrogen content, which is usually transformed into ammonia and therefore has the opposite effect.
5. Biodegradability is reached when dechlorination is complete.
6. Ozonation much reduces pesticide mineralization, however, dechlorination is still complete, but with much longer reaction time.
7. Chlorated solvents are only mineralized by photo-Fenton and with great difficulty by TiO_2. In this case, combination with a biological treatment is not pertinent, since complete mineralization is simultaneous with dechlorination. Both ozonation and TiO_2 produce great losses of contaminants volatilized into the atmosphere [Malato et al., 2005f].

The positive and negative results, based on elimination, mineralization and biodegradability during laboratory and pilot plant experiments [Gernjak y col., 2005a, 2005b; Malato et al., 2005a, 2005b, 2005c, 2005d; Maldonado et al., 2005a, Oller et al., 2005a; Rodríguez et al., 2005], are summarized in the following table. This table provides the key information for selection of the best treatment system developed in the CADOX project.

From these conclusions real water from the final user (DSM-DERETIL) was used in a test campaign to find the design parameters for the demonstration plant. These experiments were limited to treatments with photo-Fenton and ozonation as the prior stage to a fixed-bed bioreactor using biomass from the DSM-DERETIL treatment plant. Femac (550 mgf/L, a nonbiodegradable compound) was completely degraded with a hydrogen peroxide consumption of 30-35 mM (Figure 75).

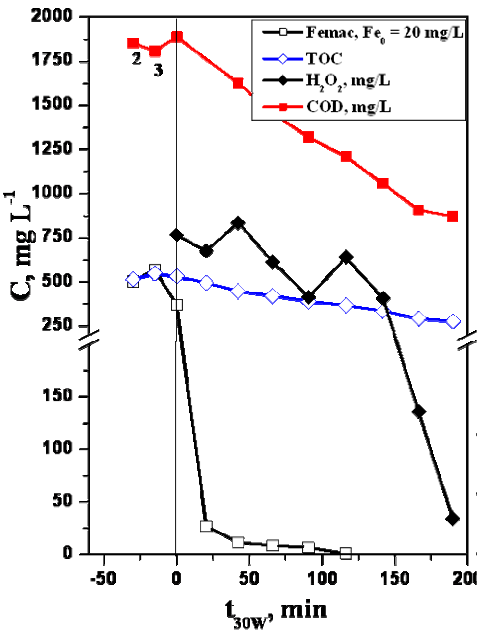


Figure 75. Photo-Fenton degradation of water from DSM-DERETIL

During testing, the mean oxidation state (ratio of COD to TOC) became constant at the same time

Table 5. Selection of the best combination of treatments for the demonstration plant

		Photo-Fenton	TiO_2	Ozone	Biotreatment
Lab scale	Pesticide	Mineralization a 56 mg Fe/L	No mineralization	Results not conclusive	Adequate biodegradability after de pre-treatment
	Femam	Mineralization a 56 mg Fe/L	No mineralization	Results not conclusive	-
Evaluation		++	+	NA	++
Scale up	Pesticides and FEMAC	Recovery of the catalyst can be avoided by working with Fe	Recovery of the catalyst possible but expensive	Ozone is efficient if COD is ≤ 500 mg/L	Fixed-bed bioreactor best option
Evaluation		+	-	+	+
Prototypes	Pesticides	Best point of biodegradability found	Best point of biodegradability found takes a long time	Best point of biodegradability found	With fixed-bed bioreactor treatment achieved up to the end
	FEMAC	Best point of biodegradability found	Best point of biodegradability found takes a long time	Best point of biodegradability found	With fixed-bed bioreactor treatment achieved up to the end
Evaluation		++	-	+	++
Selection		+ Photo-Fenton		+ Ozone	+ Biological

that Femac was completely degraded. This also coincided with the time when the water became biodegradable, as determined by the Zahn-Wellens test. Femac was also degraded by ozonation, but after a longer treatment time (approx. 700 min.) and with an ozone consumption of about 2 mg of O_3 per mg of Femac. As with photo-Fenton, biodegradability was reached by ozonation when Femac was completely decomposed. In addition to demonstrating biodegradability with the Zahn-Wellens test, the effluent from both treatments was fed to a fixed-bed bioreactor for several months. Operating under these conditions, the bioreactor achieved biodegradation of better than 80%.

Based on these results, (which are only sketched very briefly here) the demonstrate plant designed consisted of 100 m^2 of CPCs (around 1300 L illuminated volume) with a 3000-L recirculation tank, an ozonizer with two contact columns (Ø800- h 2500 mm y Ø500- h 2100 mm) in series, which is able to produce up to 1 g O_3/h and a biotreatment made up of several tanks (neutralization, conditioning, bioreactor) in which the biomass is set at a 700 L filler. The plant was finished at the end of 2005, and will be tested in 2006. Figure 76 shows the various demonstration plant components

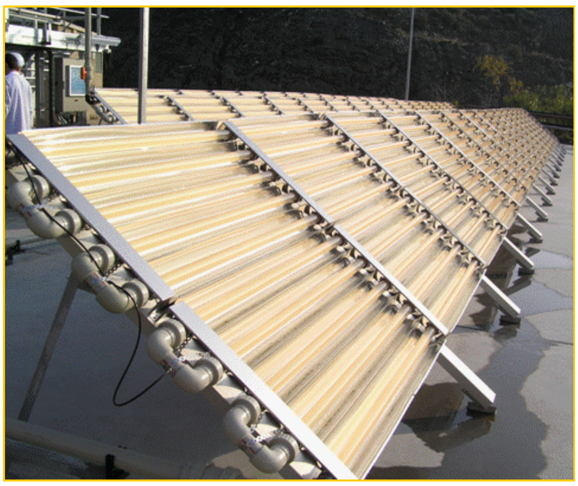


Figure 76. CADOX project demonstration plant ozonation system and fixed-bed bioreactor (left), and solar collector system (right)

SOLAR DRINKING WATER DISINFECTION PROCESSES

Solar disinfection of drinking water (Solwater Project)
http://www.psa.es/webeng/solwater/index.html

The SOLWATER project (official name: "Cost effective solar photocatalytic technology to water decontamination and disinfection in rural areas of developing countries") is a project funded by the European Commission (contract nº: ICA4-CT-2002-10001) under the INCO program (EU-DG Research, Confirming the International Role of Community Research for Development). This 3-year (November 2002-October 2005) project is coordinated by the Environmental Applications of Solar Energy Group and has a budget of 1818,6 k€ and both European (ECOSYSTEM-Spain, AOSOL-Portugal, Complutense University of Madrid-Spain, National Technical Univ. of Athens-Greece, Ecole Polytechnique Federale de Lausanne-Switzerland) and South American (Mexican Institute of Water Technology-México, National Atomic Energy Commission-Argentina, National University of Engineering-Peru, TINEP S.A. de C.V.-Mexico), participants, because the area of potential application of the results is Latin America.

The main goal of this project is to develop a completely autonomous solar system for the disinfection of drinking water in rural areas without having to use any chemical additive [Fernández-Ibáñez et al., 2005a; Rincón and Pulgarín, 2005; Sarria et al., 2005a, 2005b]. The final system will treat water based on the combination of two photocatalytic processes activated by sunlight for the generation of powerful oxidants that may be efficient for the inactivation and elimination of pathogens in water. The first of these processes is the use of titanium dioxide immobilized on an inert matrix to generate hydroxyl radicals ($^{\bullet}OH$) and the second is the generation of singlet oxygen ($^1O_2$) from a photosensitizer based on Ruthenium (II) complexes fixed on a polymer matrix. Furthermore, the final system is expected to also be able to eliminate potential persistent organic pollutants.

During the development of this final system, several different prototypes were designed and built (Figure 77, left) in order to experimentally compare the behavior and efficiency of two different photoreactor concepts, one concentric with a tube inside the cylindrical reactor where the catalyst is fixed and another flat, inserted vertically inside the tube (Figure 77, right). In both cases, the optics used were based on 1-m^2 CPC solar collectors. For each of these photoreactor concepts, two different catalysts were used, TiO_2 supported on a special paper developed by the Ahlstrom Paper Group (France), and RU(II) complexes with polyazo heterocyclic ligands immobilized on polymer supports developed by the Complutense University of Madrid [Sichel et al., 2005a]. In 2005, these prototypes were tested using *E. coli* as the reference to study the disinfection efficiency of the different systems.

