Plataforma Solar de Almería

Annual Report 2006

MINISTERIO DE EDUCACIÓN Y CIENCIA

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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A message from the Director

Diego Martínez Plaza

2006 was marked by a very special event for all of us, the celebration of the 25th anniversary of the Plataforma Solar de Almería.

For this reason, the year was full of illustrious visits. Special mention should be made of the visits this year by both of the Ministers of Education and Science who held the office, María Jesús Sansegundo and Mercedes Cabrera. The Minister of Industry, Commerce and Tourism, Joan Clos, also visited us accompanied by the Counselor for Innovation, Science and Enterprise of the Andalusian Government, Francisco Vallejo.

The celebrations reached their high point at a reception held at our facilities on October 28th. Those of our fellow workers who were here at the PSA on September 21, 1981 and who continue to lend their services at our Center were recognized at an endearing ceremony at which the Director General of CIEMAT presented a commemorative award to each of them.

This may be a good time for us to reflect that in view of the present commercial deployment of this technology, with the first solar thermal power plants on the verge of taking off, we have been given the best anniversary present we could wish for.

Furthermore, our Center is growing, as if in these twenty-five years it had reached adulthood. The PSA is consolidating nationally and even worldwide, as the center of reference for the study of solar concentrating technology. We are growing in both quantity and quality of human resources, and also in material resources to carry out our task.

Of course, the decisive support of our superiors at the CIEMAT-Moncloa is clearly a catalyst for this growth.

The interest of industry in the applications we are developing at our Center is stronger all the time. We receive a large number of visits from businesses who want to know more about the technology and important collaboration agreements have been signed with industry.

To finish rounding off the year, the PSA was one of the organizers of the ‘13th SolarPACES Symposium’ along with the University of Seville School of Engineering and the Spanish Association of businesses in the solar thermal electric sector ‘PROTERMOSOLAR’. The symposium, held at the School of Engineering, was the most successful of all the SolarPACES Symposiums thus far. Again, the boom this technology is experiencing, reinforced by the focus on industry by the organizers, contributed to this success.

Similarly, and as has come to be our custom, we had a stand at the third ‘Renewable Energies and Water Technologies Fair’ in Almería.

Our research activities have been successful in all of the following ways during the year:

First of all, the PSA is now fully integrated in the national program called ‘Access and Improvement of Unique Scientific Installations’, having signed two consecutive contracts, one in 2005 and another in 2006, and has already acquired commitments up to 2008 to provide access to our facilities to the Spanish scientific community.

Noteworthy successes also in the **Environmental Applications of Solar Energy and Characterization of Solar Radiation (AMES)**, with special reference to the award of a National R&D Plan CONSOLIDER project. This project, called ‘TRAGUA’ was the only one on water treatment awarded. In addition to this, up to six new international projects were approved for cofinancing by the European Commission.

The **Solar Concentrating Systems Unit (SSC)** continues to work on direct steam generation technology (DSG) by two parallel processes. The first of them, from the point of view of research, has to do with clearing up the last technological unknown in the DSG process, thermal storage. To do this, the PSA is participating in the European DISTOR project. The second process has more to do with technological development and demonstration, and consists of promotion of an industrial consortium that will build and operate a commercial 3 MW_e DSG solar plant on the PSA grounds.

The SSC Unit’s activity in central receiver technology focused on technological collaboration with the companies promoting the PS10 and SOLAR TRES commercial tower plants.

Institutional cooperation has also been reinforced this year. In the first place, it should be mentioned that the Spanish-German Agreement with the German Aerospace Agency (DLR), in force since the inauguration of the PSA, has been renewed for another three years.

Furthermore, intense collaboration with the University of Almería (UAL) continues to focus on the CIEMAT-UAL mixed center for joint research in solar energy applications (CIESOL). CIESOL is physically represented in a laboratory building located on the UAL campus that was inaugurated in 2005. Apart from the projects that are being developed by groups from both institutions, this year, special mention should be made of the start of the first CIESOL ‘Master’s Degree in Solar Energy’ program.

Educational and dissemination activities continue strong, because we are aware that we must not ignore our facet of informing society about the existence of this renewable energy option. Educational agreements are maintained with several different universities and research centers throughout the world.

I do not want to end this introduction without extending my appreciation to the entire PSA staff for their fine work and professionalism.

Diego Martínez Plaza
Director de la Plataforma Solar de Almería

1 General Presentation

1.1 The PSA as a large solar installation: general information

The Plataforma Solar de Almería (PSA), a dependency of the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), is the largest concentrating solar technology research, development and test center in Europe. PSA activities are integrated in the CIEMAT organization as an R&D division of the Department of Energy.

The following goals inspire its research activities:

- Contribute to establishing a sustainable clean world energy supply.
- Contribute to the conservation of European energy resources and protection of its climate and environment.
- Promote the market introduction of solar thermal technologies and those derived from solar chemical processes.