Figure 77. Solar reactor prototype for water disinfection with catalyst fixed on two different supports (flat plate or concentric tube, see right) arranged inside the glass tube

One of the main CIEMAT tasks in this Project was to experiment to find out the optimum operating conditions, that is, those that disinfect the water effectively at the lowest cost, fastest and using the least energy possible. The main photoreactor operating parameters affecting the process were therefore analyzed. Therefore, various experiments were performed for disinfection of water containing *Escherichia coli*, at an initial concentration of 10^7 CFU/mL, at three different flow rates 2, 5 and 10 L/min. Figure 78 shows that *E. coli* is deactivated faster when the reactor works at 2 L/min than at 5 or 10 L/min. During photocatalysis, interaction (adsorption) with the agent to be destroyed on the catalyst surface plays a fundamental role. Therefore, better disinfection efficiencies are to be expected when the interaction conditions between bacteria and catalyst are optimum, that is, at low recirculation flow rates in the reactor [Sichel et al., 2005b]

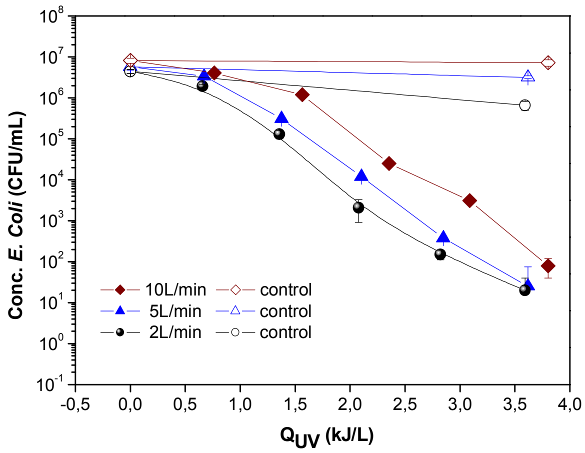


Figure 78. Photocatalytic efficiency of TiO_2 on Ahlstrom KN47 paper at three different reactor flow rates: 2, 5 and 10 L/min. Progress of *E. Coli* concentration is plotted over Q_{UV} (UV energy input by unit of photoreactor volume)

Photocatalytic degradation experiments were also performed with gallic acid, a model organic compound. The concentrations of this pollutant were relatively low (20 and 50 mg/L), because humic acid pollution in natural groundwater is usually found at such concentrations [Gumy *et* al., 2005]. Figure 79 (left) shows the results of gallic acid degradation in the photoreactor described above with Ahlstrom KN47 paper coated with titanium dioxide (20.7 g/m²) on the concentric support. Degradation of the compound at two different initial concentrations is very different. When the initial concentration is 20 mg/L, it is adsorbed on the catalyst better than when the initial concentration is 50 mg/L. which is why the process is more efficient with the first one. Photocatalytic behaviour with flat and concentric-support reactor configurations was also compared. Figure 79 (right) shows degradation of gallic acid in the two systems (initial concentrations 30 and 35 mg/L). The concentration of gallic acid is plotted over UV energy accumulated in the reactor per unit volume (Q_{UV}). The organic concentration decreases faster with the flat support, as the illuminated volume of water is greater with this configuration, and therefore better use is made of the photons entering the system and of the radicals generated on the illuminated catalyst [Sichel et al., 2005b and 2005c].

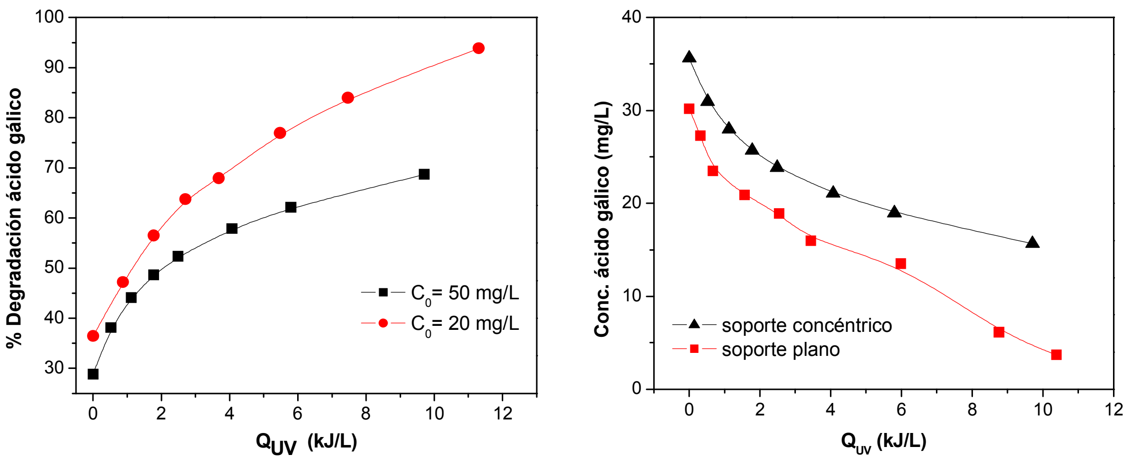


Figure 79. Photocatalytic degradation of gallic acid in a CPC solar reactor with TiO^2 immobilized on Ahlstrom KN47 catalytic paper 20.7g/m² TiO2-PC500. Left: Concentric support with 20 and 50 mg/L initial concentration of gallic acid. Right: concentric and flat supports, 30 and 35 mg/L initial concentration

According to the results of experiments by the PSA [Fernández-Ibáñez y col., 2005b y 2005c], and other participants in the project (UCM, NTUA, EPFL y LACE), the final system has been designed, which was tested in 2005 in remote rural areas at three different sites in South America, Argentina, Peru and Mexico in the framework of the SOLWATER project. The purpose is to analyze the results obtained 3 socioeconomic environments at different solar latitudes. Figure 80 shows two photos of the two final reactors installed in Jiupetec (Mexicio) and Tucumán (Argentina) for the field tests.

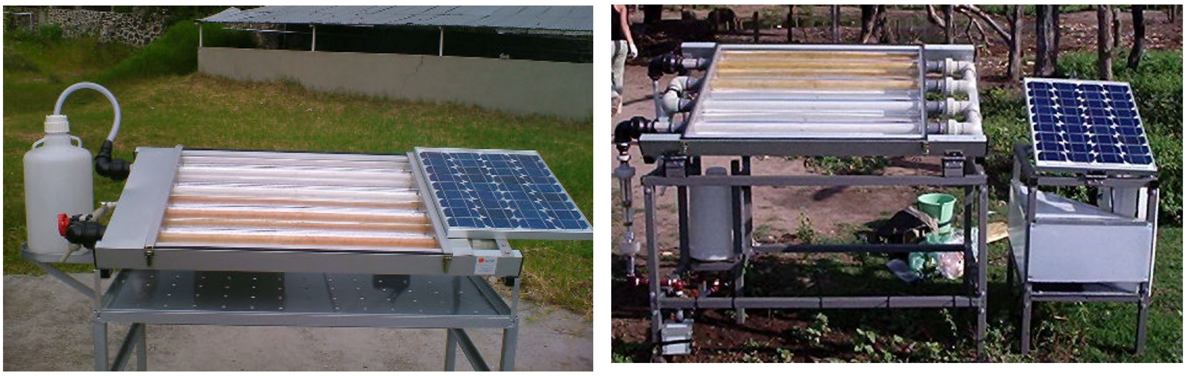


Figure 80. **View of the final system developed and prepared for testing in Mexico, Mexican Institute of Water Technology (left) and Argentina, National Atomic Energy Commission (right.)**

Detoxification and purification of drinking water by photocatalysis in semiarid countries (AQUACAT Project) http://aquacat.univ-lyon1.fr/

In addition, and conceptually linked to the SOLWATER project, the Solar Chemistry Group participates in another European project 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 purposes of the AQUACAT project are basically the same as those in the SOLWATER project, except the region the final system is designed for is the Mediterranean. It will be tested in communities in Egypt, Morocco and Tunisia [Chapelon y Herrmann, 2005].

The participants in the AQUACAT project are the Univ. Lyon-1 (France, Coordinator), CIEMAT-PSA (Spain), ECOSYSTEM S.A. (Spain), AO SOL Lda. (Portugal), Univ. Poitiers (France), AHLSTROM (France), ENIG (Tunisia), UNIV. DE FES (Marruecos), PROJEMA, S.A. (Morocco), PHOTOENERGY CENTER (Egypt), Univ. Complutense (Spain), EPFL (Switzerland). The total budget is 1700 k€ with a contribution by the European Comisión of 1000 k€.

The final AQUACAT solar photocatalytic water disinfection system was developed, manufactured and installed in three North African countries, Tunisia, Morocco and Egypt. Figure 81 shows two photos of the reactors installed in the School of Engineers of Fez (Morocco) and in the Photoenergy Center of El Cairo (Egypt), where they were tested in the field with real water.


Figure 81. **View of the final system developed for testing at the Ecole Supérieure de Technologie de Fes, Morocco (left) and Photo Energy Center, Cairo, Egypt (right)**

Emerging technologies for water treatment in developing countries (Solarsafewater Project)

http://www.cnea.gov.ar/xxi/ambiental/ssw/indesp.htm
http://www.psa.es/webesp/projects/solarsafewater/index.html

The goals of the *Emerging technologies for water treatment in developing countries (SOLARSAFEWATER Project* FP6-510603, EC 6th Framework Program) are:

1) Publicize the most recent results and promote transfer, use and evaluation of solar photocatalytic technologies for depollution and disinfection of water, applied to rural areas in developing countries.
2) Contribute to regional work in solar water treatment by capable teams integrated in networks with European participation
3) Explore possible future European Commission Research and Technology Development, (EC RTD) activities related to pilot tests using the technology developed in the SOLWATER Project (Economic Solar Photocatalytic Technology for Decontamination and Disinfection of Water in Rural Areas in Developing Countries).

The SOLARSAFEWATER initiative is related to treatment of water until fit for drinking. The implementation of these Specific Support Activities allows experience and know-how to be exchanged by active R&D teams and contribute to the diffusion of knowledge on this subject, especially for its application in rural areas and outlying urban areas in third-world countries. SOLARSAFEWATER has carried out two key activities for this purpose:

- A **Course** on Possibilities for Safe Water Supply Using New Technologies. The course was given in Port Iguazú (Misiones, Argentina) on Friday the 14th and Saturday the 15th of October 2005. The two-day event included lectures on the technical characteristics of the new technologies available for procurement of water, in particular, those that make use of sunlight. It was directed at young scientists and engineers, and was attended by approximately 50 people, almost all of them from Latin America. The presentations at the course and the texts prepared by the professors are available on the event's web page [Fernández-Ibáñez, 2005a; Blanco, 2005a.

- A **Symposium** in continuation of the Course, addressed scientists and engineers working on the subject, for discussion of *The Challenge of Supplying Safe Drinking Water: Technologies for Latin America*. The main language of the Symposium was Spanish, but the lectures and talks were given in the speaker's original language. the Symposium was a three-day event (October 17, 18 and 19, 2005) discussion of the state-of-the-art of photocatalytic technology and other Advanced Oxidation Technologies (AOTs) for water purification and for publicizing the abilities of available technologies among potential users and small and medium-sized businesses and high-ranking government employees in nearby countries. Participation by members of the SOLWATER

Figure 82. **View of the SOLARSAFEWATER project events website (http://www.cnea.gov.ar/xxi/ambiental/ssw/indesp.htm)**

project provided a suitable environment for comparative evaluation of the options available for technical solutions and the market offer. The Symposium, starting out from the SOLWATER project results, explored possible future research activities, including solar photocatalytic pilot tests and/or other possible options. The Symposium also was useful for exploring the possibility of expanding the CYTED Latin American photocatalysis network to include European participation in general. The Symposium included several Plenary Lectures, Guest Lectures, poster sessions and round table discussions on specific subjects.

SOLAR GAS DETOXIFICATION PROCESSES

Photocatalytic destruction of gas in gluing and metal degreasing booths (CMP)

The new regulation on industrial emissions of volatile organic compounds (VOCs) that is to go into effect in 2007 following European Union directive (1999/13/CE), sets much stricter limits on the amount of pollution that can be released into the atmosphere. The greatest concern for this air pollution is not only its intrinsic toxicity, but also its participation in photochemical reactions that generate ozone in the troposphere. There is therefore a growing demand for new pollution control systems that make it possible to comply with legislative requirements without high investments by the companies in the sectors involved (textiles, shoes, paints, varnishes, etc.). In this context, the CMP S.L., company, automobile parts manufacturer with factories in La Rioja and Navarra, has funded a project for developing a solar solvent emissions treatment system. These studies were done by the Solar Gas Detoxification Group in cooperation with the CSIC -ICP Catalytic Processes Engineering Dept.

The source of CMP S.L. emissions is forced evaporation of solvents used in gluing and degreasing during manufacturing. Since the composition and concentration of the emissions conditions the choice of treatment method, the first step was the analytical characterization of the effluent. A gas micro-chromatograph was used to analyze samples taken at the plant and it was found that emissions consisted of aromatic compounds (toluene, xylene) and minor amounts of chlorides (tetrachloroethylene, dichloromethane) and oxygenates (butanol, methyl-ethyl-ketone, etc.). The average emissions concentration is around 100 ppmv.

With these parameters, the feasibility of photocatalytic emissions treatment of some representative pollutants (toluene and trichloroethylene) was evaluated in photocatalytic oxidation tests in a solar photoreactor designed for ceramic catalysts synthesized at the ICP-CSIC. However, the efficiencies obtained under the conditions required for real emissions treatment were not good enough to ensure compliance with the future regulation. Therefore, keeping in mind the considerable increase in flow rate due to centralization of the plant's gas extraction system, the use of photocatalysts for the treatment of these effluents was discarded. As an alternative method, a combination of pollution adsorption and catalytic combustion. This new strategy consists of a cyclic process in which the organic compounds are first concentrated by keeping them in the adsorbent bed until saturation, and then it is desorbed by a reduced flow of hot air that takes them to the catalytic bed where they are combusted. In order to keep up a continuous decontamination process, a double adsorbent bed has to be used so that while one of them is accumulating organics, the second is being regenerated. The thermal energy necessary for the desorption and catalytic oxidation would come from parabolic trough solar collectors (PTC). A diagram of the system proposed is shown in Figure 83.

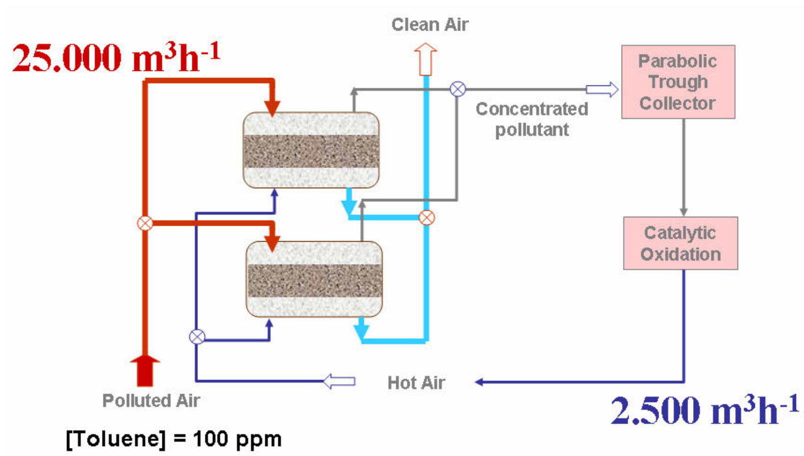


Figure 83. Diagram of the gas treatment system proposed for the CMP S.L. company based on adsorption-desorption processes and catalytic combustion with solar thermal energy supply.

The catalyst was monoliths containing Pt as the active phase and that has been shown to be highly effective in the combustion of toluene in concentrations up to 3600 ppmv with residence times short enough to be used in the CMP S.L. plant. Combustion of the organic compounds is generally an exothermic process which can be used to recover heat generated, and also helps keep up the reaction during transients when the solar thermal supply is insufficient.

Concerning the adsorbent, several different porous materials have been tested both as monoliths and extrudes. The most satisfactory results were with activated carbon monoliths that retained up to 70 mg of toluene per gram of adsorbent in dynamics at a temperature of 35°C. These organics can be desorbed by heating the bed to over 80°C. In the tests performed with the PTC installed at the CIEMAT in Madrid, a 30 L/min air stream was heated to 250°C using just one 2.25 m-long module with an uncovered glass absorber tube and global radiation of around 700 W/m^2.

The experiments performed to test the efficiency of combining the desorption system and catalytic combustion were also positive, and it could be proved that the use of the two methods together for the treatment of volatile organic pollution is effective. Therefore, the project is to be extended to installation in the plant of a demonstration system to determine the feasibility of using the three technologies involved in the emissions treatment: adsorption, catalytic combustion and solar heating.

DEVELOPMENT OF ALTERNATIVE METHODS FOR PREPARATION OF HIGH-EFFICIENCY PHOTOCATALYTIC MATERIALS

The basic purpose of this project is to develop advanced photocatalysts to satisfy the growing demand for suitable materials for treatment of Volatile Organic Compound emissions (VOCs). This goal is particularly relevant in the scope of photocatalytic elimination of indoor air pollution, which is currently at a beginning stage of commercial development, with commercial prototypes that incorporate this technology in air conditioning systems. The photocatalyst most used is by far TiO_2, both anatase and in mixtures of anatase and rutile. For its application in treating aqueous effluents, TiO_2 is frequently used as a powder. However, gas treatment requires photocatalysts supported on open structures that allow the treatment of high flow rates without taking the photoactive component away with it. It is also desirable for the support used to be transparent to the radiation used for activating the photocatalyst (UVA), since this would allow more effective use of the incident photons.