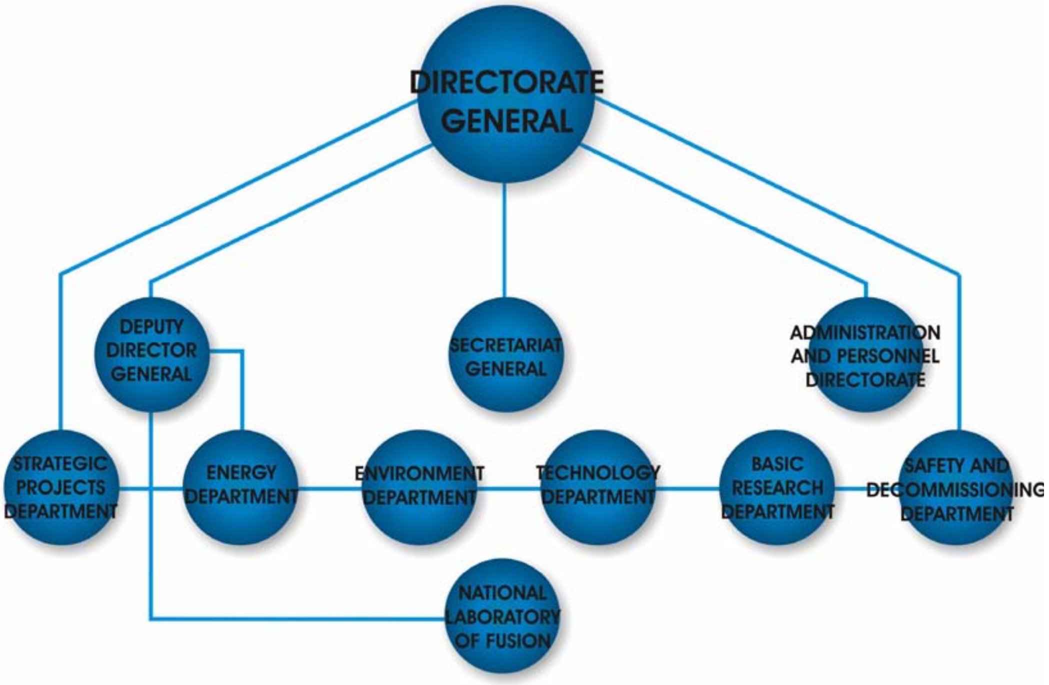

Figure 1.1 Integration of the PSA in the CIEMAT organization

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

Figure 1.2 Aerial view of the Plataforma Solar de Almería

1.2 Functional Structure

In 2006, research activity at the Plataforma Solar de Almería was structured around two R&D Units:

- Solar Concentrating Systems Unit
- Environmental Applications of Solar Energy and Characterization of the Solar Resource Unit

The first is devoted to developing new and better ways to produce solar thermal electricity and the second to exploring the chemical possibilities of solar energy, especially its potential for water detoxification, desalination and disinfection.

Supporting the R&D Units mentioned above, the management and technical services are grouped together in the PSA Management Unit.

These units are largely self-sufficient in the execution of their budget, planning, scientific goals and technical resource management. Nevertheless, the two R&D units share many PSA resources, services and infrastructures, so they stay in fluid communication with the Management Unit, which coordinates technical and administrative support services. For its part, the Office of the Director must make sure that the supporting capacities, infrastructures and human resources are efficiently distributed. It is also the Office of the Director that channels demands to the various general support units located at the CIEMAT’s main offices in Madrid.

1.3 Human and Economic Resources

The scientific and technical commitments of the PSA and the workload this involves are undertaken by a team of 112 persons that as of December 2006 made up the permanent staff lending its services to the Plataforma Solar. In addition to this staff, there is a significant flow of personnel in the form of visiting researchers, fellowships and grants handled by the Office of the Director.

Of the 112 persons who work daily for the PSA, 55 are CIEMAT personnel, 21 of whom are located in the main offices in Madrid.

In addition, the 12 persons who make up the DLR permanent delegation as a consequence of its current commitments to the Spanish-German Agreement also make an important contribution.

The rest of the personnel are made up of a no less important group given the center's characteristics. These are the personnel working for service contractors in operation, maintenance and cleaning in the various different facilities. Of these 32 persons, 14 work in operation and 18 in maintenance.

The auxiliary services contract accounts for 8 administrative personnel and secretaries, 2 IT technicians and 5 security guards.

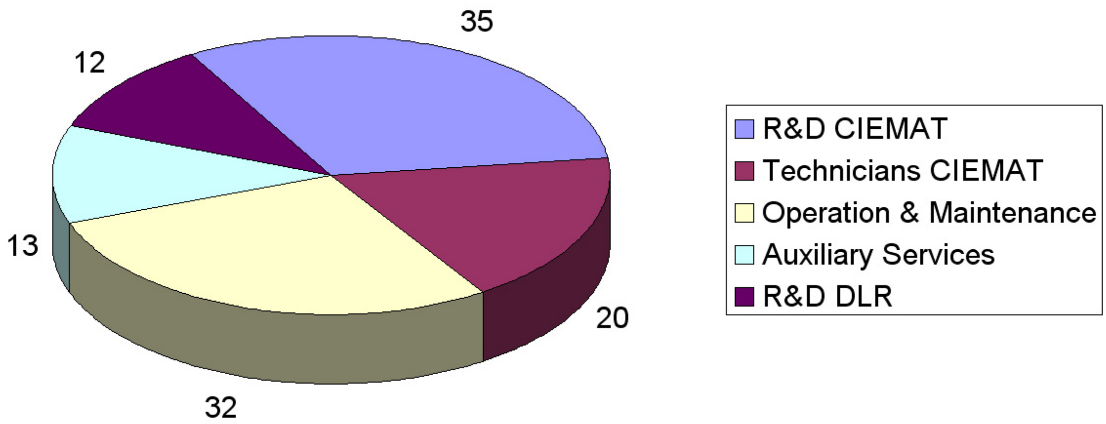

Figure 1.3 Distribution of PSA permanent personnel as of December 2006

The effort CIEMAT has made for the last several years to provide the PSA with the necessary human resources should be emphasized. This continued effort is allowing us to undertake our task with greater assurance of success.

The PSA budget has an upward trend, in large part due to higher revenues. Income from the European Commission has been an outstanding contribution of our longstanding partner DLR. A good number of the new joint projects proposed to the EC have allowed the DLR to continue at the PSA in a new relationship based on specific projects, and the fruit of this success is the relevance of the German delegation at the PSA.

The significantly increased number of projects financed by the National Plan for R&D reflects a growing decision for renewable energies and in particular, for solar concentrating technologies.