Against this background, during the first year, research has concentrated on the selection of high-efficiency TiO_2 photocatalysts and on the other, on the search for supports permitting maximum performance of the photoactive component. The most relevant results are the following:

- **Preparation of photocatalyst thin films on borosilicate glass**. Borosilicate glass is a very suitable support for photocatalysts since they combine adequate transparency in the UVA region (see Figure 84) with good chemical affinity for TiO_2, which enables excellent fixation of the photoactive material. It is therefore relatively simple to achieve thin films by the dip-coating method. TiO_2 and TiO_2 –ZrO_2 thin films have been made this way on glass Rashig rings and thin glass plates. These materials have been proven to be highly effective in the elimination of different types of compounds such as Sh_2, toluene and trichloroethylene.
- **TiO_2 coatings on porous ceramic supports.** Adsorption is a basic stage in any heterogeneous catalytic process. In general, the increase in adsorption capacity translates into greater pollution degradation reaction efficiency. From this viewpoint, TiO_2 was coated on porous natural sepiolite silicate ceramic supports, using different preparation methods. Fixation of commercial TiO_2 powders is possible with suspensions of these materials in isopropanol with some additives to increase viscosity. This way TiO_2 coatings have also been deposited using stabilized sols in the slip-casting process. The photoactivity results of using these materials are very promising and seem to confirm the positive influence of porosity on increased efficiency.
- **Photoactive films on polymeric supports**. The use of organic substrates has the advantages of its light weight (which can be determinant in certain applications), its malle-

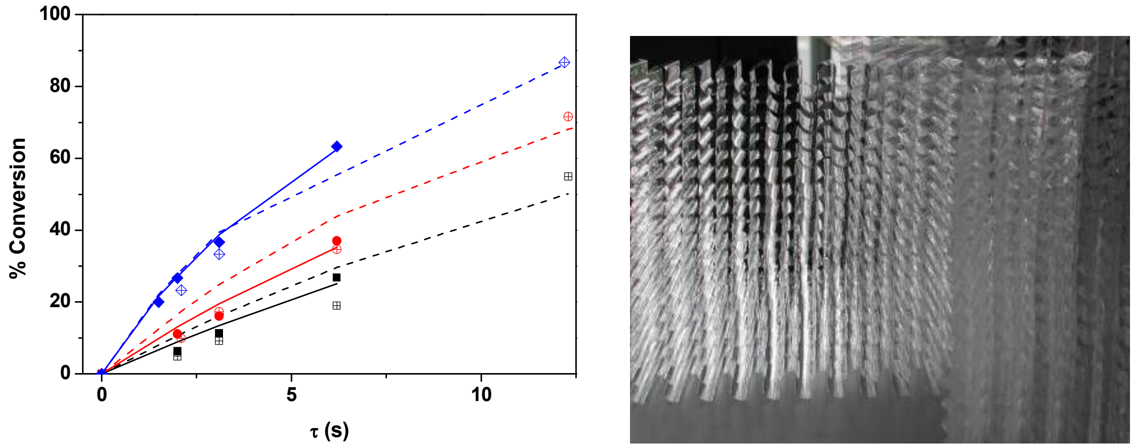


Figure 84. Left: Variation in TCE conversion with residence time for two different TiO_2 coatings (solid and hollow symbols) at different input concentrations: 30 (diamonds), 81 (circles), 142 (squares); Right: TiO_2-coated plastic used in these tests.

ability and its relatively low cost. If, moreover, UVA transparent materials like PET are selected, then highly-efficient photocatalytic materials are sure to result. Nevertheless, TiO_2 deposition on such supports presents a considerable challenge, as these thermo-sensitive materials cannot be used in calcination processes to attach and crystallize the photoactive layer. Furthermore, due to the considerable hydrophobicity of the organic materials, it is very difficult to fix homogeneous metal oxide films based on aqueous sols to them. TiO_2 photocatalytic activity itself and/or the effect of the radiation could degrade the support that could eventually lose its transparency and/or mechanical consistency. Therefore, in this study, an SiO_1 layer was proposed as a protective barrier shielding the support. Various strategies were tested to improve adhesion including the addition of surfactants and deposition of loaded polymers that foster fixation of the inorganic films. The first results with these materials are quite promising and have recently been published [Sánchez et al., 2006]. On example of the photoactivity of these materials for the degradation of trichloroethylene over residence time is shown in Figure 84. it is important to point out that these results show that although TiO_2 was not subjected to any high-temperature treatment, its efficiency is comparable.

SOLAR SEAWATER DESALINIZATION

AQUASOL Project

The main goal of this European Project is the development of a hybrid solar/gas seawater desalination technology based on multi-effect distillation (MED) which complies with the principles of energy efficiency, low cost and zero discharge.

The participants in the AQUASOL project are: CIEMAT (coordinator), INABENSA (Spain), Ao Sol Energias Renováveis (Portugal), National Technical University of Athens (Greece), INETI (Portugal), Cajamar (Spain), Hellenic Saltworks (Greece), Las Cuatro Vegas Irrigation Community of Almería (Spain) and Weir-Entropie (France). The four-year project is divided into two stages: a first research stage lasting two and a half years and a second demonstration stage lasting a year and a half. The project started officially in March 2002.

The AQUASOL Project focuses particularly on the technological development of three basic points:

1) Incorporation of a hybrid solar/gas energy source based on high-efficiency, low-cost stationary compound parabolic collectors (CPC)
2) Develop an optimized double-effect absorption heat pump (LiBr/H2O) for its installa-

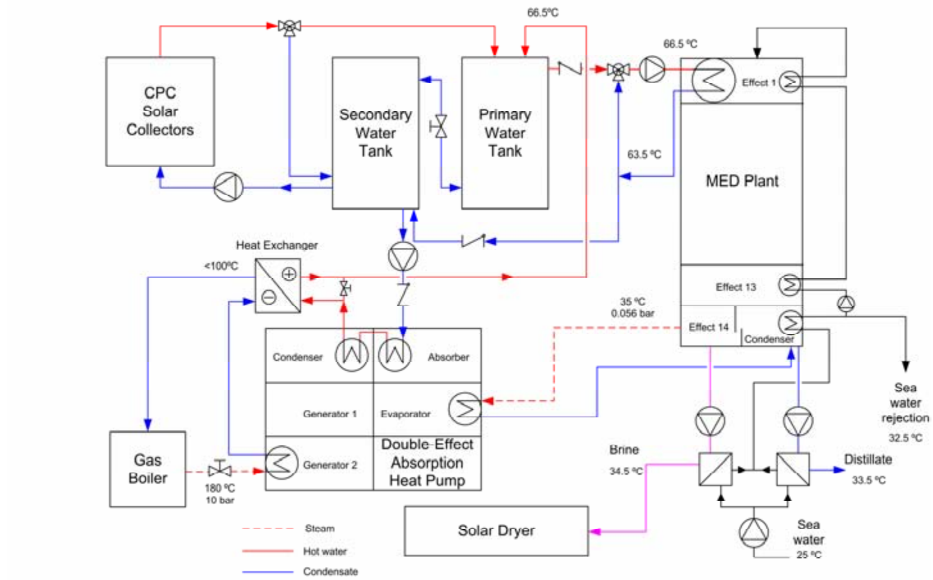


Figure 85. General AQUASOL desalination system flow diagram

tion in the MED process which reduces the energy consumption required by a conventional MED plant by half.

3) Reduce any kind of discharge from the distillation process to zero by recovering the salt from the brine.

In 2005, development of the demonstration phase continued concluding with the installation of all the subsystems that make up the AQUASOL desalination plant (stationary CPC solar collector field, thermal storage tanks, gas boiler, double-effect absorption heat puma and advanced solar dryer), as shown in the flow diagram in Figure 85.

Figure 86. Double-effect absorption heat pump (LiBr-H_2O)

The new double-effect (LiBr-H_2O) heat absorption pump has been noticeably improved over the first prototype that was tested at the PSA at the beginning of the nineties. Contrary to this last, in which steam condensation produced in the low-temperature steam generator was performed directly in the first effect of the MED plant, the new one developed incorporates its own low-temperature condenser, and all the heat transfer takes place in internal heat exchangers. The heat yielded by the pump absorber and the condenser increase the enthalpy of a stream of water powering the first effect of the distillation plant. The use of water as the heat transfer fluid to receive the heat supply from the pump favors the use of hybrid supply schemes in which the final energy required by the desalination process can come from the solar collector field and the absorption machine at the same time, the proportions depending on the available solar resource at the time.

This year, the piping between all of the above subsystems was also installed, and so was the design and implementation of the new control system which makes it possible to operate the entire plant (MED plant+heat pump) from a single panel. The data acquisition system that monitors and evaluates data during experiments was also completed.

Figure 87. Front view of the MED distillation plant building, with the two thermal storage tanks, the propane gas tank (right) and part view of piping.

Figure 88. **Advanced solar dryer developed in the AQUASOL Project**

In the research stage of the AQUASOL Project, an advanced solar dryer was designed to increase the concentration of the brine from the MED plant to the point of calcium carbonate saturation (16°Be, Baumé scale). This design consists of three parallel connected evaporation channels (4-m x 17-m), connected to each other, inside which the brine circulates. These channels are provided with a plastic cover, a preheating section at the inlet and a solar chimney at the other end to drive the air flow inside the channels. This experimental device is installed at the Kalloni salt works (Island of Lesbos, Greece), property of the Greek Hellenic Saltworks company. A fourth open-air channel has been added on for the sake of comparison of the new solar dryer behavior. Simulation models predict an increase in evaporation efficiency 2.5 times open-air evaporation ponds in a conventional salt works.