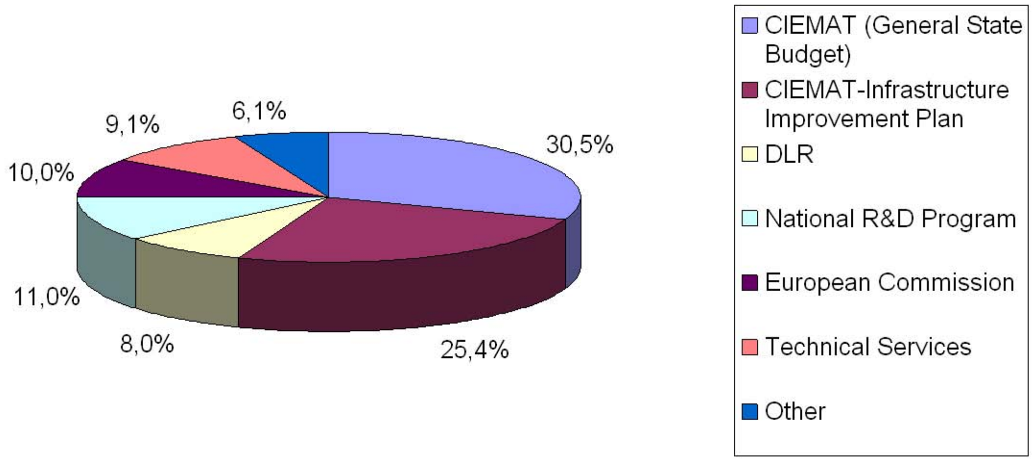

Figure 1.4 Distribution of PSA Income in 2006

The PSA budget in 2006 reached 8.54 million Euros (not including R&D personnel). The CIEMAT contribution was increased in order to undertake the activities approved for this year in the Plan for PSA Infrastructure Improvement. This plan is devoted to major improvements necessary in the main infrastructure, building, heliostat fields, etc.

1.4 Scope of collaboration

As mentioned above, the PSA since 1987 has been the subject of a Spanish-German Cooperation Agreement between the CIEMAT and the DLR (German Aerospace Research Center), commonly known as the CHA. At the present time, scientific relations and cooperation commitments are governed by Annex V of this Agreement, which includes the commitment to maintain a permanent DLR delegation at the PSA from 2006 and 2008. The new Annex V was signed on June 13th at the DLR main offices in Cologne (Germany).

In all, the scope of collaboration in which the PSA moves is remarkably wide. In the international sphere, the PSA actively participates in Tasks I, II and III of the International Energy Agency 'SolarPACES' Program, where information is exchanged and costs are shared with similar centers in the other member countries (USA, Mexico, Italy, Germany, France, Switzerland, European Commission, South Africa, Israel, Algeria and Egypt).

Moreover, the PSA-CIEMAT is a member of the 'Alliance of European Laboratories on Solar Thermal Concentrating Systems' (SolLAB). This virtual laboratory is made up of the main European concentrating solar energy research institutes, that is, PROMES-CNRS in Odeillo (France), the DLR Solar Energy Division in Cologne (Germany), the Renewable Energies Laboratory of the Federal Institute of Technology in Zurich (Switzerland), the Renewable Energies Laboratory of the Federal Institute of Technology in Zurich (Switzerland) and the CIEMAT itself. The agreement was signed in October 2004 and the coordinated tasks have begun to give fruit, especially in the fields of flux and temperature measurement and Ph.D. student education. The 'Paul Scherrer

Figure 1.5 Participants in the 'SolLAB' Executive Committee Meeting on October 15th in Monte Veritá

Institute" in Switzerland formalized its adhesion to 'SolLAB' as a new member in 2006.

The intensity of 'SolLAB' activity increases every year, having already created several working groups with concrete lines of collaboration, which performed the following activities in 2006, in chronological order:

- Creation of the working group on 'Receivers for high temperature processes'. The first meeting was held on January 24th at the PSA.
- Meeting of the working group on flux and temperature measurement, coinciding with the SolarPACES Symposium in June at the Seville School of Engineering.
- General meeting with representatives of the European Commission. Brussels, August 8th.
- Creation of the working group on materials testing and qualification for high temperature solar processes. First meeting at PROMES-CNRS, Odeillo (France) on September 4th.
- Publication of descriptive 'SolLAB brochure in October.
- Meeting of the executive committee on October 15th in Monte Veritó (Switzerland).
- Annual general seminar for Ph.D. students from October 16th to 18th in Monte Veritá (Switzerland).
- Radiometer comparison campaign in the DLR solar furnace in Cologne (Germany) in the months of October and November.

In training activities, there is an agreement with the University of Almería (UAL) for managing joint fellowships and educational agreements for receiving students from universities around the world.

In fact, this long-lasting collaboration with the UAL has recently been enlarged and consolidated with the creation of the 'CIEMAT-UAL Mixed Center for Solar Energy Research' called 'CIESOL'.

Apart from the joint projects carried out in several fields of science, this year, the 1st Master's Degree in Solar Energy' was offered by CIESOL.

This one-year Master's degree will be listed in the University of Almería's catalogue of 'coursework'.

From the moment of its conception, this Master's Degree was intended to make the best use possible of PSA-CIEMAT availability. It was therefore decided that the scope should be 'solar-only', not delving into other sources of renewable energy, although it does touch on all the possible applications of solar energy, from its use in greenhouses to high-temperature applications in solar furnaces, and photovoltaics to hydrogen production.

The 30-student quota was not only completely filled, but had to be selected from among 76 applications received this first year it is offered.

Apart from all these institutional cooperation programs, it should be pointed out that each of the two R&D Units keeps up a stable range of collaboration, including national and international universities, SMEs and large companies.

Among the universities, we could mention the large volume of joint activities with the UAL (CIESOL), Seville, La Laguna and the UNED.

Collaboration is also intense with important Spanish companies such as IBERDROLA, SOLUCAR (ABENGOA Group), GAMESA, SENER and ECOSYSTEM.