Figure 89 and Figure 90 show evaluation of the first experimental results from the AQUASOL system. In the first one, distilled water production is shown with the corresponding thermal energy consumption when the plant is operating in solar-only mode. For an MED Plant first effect inlet temperature of 71.5°C, average product was 3.23 m^3/h, and specific consumption was 69.17 kWh_t/m^3. If the inlet temperature is reduced to 68.5°C, then the average specific consumption of thermal energy falls to 67.8 kWh_t/m^3. The second figure shows plant behavior in fossil-only mode with the heat pump, and it can be observed how this device enables the performance factor to increase (kg of distillate produced per 2326 kJ thermal energy supplied to the system) from an average of 10 up to an approximate 20 [Alarcon y col., 2005].

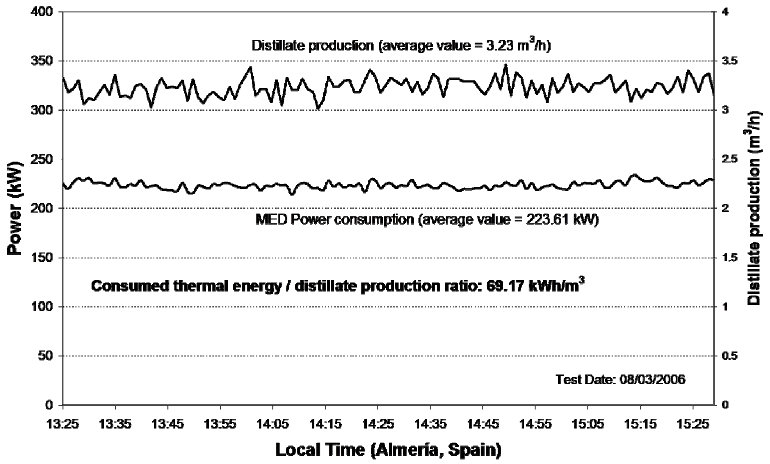


Figure 89. **Distillate production and total thermal energy consumption in AQUASOL plant (solar-only mode)**

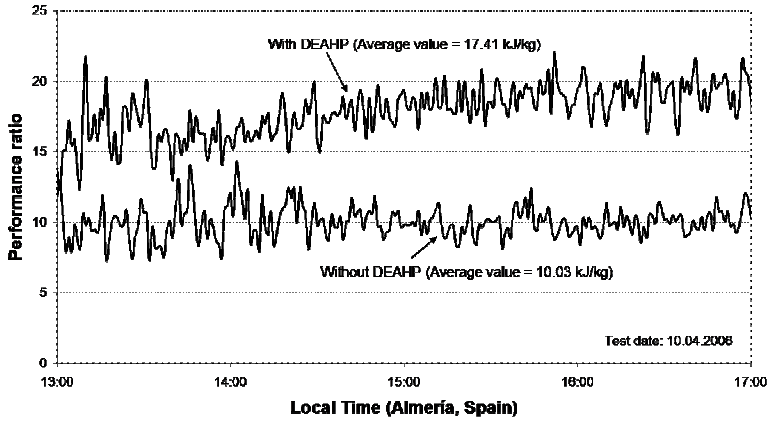
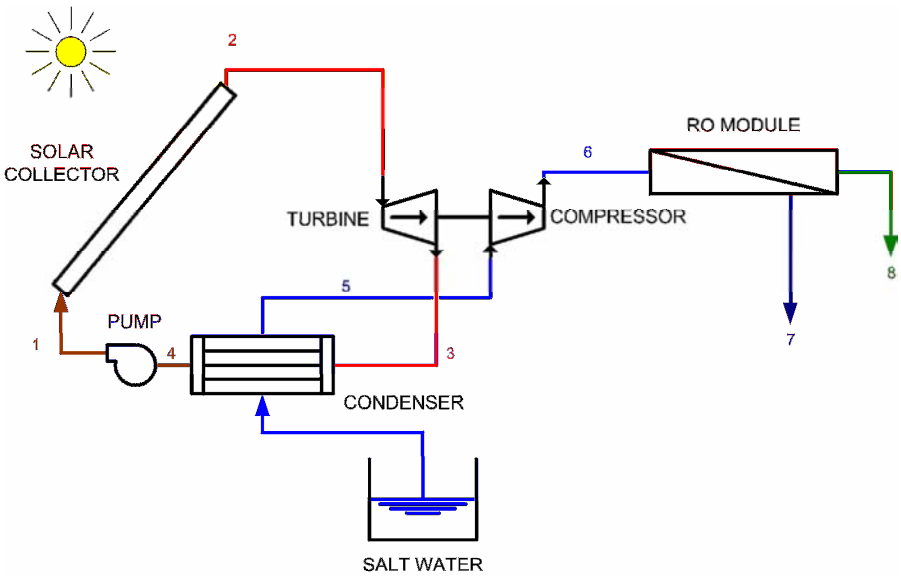


Figure 90. AQUASOL plant with the heat pump (fossil-only mode) performance factor

OSMOSOL Project

Activities in the new OSMOSOL Project (Solar thermal reverse osmosis desalination), financed by the Ministry of Education and Science, began in 2005.

The main goal of this project is the development of an innovative technology based on the application of solar thermal energy to desalination by reverse osmosis, which meets the principles of both environmental sustainability and economic feasibility. For this it is intended to use the thermal energy collected and concentrated by a solar device to feed a thermodynamic cycle based on a fluid that evaporates at a relatively low temperature and which, connected to a turbo compressor system, enabling direct transformation of thermal energy into the mechanical energy required for osmosis.



1. Working fluid, minimum temperature, maximum pressure [Ammonia, 30°C – 40 bar]
2. Steam working fluid, maximum temperature and pressure. [Ammonia, 80°C – 40 bar]
3. Steam working fluid, minimum temperature and pressure. [Ammonia, 30°C – 12 bar]
4. Liquid working fluid, minimum temperature and pressure. [Ammonia, 30°C – 12 bar]
5. Preheated salt water.
6. High-pressure salt water.
7. Brine.
8. Product.

Figure 91. Generic reverse osmosis system connected to a solar engine. On the right, states of working fluid throughout the cycle and temperatures and pressures for a specific example (ammonia)

The participants in the three-year OSMOSOL Project, which began in December 2005, are: University of La Laguna (Coordinator), CIEMAT and the University Rovira i Virgili. The specific objectives of this project are:

- Selection and modeling of a thermodynamic cycle to feed the reverse osmosis unit (selecting the best thermodynamic boundary conditions).
- Optimize the solar desalination system to desalinate both brine and sea water.
- Select the various subsystems that make up the desalination system.
- Develop and test a stationary solar collector optimized for this application.
- Complete preliminary design of the technology developed for a 100-1000 m³/day system with gas backup
- Complete thermodynamic, technical, economic and environmental evaluation of the solar osmosis system proposed.
- Comparison of the technology developed to other solar and conventional desalination technologies.
- Analysis of exploitation of results.

CHARACTERIZATION OF SOLAR RADIATION

Durante el año 2005, las actividades relacionadas con el estudio y la caracterización de la Radiación Solar se han centrado en la participación en Proyectos relacionados con la:

- Medida de la radiación solar.
- Estudio de la distribución espectral de la radiación solar.
- Tratamiento de imágenes de satélite para cálculo de la radiación solar.

A continuación se describen en detalle las actuaciones más relevantes referentes a estas líneas de actividad.

ACCESS TO CIEMAT RADIOMETRIC INFORMATION

This project, financed by the ERDF, Spanish National RD&I Plan and internal funding, responds to the desire for on-line access to quality solar radiation data, basically for its use as energy in the context of CIEMAT activities in general and the PSA in particular. The project began in 2001 and will continue until 2010, depending on the availability of funding for its maintenance.

From 2001 to 2004, it mainly concentrated on perfecting the information to be distributed, basically data from a **new PSA radiometric station** (high quality dating conforming to BSRN standards) and solar radiation data from **satellite image treatment.**

In 2004, a new **radiometric station** was also installed at the **CEDER** (Soria), to improve satellite image treatment models and the quality of solar radiation databases in Spain.

Figure 92. Information available on the web

With all of the above, the Solar Radiation Group at the PSA has information from the following three sources available to it:

1) **PSA BSRN Radiometric Station:**

From 2001 to 2003:

- The best site and locations of structural components were chosen

- Instrumentation was chosen.
- The data acquisition system was configured

In 2004, the main action was related to designing the database and implementing the tools, and finally, in 2005, perfecting use of tools and filters.

2) **Radiometric Station at the CEDER (Soria).**

In 2005, information from this station was included in the data generated by the Solar Radiation Group. Although it is not as completely instrumented, it is completely autonomous, because it is configured with very robust commercial components. The information from this station is filtered weekly with external tools and uploaded to the main server.

3) **Satellite Imaging.**

This activity has been carried out in the context of the Spanish National Plan for RD&I Projects since 1999. Up to 2004 it concentrated on:

- Developing the methodology
- Acquiring and perfecting the satellite databases
- Acquiring and perfecting the terrestrial databases
- Developing the imaging models
- Applying the models developed to all of the images
- Generating the results

In 2005, the information was adapted for consultation over the web. The main problem consisted of providing the information from the Meteosat satellite images with a characteristic projection making them usable with certain geographic coordinates.

At the present time, the application has 66 users:

- 4 administrators (2 at the PSA and 2 in Madrid). With complete data acquisition system and database access, modification and usage control privileges. This includes access to data recorded every second.
- 25 PSA/CIEMAT users with access to average minute data (mean, minimum, maximum and standard deviation) of variables recorded at the measurement stations.
- 37 outside users with access to hourly and daily data from measurement stations.

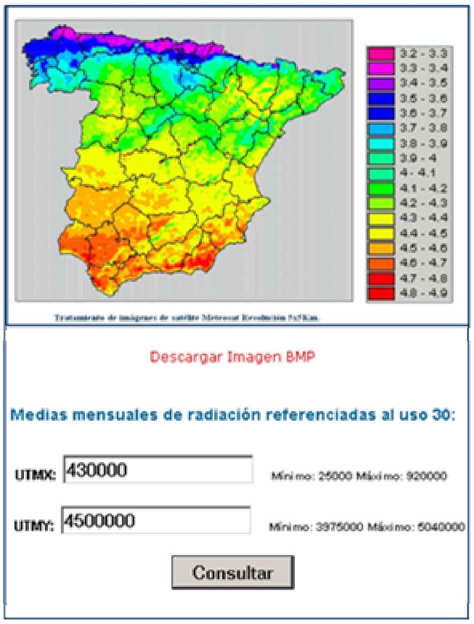


Figure 93. **Access to solar radiation calculated from satellite images**

Mes	Valor Radiación
Enero	2.26
Febrero	3.09
Marzo	4.44
Abril	5.35
Mayo	5.94
Junio	6.80
Julio	6.83
Agosto	6.17
Septiembre	4.73
Octubre	3.62
Noviembre	2.52
Diciembre	1.85

Almería, 12 de Mayo de 2006
Plataforma Solar de Almería
Ciemat

Figure 94. **Presentation of monthly average daily global radiation on horizontal surface (in kWh/m²/day) at a specific site.**

MEDERAS PROJECT

The complete name of this project, which receives funding from the Spanish National RD&I Plan, is "Measurement of the Spectral Distribution of Solar Radiation and Characterization of its Influence on Photovoltaic Generation by Different Technologies[2]". In the context of this project, launched in the second semester of 2005, the following main goals were pursued:

- Development of automatic spectral measurement filtration and classification methodologies

Starting with the operation of the PSA spectroradiometer, there is now an extensive solar spectral radiation database. 2 of these spectra are recorded automatically for each of the solar radiation components every hour from sunrise to sunset. In contrast, the majority of spectral information is recorded only in specific campaigns where the volume of information is much smaller, and cannot be filtered or visually checked. In this case, the need for filtering is must be met automatically, and there are no tools developed for it.

- Validation of global, diffuse and direct normal spectral solar radiation models

There are several spectral models available, but they were developed with certain starting hypotheses. In the context of this project, these models were validated in the atmospheric conditions recorded during the measurement campaign.

- Characterization of local atmospheric parameters from spectral distribution of solar radiation in the desert of southeastern Spain.

Spectral information is an important source of information for characterizing local atmospheric parameters. These parameters, which in turn determine the solar radiation that reaches the Earth's surface at a specific site, are insufficiently developed in desert atmospheres like the one at the PSA.

- Characterization and analysis of the influence of the spectral distribution of solar radiation on different technologies.

Another of the outstanding goals of this project concentrates on the influence of the distribution on solar energy applications. To date, the influence best characterized is the effect of the spectral distribution on photovoltaic generation. In the context of this project,

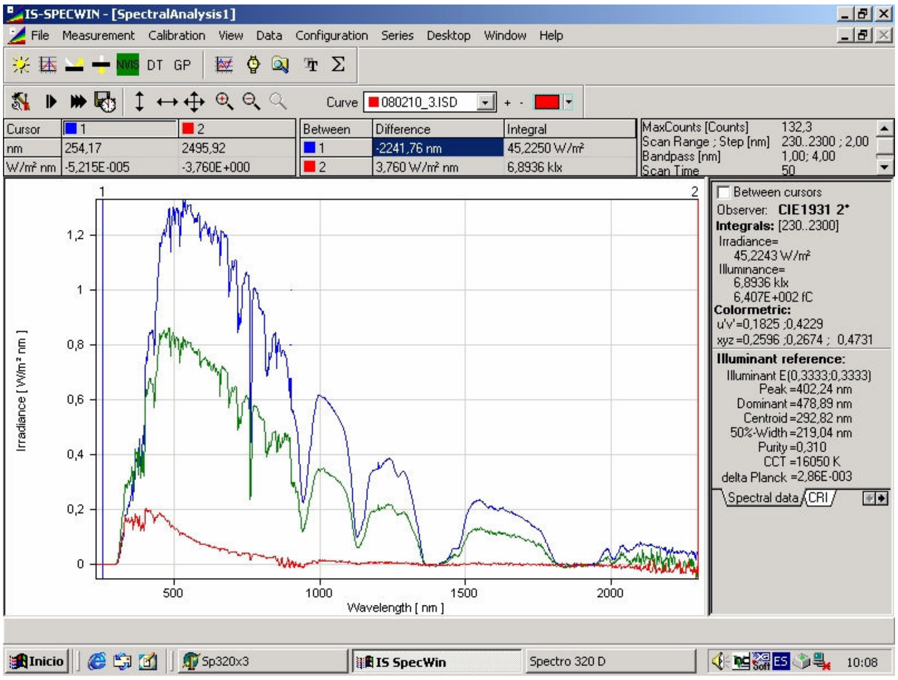


Figure 95. **Spectral measurements recorded at the PSA.**

[2] "Medida de la Distribución Espectral de la Radiación Solar y Caracterización de su Influencia en la Generación Fotovoltaica por Distintas Tecnologías"

photovoltaic panels with different technologies were installed along with solar spectral radiation measurement devices in order to quantify the relationship in each case.

This project has been invited to present an extension, enlarging the study of the effect of spectral distribution on other technologies using solar radiation.

PROJECTS IN COLLABORATION WITH COMPANIES BUILDING SOLAR POWER PLANTS

In 2005, as a result of the socio-political situation in the Spanish power market, the number of solar power plant projects has begun to grow considerably in Spain. To the extent that increased activity in this sector requires better knowledge of solar radiation as an energy resource, it is beginning to have an interest as relevant to cost-benefits studies as any other business activity.

During the year, numerous contacts were made with companies that have finally materialized in technical assistance and three Collaboration Agreements. Due to the confidential character of these relations, below only the content of the agreements are described with a symbolic name.

COLLABORATION AGREEMENT A

This agreement with a Solar Power Tower Plant (in the framework of a European Project) is for the Solar Radiation Group to perform the following tasks:

1) Selection of the plant site and the measurement station
2) Configuration of the measurement station and assistance in its installation
3) Filtering and analysis of data recorded
4) Long-term extrapolation of measurements using satellite estimations
5) Generation of representative series for energy applications studies

In 2005, work on Tasks no. 1, 2 and 3 were completed, and satellite imaging and generation of the model for the fourth task have begun.

COLLABORATION AGREEMENT B

In this case, collaboration is with a builder of Photovoltaic Farms. The purpose is mainly supply and treatment (by CIEMAT) of all information available on the solar radiation potential at specific sites in which this company is interested in building a particular project. In addition to treatment of the measurements available, the results from satellite imaging will be used and adapted to the study site. This collaboration includes supply by CIEMAT to both investors and financial entities of any scientific and technical documentation required for finding the solar radiation potential.

COLLABORATION AGREEMENT C

This agreement with a company promoting both types of facilities mentioned in Agreements A and B, includes all of the tasks mentioned above. Assistance will therefore be given in the configuration and installation of the measurement station, and a study of the incident solar radiation on the collector surface plane for the technology being used at each particular plant (direct radiation, global radiation on inclined surfaces, and global radiation with tracking). The methodologies used are different in each case, adapted to the particular needs of each initiative.

These collaboration agreements require the complete dedication of technicians for each one of them, so they can be kept confidential and there is a constant response capability. In 2005, the maximum dedication possible in this matter was reached, and this situation is expected to continue through 2006 based on the contractual relationships acquired.

PSA Infrastructure and Meteorological Station

The Plataforma Solar de Almería (PSA) radiometric and meteorological station is located at Latitude 37º5'N Longitude 2º21'W and at an altitude of 497 m above sea level. The PSA is between the Sierra de Filabres Mountains to the North, the Sierra de Gádor Mountains to the Southwest and the Sierra de Alhamilla to the South, with maximum elevations over the horizon of 5.2º, 2º and 4.2º respectively, in a semiarid climate.

The sensor signals are recorded every second and, from that data sample, the hourly averages are obtained. Wind speed and direction measurements are found after conversion to their Cartesian coordinates.

This meteorological report was prepared with data collected during 2005 at this radiometric and meteorological station. In all the graphics show GMT time. The average data corresponding to the months of January and July are shown because they are the most representative months in winter and summer, respectively.