Figure 1.6 'Ciesol' Master's Degree announcement poster

In the international sphere, assiduous collaboration with such research centers as the 'Fraunhofer Institute for Solar Energy Systems' and the ZSW in Germany, and the Weizmann Institute of Science' (Israel) should be mentioned. We also collaborate with companies like 'FLABEG Solar', FICHTNER and 'Schlaich, Bergermann und Partner' in Germany and ORMAT (Israel).

New lines of research in 'Solar Fuels and Process Heat' have given rise to new cooperation with the Institute of Ceramic Technology of Castellón, the Venezuelan company 'Petroleos de Venezuela, S.A.', the ENEA in Italy and the CEA in France.

Very recently, ambitious lines of collaboration have been launched with Maghreb countries, specifically, in agreements signed in the frame of agreement with the Moroccan CNRST and the NEAL (New Energy Algeria) in Algeria.

There is also more and more collaboration with local entities, for example DERETIL, CAJAMAR, COEXPHAL and the Comunidad de Regantes Cuatro Vegas.

In Central and South America there is stable collaboration with the Centro de Investigaciones Eléctricas and the Univ. Nacional Autónoma of México and the National Atomic Energy Commission of Argentina.

1.5 Training activities

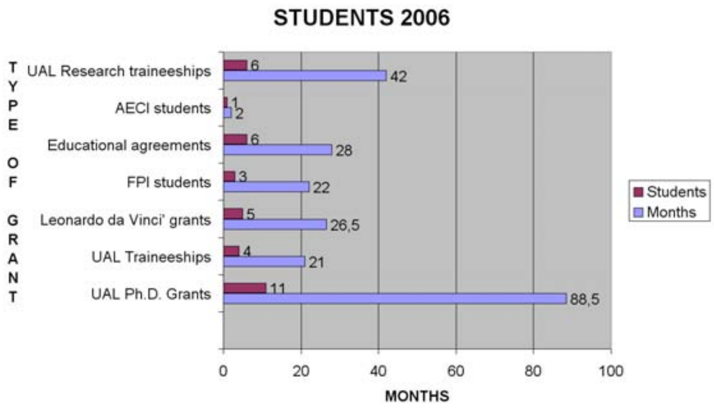

Figure 1.7 Students 2006

The ruling principle of the **Plataforma Solar de Almería training program** is the creation of a generation of young researchers who can contribute to the deployment of solar thermal energy applications. Through this program, about thirty students of different nationalities are admitted each year so that we can transmit the knowledge of solar thermal technology accumulated at the PSA in its twenty-five years of experience to new generations of university graduates.

The main features of this training program are:

- Management of the Ph.D. fellowship program in association with the annual agreement with the University of Almería (UAL)
- Management of traineeship grants associated with an annual agreement with the UAL Mediterranean Foundation.
- European funded 'Leonardo da Vinci' grants, for students from other countries, mainly German.
- Management of miscellaneous specific educational cooperation agreements with other entities for sending students to the PSA.

Founding in 2004 of the virtual European solar laboratory 'SolLAB', has opened new possibilities for scientific development of researchers in training at the PSA. One of the first joint activities initiated by SolLAB was an annual seminar for Ph.D. students from the four different institutions. This year, from October 16-18th, thirty Ph.D. students attended the seminar organized by the

Figure 1.8 Ph.D. students who attended the seminar held in Monte Veritá

Federal Polytechnic Institute of Zurich (ETHZ) at their main campus in Monte Veritá (Switzerland).

A similar internal event took place in the CIEMAT Dept of Energy. It was held from September 25th to 27th and was attended by all of the Department's doctoral students.

1.6 PSA National Access Activities

In 2005, the National Plan for R&D started a new line of activity for promoting Large Scientific Infrastructures (LSI). This line, managed by the General Subdirectorate for Scientific Infrastructures, annually announces the LSI programs, consisting of two clearly differentiated sections, one called 'Aid for Improvement' and the other 'Offers for Access'. The offer for access is designed to optimize the use of national LSIs by paying for access by researchers from other institutions.

This access is given based on annual public announcements that must be issued by the PSA. An 'External Experts Committee' then evaluates the proposals received for their scientific quality and assigns 'user time' to those selected.

The PSA announcements in this national access and improvement program had a very successful response in 2005 and 2006, and it is currently offering access for 2008.

Information on the current offer for access to the PSA may be found on our website at:

http://www.psa.es/webesp/projects/acceso_nacional/index.php

2 Facilities and infrastructure

2.1 General Description of the PSA

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

The PSA is 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, making it a privileged site for evaluation, demonstration and transfer of solar technologies.

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 and direct steam generation for electricity production research
- HTF test loop, a complete oil circuit for evaluation of new parabolic-trough collector components