SOLAR RADIATION

Figure 96and Figure 97 show the monthly average hourly direct and global irradiation, where it may be observed that the highest average direct irradiation is at midday en the month of January and in the summer months of June and July. Values are high, although not as high as these, at midday in April. The maximum direct irradiance was recorded in 2005 **1113 W/m²** on February 14th at 1 p.m. (GMT). The annual daily average direct irradiation was **5717 Wh/m²day**, with **6860 Wh/m²day** in January, and **8400 Wh/m²day** in July.

Figure 97 shows the highest average global irradiation at midday in the summer months of June and July. Values are also high at midday in the month of April. This high global and direct radiation in April is attributable to a very transparent atmosphere at that time of year. The maximum global irradiance recorded in 2005 was **1268 W/m²**, on May 22nd at solar noon. The annual average daily global irradiation was **5145 Wh/m²day** with **3350 Wh/m²day** in January and **8020 Wh/m²day** in July.

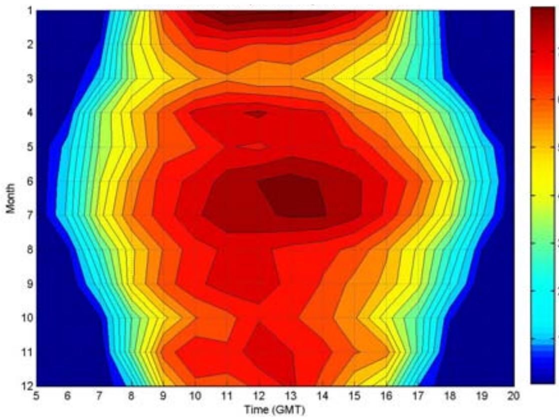


Figure 96. Profile of monthly average hourly direct radiation (Wh/m²) in 2005

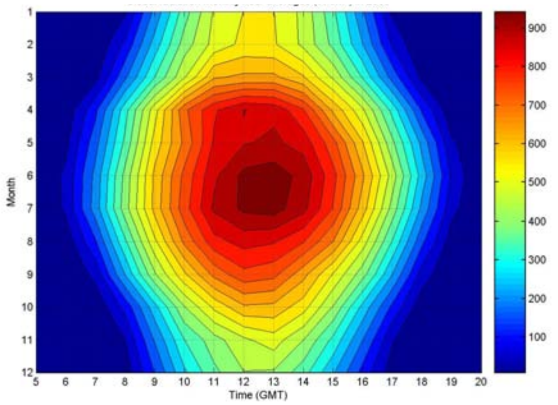


Figure 97. Profile of monthly average hourly global radiation

TEMPERATURE

Figure 98 and Figure 99 show the monthly average, maximum and minimum temperatures and profile of monthly average of hourly temperatures, respectively. Maximum temperatures recorded were **42.0ºC** on the 2-m-high sensor and **41.1ºC** on the 10- m-high sensor, both on July 17th after solar noon. The minimums are **-5.7ºC** and **-4.2ºC** at 7 a.m. (GMT)

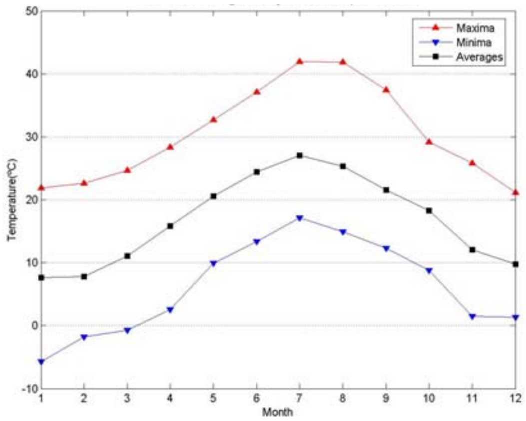


Figure 98. **Plot of monthly maximum, average and minimum temperatures.**

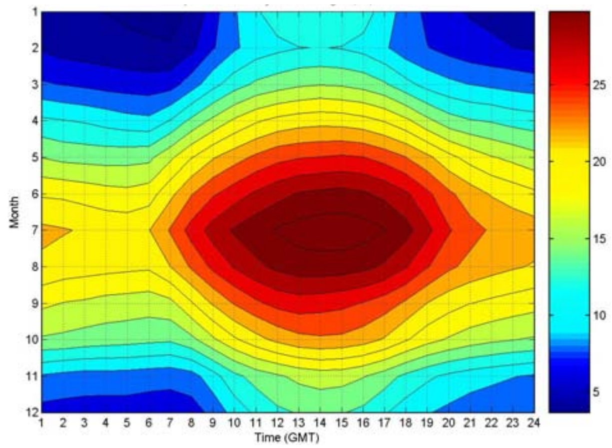


Figure 99. **Profile of monthly averages of hourly temperatures.**

on January 27th. In January, the monthly average at 2 m was **8ºC** and at 10 m was **9ºC**. In July, the monthly average was **27ºC** at both heights. The annual average is **17ºC**.

The figure shows the inertia of high temperatures that are prolonged during the summer afternoons, especially in the month of July. The temperatures at solar noon are also very stable during the months in January and February.

RELATIVE HUMIDITY

Figure 100 and Figure 101 show the monthly average, maximum and minimum and profile of monthly average of hourly humidity, respectively, at 2 m. The maximums recorded were **93.6%** on the 2-m-high sensor at 9 a.m. on March 20, 2005 and **95.1%,** recorded at the same time on the 10-m sensor. The minimums of **6.0%** and **5.1%** were both recorded at 3 p.m. (GMT) on June 30th. In January, the monthly average at 2 was **56%** and at 10 m, **55%**. In July, the monthly average at 2 m was 40% and at 10 m 42%. The annual average is 53% at both heights. Figure 6 shows the lowest humidity concentrated at midday in the months of May, June and July. The highest humidity was recorded at night in the transition seasons, spring and autumn.

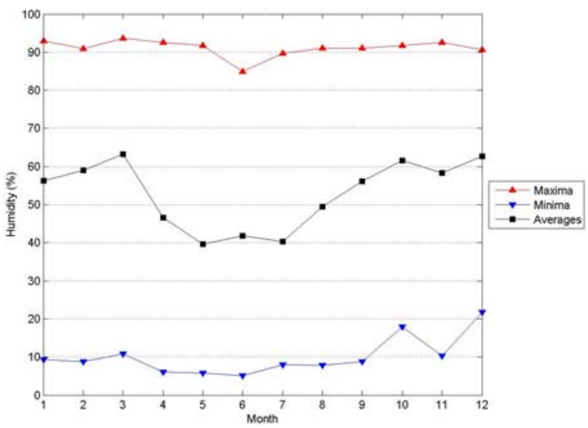


Figure 100. **Plot of monthly maximum, average and minimum humidity.**

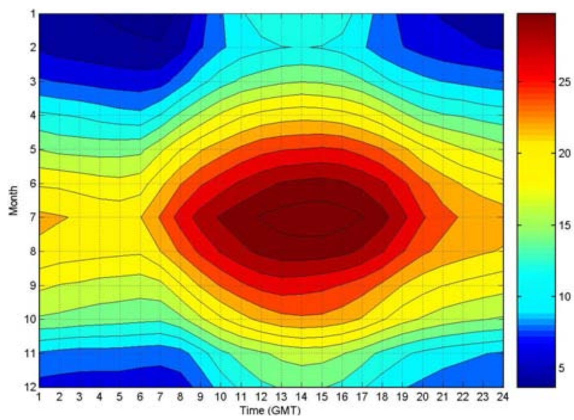


Figure 101. **Profile of monthly averages of hourly humidity**

WIND

Figure 102 shows the monthly minimum, average and maximum wind speeds recorded at 2 m and 10 . The strongest gust of wind, recorded on the anemometer at 2 m on the morning of November 26th, was **17.1 m/s** (61.6 km/h). The strongest gust at 10 meters was **19.9 m/s** (71.6 km/h), recorded on the morning of February 15th.

Figure 103 shows the profile of the monthly average hourly wind speed at 2 m. It may be seen in this figure how the nights are usually very calm and the wind picks up from midday onward.

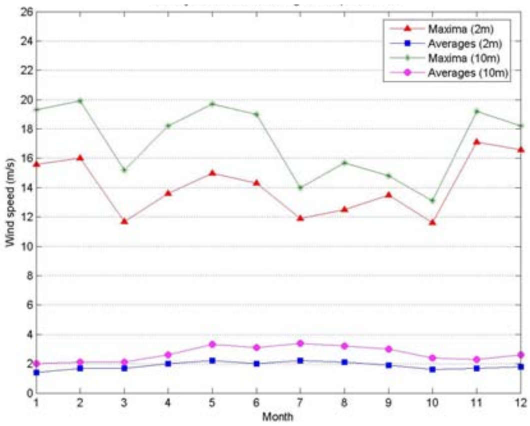


Figure 102. Plot of monthly maximum, average and minimum wind speed at 2 m and 10 m.