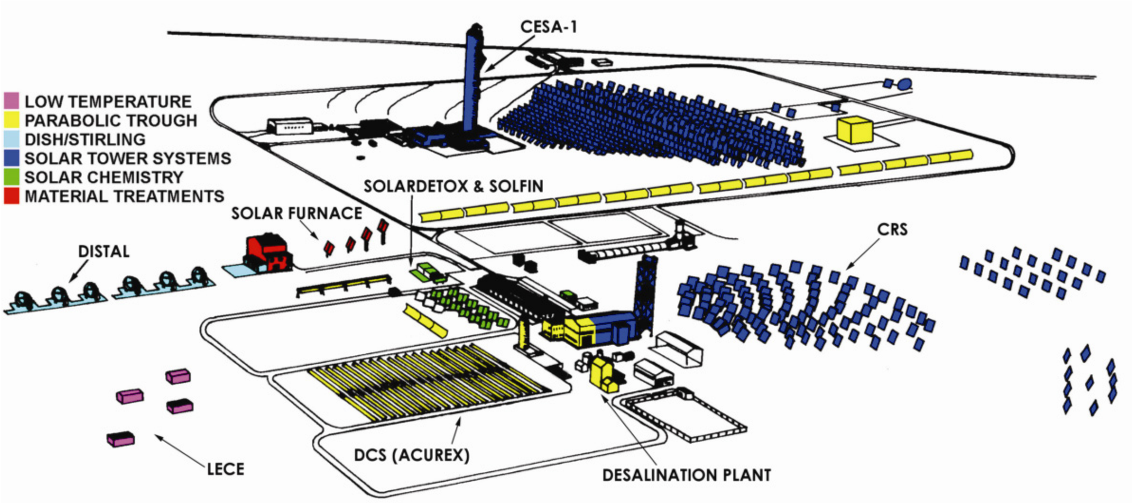

Figure 2.1 Location of the main PSA test facilities

- 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 photo-reactors for different types of trials.
- Laboratory for Energy Testing of Building Components[1] (LECE).
- Meteorological station.

2.2 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-kilowatt range. They are outdoor laboratories specially conditioned for scaling and qualifying systems prior to commercial demonstration.

2.2.1 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 high flux solar radiation 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.

Direct solar radiation is collected by the facility's 330 x 250-m south-facing field of 300 39.6-m^2 heliostats distributed in 16 rows. The heliostats have a

Figure 2.2 The CESA-I facility seen from the East with heliostat rows focusing on the medium-height test level (60 m.)

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

nominal mean 90% reflectivity, the solar tracking error on each axis is 1.2 mrad and the reflected beam image quality is 3 mrad. The CESA-1 facility has the most extensive experience in glass-metal heliostats in the world, with first generation units manufactured by SENER and CASA as well as second generation units with reflective facets by ASINEL and third generation facets and prototypes developed by CIEMAT and SOLUCAR. 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 from it. 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 and 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

2.2.2 The 2.7-MW$_{th}$ 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 are the completely autonomous intelligent heliostat-control units installed in 2003, powered by photovoltaic energy and communicating the entire field by radio by a concept developed and patented by PSA researchers. This first autonomous heliostat field, which does not require the use of channels or cabling, was made possible by financial assistance from the Ministry of Science and Technology's PROFIT program.

The nominal average reflectivity of the field is 87%, the solar tracking error is 1.2 mrad per axis and the optical reflected beam quality is 3 mrad. Under typical conditions of 950 W/m^2, total field capacity is 2.7 MW$_{th}$ and peak flux 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.

Figure 2.3 A CRS field heliostat reflecting the tower

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.

The test bed (Figure 2.4) 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 for indirect 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.

Figure 2.4 Front view of the 200-350-kW volumetric receiver test bed in the CRS tower

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.

2.3 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.

2.3.1 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/400ºC) steam in parabolic-trough collector absorber tubes. The DISS experimental plant is the only facility in the world where two-phase-flow water/steam processes in parabolic-trough collectors can be studied under real solar conditions. It is not only very suitable 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 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, 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.

Figure 2.5 View of the DISS plant solar field in operation

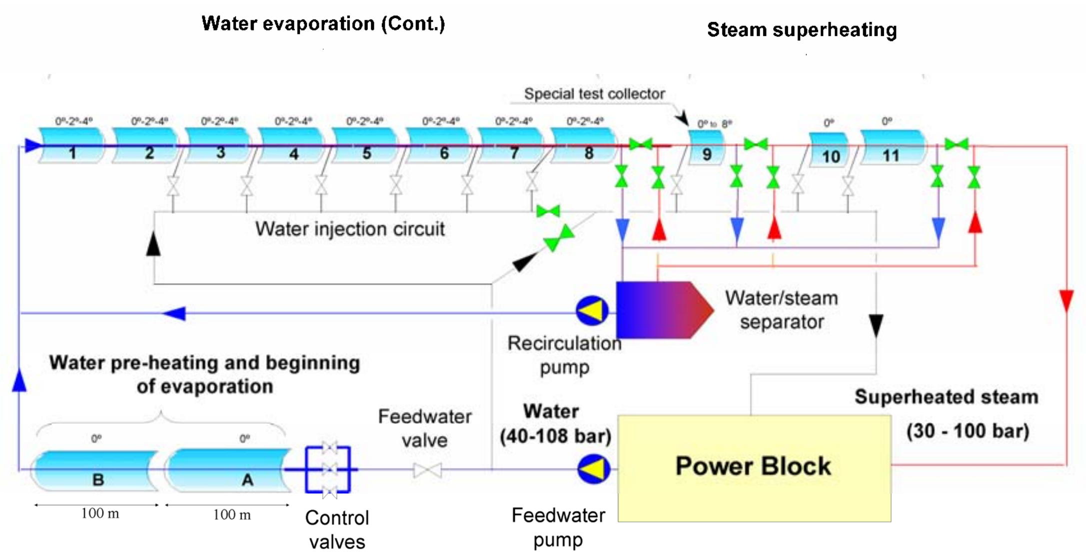

Figure 2.6 Simplified diagram of the PSA DISS plant

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 2.6 shows a simplified diagram of the DISS loop in which the solar field is shown as one row of 13 parabolic-trough collectors on 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.

2.3.2 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 appropriately instrumented for measurement and monitoring.

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 274-m^2 collecting surface. The thermal oil used in this facility (Syltherm 800) has a maximum working temperature of 420ºC, and a freezing point of –40ºC. The east-west rotating axis of the solar collector increases the number of hours per year in which the angle of incidence of the solar radiation is less than 5º. The facility's oil circuit, which has a maximum working pressure of 16 bar, is made up of the following elements:

Figure 2.7 General view of the HTF

- 1-m^3-capacity oil expansion tank, with automatic nitrogen inertization
- 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.

Parallel to the original HTF test loop 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 not only apt for solar thermal power plants, but also for other large applications, such as desalination of seawater or industrial process heat in the 150ºC-425ºC range. At the conclusion of the EUROtrough project, the project partners donated this first prototype to CIEMAT for its operation and maintenance, and it now forms part of the PSA parabolic-trough collector facilities, increasing the system's collecting area has to 685 m^2.