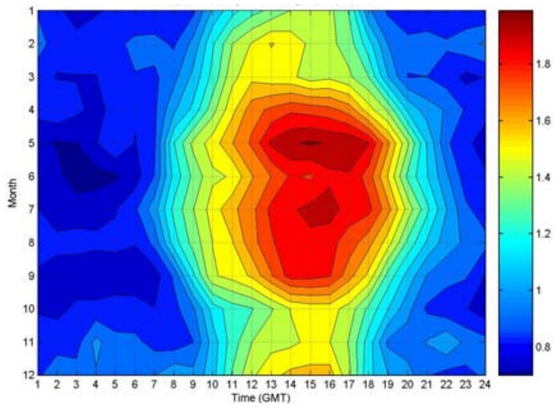


Figure 103. Perfil de medias horarias mensuales de velocidad del viento a 2m.

Figure 104 is a plot of the percentages of wind direction frequency. In 2005, the predominant winds were from the east with 29%. After the east, wind is most commonly from the southeast, southwest and northeast, in this order. The predominance of these directions is attributed to the location of the surrounding mountains.

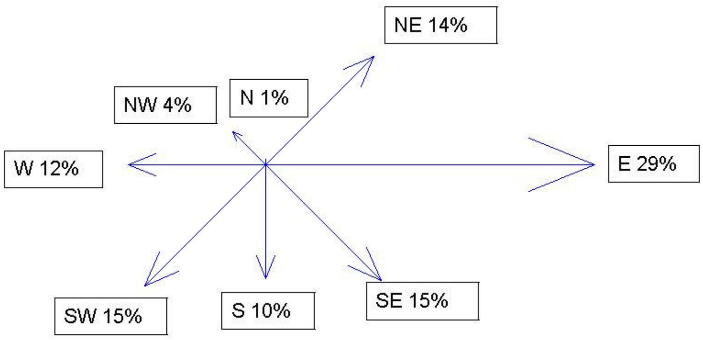


Figure 104. Porcentajes de ocurrencias de la dirección de procedencia del viento en el 2005.

PRECIPITATION

In 2005, a total of **127 l/m²** were collected on 32 rainy days. No precipitation was recorded in the month of July and practically none in August. The months when it rained the most were March and November, in the transition seasons, spring and autumn. The most rainfall was recorded on September 7th, with **12.3 l/m². Figure 105** is a bar diagram of the rainfall collected each month, the maximum collected on one day in each month and the number of days of rain each month.

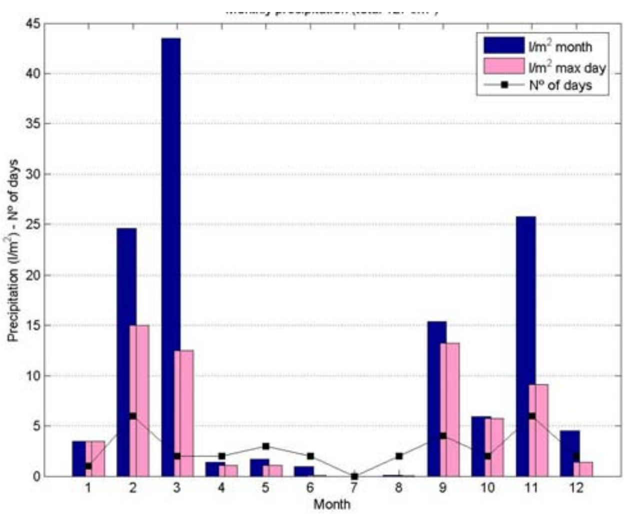


Figure 105. Plot of monthly rainfall, maximum collected in one day and number of rainy days per month.

Events

On June 10th we received a visit from Mr. Hinrichs-Rawles, Director of the 'Central Department' of the German Ministry of the Environment and Nuclear Safety (BMU). This department is in charge of BMU activities related to renewable energies and climate protection. The reason for the visit was to acquire first-hand information on joint DLR and CIEMAT research activities at the PSA.

Figure 106. Mr. Hinrichs-Rawles expressed BMU interest in our activities

On July 9th, we were awarded the *Fundación Terra* 'Sun and Peace 2005' prize for "Collective Work". The prize was awarded at the "Encuentro Solar 2005" meeting which took place in the Parque de las Ciencias in Granada, and was attended by the Counselor for Education of the Andalusian Government, Ms. Cándida Martínez López.

Figure 107. Photo of the Counselor with all the prize winners

On July 13th, we received a visit from the Minister of the Environment, Ms. Cristina Narbona Ruiz and the then Secretary of the State for Universities and Research, Mr. Salvador Ordónez Delgado.

Both celebrities were received by the Director General of the CIEMAT, Dr. Juan Antonio Rubio Rodriguez and by the Director of the Department of Energy, of which the PSA is a dependency, Mr. Cayetano López Martínez.

They were shown all the PSA test facilities, with special attention to those related to solar water treatment.

Figure 108. The Director General of CIEMAT welcoming the Minister

Figure 109. Visiting the desalination project facilities

This year another step in strengthening collaboration with the University of Almería was taken with the inauguration of the CIESOL Building on the La Cañada Campus.

Mr. Cayetano López, Director of the CIEMAT Department of Energy and Mr. Alfredo Martínez Almécija, Rector of the UAL, presided at the inauguration ceremony of the building housing the mixed CIEMAT-UAL center. This building will be devoted to laboratories, meeting rooms and classrooms for courses given by both institutions.

Figure 110. The official inauguration

Figure 111. From left to right: Amadeo Rodríguez (UAL-CIESOL Director), Alfredo Martínez (Rector of the UAL), Cayetano López (Director of the CIEMAT Department of Energy) and Sixto Malato (Asst. Director CIEMAT- CIESOL)

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List of Acronyms

AOP	advanced oxidation process
ASP	active server page
BMU	German Ministry of the Environment
BOD	Biological Oxygen Demand
BOE	Boletín Oficial del Estado (Official State Bulletin) (E)
BOP	balance of plant
BSRN	Baseline Surface Radiation Network
CASA	Construcciones Aeronáuticas S.A.
CCD	charge-coupled device
CEA	Commissariat for Atomic Energy (F)
CESA-1	Central Eléctrico Solar Almería-1
CHA	Spanish-German Cooperation Agreement
CICYT	Comisión Interministerial de Ciencia y Tecnología (E)
CIEMAT	Centro de Investigaciones Energéticas Medio Ambientales y Tecnológicas (E)
CNRS	Centre National de la Recherche Scientifique (F)
COD	chemical oxygen demand
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)
DSG	direct steam generation
EC	European Commission
EPFL	Ecole Polytec. Federale de Lausanne (CH)

ERDF	European Regional Development Fund
ETH	Swiss Federal Institute of Technology Zurich (CH)
EU	European Union
FID	Flame ionization detector
HCSTE	High-Concentration Solar Thermal Energy Group (PSA)
HDPE	High-density polyethylene
HTF	heat transfer fluid
ICP-CSIC	Instituto de Catálisis y Petroleoquímica – Consejo Superior de Investigaciones Científicos (E)
IEA	International Energy Agency
IMP	isolated measurement pod
INETI	Instituto Nacional de Engenharia e Tecnologia Industrial (P)
IPHE	International Partnership on Hydrogen Economy
IR	infrared
ITC	Institute of Ceramics Technology, Castellón (E)
LECE	Laboratorio de Ensayo Energético de Componentes de la Edificación
LFC	linear Fresnel collector
MBB	Messerschmitt Bolkow-Blohm
MED	multi-effect desalination
MTEOS	methyltriethoxysilane
MHD	Magnetohydrodynamic
MIMs	monolithic integrated modules
MPC	model predictive control
NPSH	net positive suction head
NTUA	National Technical University Athens (GR)
OPC	OLE for process control
ORP	oxidation/reduction potential
PAR	photosynthetically active radiation
PDVSA	Petróleos de Venezuela, S.A.
PROHERMES II	Programmable Heliostat and Receiver Measuring System II
PSA	Plataforma Solar de Almería
PSI	Paul Scherrer Institut
PTC	parabolic-trough collectors
PROFIT	National Scientific Research, Development and Technological Innovation Plan
SCSU	Solar Concentrating System Unit (PSA)
SEGS	Solar Electric Generation Systems
SBP	Schlaich Bergermann und Partner
SENER	SENER Ingeniería y Sistemas S.A.
SHIP	Solar Heat for Industrial Processes (IEA)
SODIS	solar disinfection

SolLAB	Associated European Solar Energy Laboratory
SPB	Schlaich Bergermann und Partner
SSPS	Small Solar Power Systems project (IEA)
STP	solar thermal power
TDC	temperature dependence curves
TOC	total organic carbon
TSA	Phoebus Technology Program Solar Air Receiver
UAL	University of Almería
UNED	National University for Education by Correspondence (E)
UVA	ultraviolet-A radiation
UVB	ultraviolet-B radiation
VOC	volatile organic compound
WFD	Water Framework Directive 2000/60/EC
WIS	Weizman Institute for Science (IL)
WMO	World Meteorological Organization
WTP	Water treatment plant
ZSW	Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (D)

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