2.4 Dish/Stirling Systems: DISTAL and EUROdish

2.4.1 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 in a high-performance thermodynamic cycle.

An alternator is connected to the Stirling motor so that the light 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.

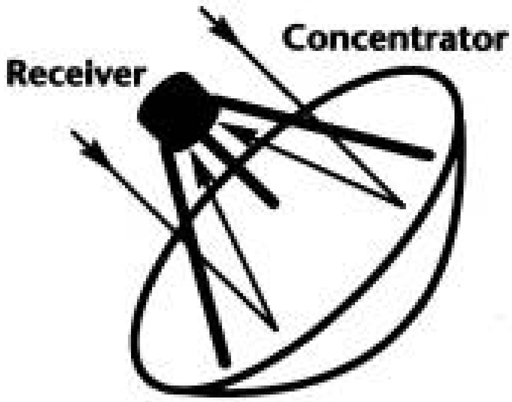

Figure 2.8 Schematic diagram of a parabolic dish with Stirling motor at the focus

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 EURОdish.

2.4.2 DISTAL I

The concentrator prototype made use of 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 EURОdish units.


Figure 2.9 A DISTAL I dish in operation

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.

2.4.3 DISTAL II

The DISTAL II was a first attempt at a system with better features and per-kW_e 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.

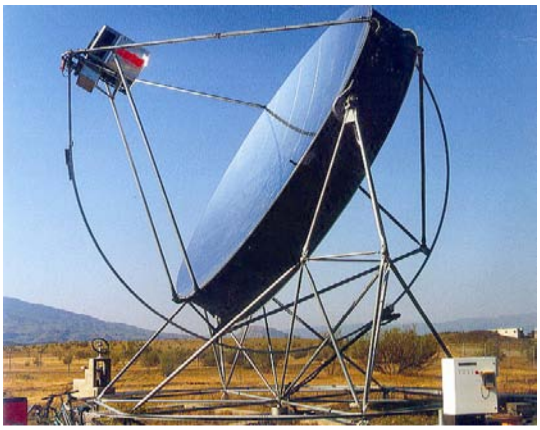
Figure 2.10 DISTAL II unit

2.4.4 EURODISH

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

- 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 2.11 Front and back views of the EUROdishes.

2.5 Solar Furnace

2.5.1 General Description and Principles of Operation

Solar furnaces reach concentrations of over 10,000 suns, the highest energy levels achievable in a solar concentrating system. Their main field of application is materials testing, either in ambient conditions, controlled atmosphere or vacuum, or 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 collector 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.

2.5.2 Heliostats

The reflective surface of the heliostats is made up of 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.

2.5.3 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.

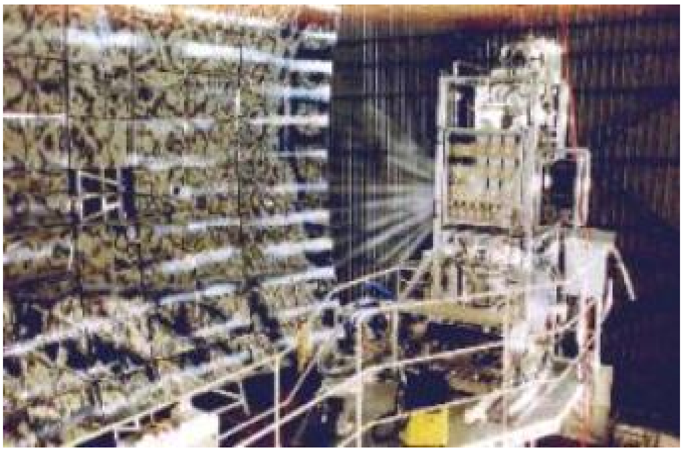

Figure 2.12 Solar Furnace: Concentrator (left) and receiver in operation at the focus (right).

2.5.4 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 55º angle to the horizontal and 0º when open.

Figure 2.13 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.

2.5.5 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.

2.5.6 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].

2.6 Solar Photochemical Facilities

The PTC (Parabolic-Trough Collector) photochemical pilot plant is presently configured in four 128-m^2 parabolic-trough solar collectors with two-axis solar tracking and a concentration factor of 10.5 suns. The 56-mm-diameter absorber tube is made of 2-mm-thick borosilicate glass.

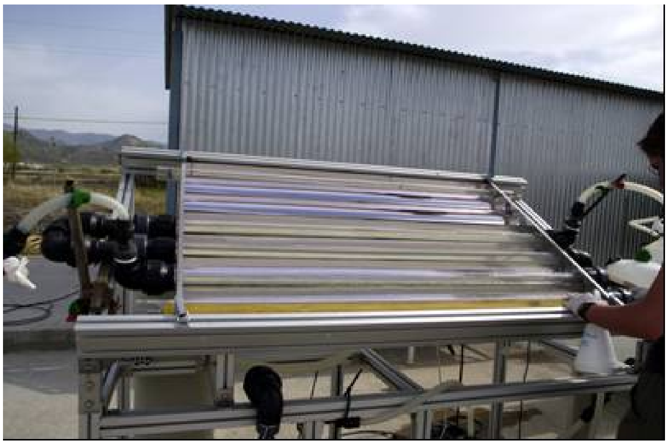

Figure 2.1 Partial view of the solar photochemical facilities. Front of solar CPC collector prototype used for water disinfection.

There are several CPC plants installed at the PSA. The oldest (1994) consists of three 3-m^2 modules tilted 37º from the horizon. The total system volume is about 250 L and the absorber tube holds 108 L (illuminated volume). In 2002, a new 15-m^2 collector for experiments of up to 300 L was installed. It also has small twin 3.08-m^2 prototypes with a 40-L total volume, 22 L of which is irradiated, for parallel experiments. Since 2004, a new CPC system, with 50-mm-diameter photoreactor, more suitable for photo-Fenton applications, with tank and recirculation pump (75 L), has been hooked up to a 150-L biological reactor based on fixed biomass on an inert matrix, and 50-L ozonization system with ozone production of up to 15 g O_3/h. All of it is monitored (pH, T, ORP, O_2, flow rate, H_2O_2,0_3) by computer. Furthermore, there are also several prototypes for water disinfection applications (Figure 2.1). There are also three ultraviolet and two global solar radiation measurement sensors placed horizontally and tilted 37º (the same angle as the CPCs) to the Earth's surface. All of the data are sent to a computer that stores them for later evaluation of results.

2.7 PSA Analysis Lab

The PSA solar chemistry lab is a 75-M^2 building designed to contain all of the conventional laboratory equipment: work benches, gas extraction hood, storage space for small amounts of chemicals, centralized gas distribution system, UPS, safety systems (extinguishers, shower, eyewash, etc.) precision scales, ultrapure water, ultrasonic bath, thermostatic bath, centrifuge and microcentrifuge, vacuum distillation system, autoclave, 2 laminar flow hoods, incubator for microbiology and many other systems normally used in a chemistry lab. A phase contrast/fluorescence combination microscope is connected to a digital photography system for analysis of our microbiological samples. The following analytical equipment is also available for environmental chemistry: liquid chromatograph (quaternary pump with diode array detector, automatic injection, simultaneous dual column chromatograph and fraction collector kit), gas chromatograph (mass spectrometer) with purge and trap system (analysis of volatile compounds dissolved in water), ion chromatograph configured for isocratic analysis of anions, ion chromatograph configured for gradient analysis of anions and cations, TOC analyzer (with automatic injector), UV-Vis spectrophotometer, turbidimeter, COD, BOD, and automatic shredder. All of these systems are computerized and integrated in a complete information network. In 2006, a Scanning Electron Microscope (SEM) was acquired and installed for solar disinfection test analyses of microbiological samples and catalysts. Equipment for ultra-thin metal coating and a critical-point dryer were also installed for the preparation of these samples. All of the above equipment is located at the Plataforma Solar de Almería Technical Building.

2.8 SOL-14 Solar Thermal Seawater Desalination Plant

This facility is composed of the following subsystems:

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

The multi-effect distillation unit is made up of 14 stages or effects, arranged vertically with direct seawater supply to the first effect. At a nominal 8 m^3/h Feedwater flow rate, the distillate production is 3 m^3/h, and the thermal consumption of the plant is 190 kWt, with a performance factor (number of kg of distillate produced per 2326 kJ of thermal energy consumed) over 9. The saline concentration of the distillate is around 5 ppm. The nominal temperature gradient between the first cell and the last is 40ºC with a maximum operating temperature of 70ºC in the first cell.

The system heat transfer fluid is water, which is heated as it flows through the solar collectors to the storage system. The hot water from this storage

Figure 2.14 SOL-14 plant stationary solar collector field (500 m²)

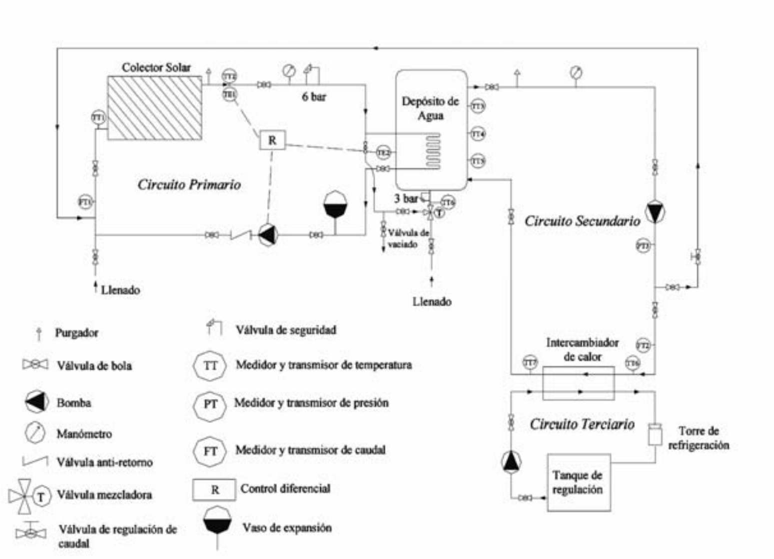

Figure 2.2 General diagram of the stationary solar collector test platform

system provides the MED plant with the thermal energy required for its operation. The solar field is composed of 252 stationary solar collectors (CPC Ao Sol 1.12x) with a total surface area of 500 m^2, arranged in four rows of 63 collectors. The maximum working temperature is 100ºC since the collectors are connected to atmospheric pressure storage tanks in an open loop. The thermal storage system consists of two water tanks connected to each other for a total storage capacity of 24 m^3. This volume allows the operation sufficient autonomy for the backup system to reach nominal operating conditions.

The double effect (LiBr-H_2O) absorption heat pump is connected to the last effect of the MED plant. The low-pressure saturated steam (35ºC, 56 mbar) produced in this cell supplies the heat pump evaporator with thermal energy, which would otherwise be discharged to the atmosphere, cutting in half the thermal energy consumption required by a conventional multi-effect distillation process. The fossil backup system is a propane water-tube boiler with a 10-bar saturated steam production capacity of 200 kg/h. This boiler ensures heat pump operating conditions (180ºC, 10 bar), as well as operating the MED plant in the absence of solar radiation.

2.9 Stationary Solar Collector Test Platform

This facility was built in 2002 for the purpose of offering additional services to the scientific research community, among which was the possibility of carrying out energy characterization of the stationary solar collectors, with special emphasis on its possible application to solar desalination processes.

The facility has three independent hydraulic circuits. In the primary fluid circuit (water or water mixed with antifreeze) is heated as it flows through the solar collector, delivering the energy acquired to the water deposited in a storage tank. In the secondary circuit, the water from the tank is pumped to the heat exchanger where its energy is transferred to the tertiary circuit. This heat exchanger simulates the hot water inlet in the first cell of a multi-effect distillation plant. Finally, the water that circulating through the tertiary circuit toes to a cooling tower where the energy from the secondary circuit is discharged into the atmosphere.

2.10 PSA Meteorological Station

Figure 2.3 General view of the new PSA radiometric 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 component characterization: (direct and diffuse) and UV.
   - Vertical wind profile: wind speed and direction at 2, 10 and 30 m
   - Miscellaneous weather information: rain gauge, barometer and psychrometer

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

Figure 2.4 Spectroradiometer probes for measuring global and diffuse radiation installed in the solar tracker

Figure 2.5 Spectroradiometer detector with three-probe connector switch

(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, there is 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***. The system was developed specifically for this purpose 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.

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. This information is currently available on the PSA website. In order to find out the demand for the information, it is necessary to log on for access.

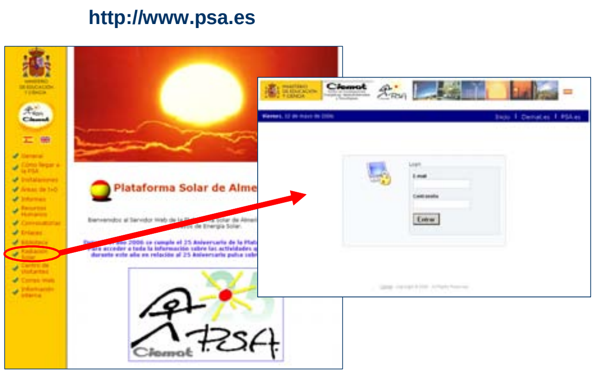

Figure 2.6 User login for access to solar radiation information.

2.11 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 6 months, quarterly, monthly or even weekly.

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

Figure 2.7 New Spectral Calibration Laboratory adjacent to the CESA-1 building

2.12 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 2.15 Views of the LECE: Cells, reference buildings and solar chimney

3 Solar Concentrating Systems Unit

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3.1 Introduction

The goal of the Solar Concentrating Systems Unit (USCS) is to develop and promote systems that make use of concentrated solar radiation, both for electricity generation and for industrial process applications that require solar concentration, regardless of whether it is to produce medium temperatures, high temperatures or high photon flow rates.

This Unit is made up of three Research Groups

- Medium Concentration,
- High Concentrating Systems, and
- Solar Fuels/Solarization of Industrial Processes

The activities carried out in the USCS in 2006 followed four master lines defined as goals:

- Development of new components for solar concentrating systems with a better quality/price ratio
- Development of simulation and characterization tools for this type of solar system
- Promote and encourage cutting-edge action related to solar concentrating technologies, opening pathways to medium and long range technological improvements

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- Facilitate development and consolidation of a Spanish industry specialized in solar concentrating systems, by scientific-technical consultation and technology transfer.

Concerning the last goal, it should be stressed that the intensive course on “Solar Concentrating Systems” given in Madrid from October 2nd to 11th was attended by representatives from all sectors (engineering, builders, equipment manufacturers, research centers) involved in technological and commercial development of solar thermal power plants. A strong effort was made by all the members of the USCS to design a compilation of texts that includes all of the different aspects of concentrating solar systems (design, component development, operation and maintenance, storage systems, perspectives for the future, etc.), for the first time. This compendium of texts covers at least an important part of the lack of bibliographic reference on al subjects related to solar concentrating systems.

The following chapters summarize the most important activities and achievements in the three R&D groups in the Solar Concentrating Unit. The large number of projects in which the Unit participated covers the whole range of solar concentrating systems.

3.2 Medium Concentration Group

The activities in the Medium Concentration Group in 2006 may be classified in two main categories:

a) Activities directly related to DSG technology (Direct Steam Generation), and

b) Activities developing new components (selective coatings and antireflective treatments), new parabolic-trough collector designs and the study of innovative working fluid and general solar plant in concepts.

Support and consultancy of businesses which have come to the PSA out of interest for solar thermal power plants with parabolic-trough collectors should also be mentioned. A strong effort has been made to give as many companies as have requested the basic technical information required to internally evaluate the commercial interest that solar thermal power plants could have for them in view of the current legal framework and the available technologies. However, due to the logical limitation of internal Group resources, all of the requests received could not be undertaken.

One of the most encouraging things for this Group in 2006 was the commercial interest that so many companies have shown in the developments that are the fruit of work carried out at the PSA during recent years in the parabolic-trough collector technology. This interest has demonstrated that the PSA was right years ago when it decided to go ahead with developments for the future although at the moment the decision was made, there was no commercial demand for them. Thanks to that confidence in the future, the PSA today has selective coatings, anti-reflective treatments and solar tracking systems (these last developed in collaboration with the PSA Technical Office) which are equal to the best on the market.

The activities and achievements in 2006 in the PSA Solar Concentrating Systems Unit’s medium Concentration Group are described below.

3.2.1 DISTOR

Energy Storage for Direct Steam Solar Power Plants

Participants: DLR (D), CIEMAT-PSA (E), Sistemas de Calor (E), INASMET (E), IBERINCO (E), DEFY Systemes (F), EPSILON Ingénierie (F), SGL Technologies GMBH (D), FLAGSOL GMBH (D), Solucar (E), ZSW (D), Weizmann Institute of Science (Il), and the Central Laboratory of Solar Energy and New Energy Sources (Bulgaria).

Contact: Javier León, javier.leon@psa.es

Total budget: 3 036 650€. Co-financed by the EC CE (Contract SES6-CT-2004-503526)

Duration: February 2004 - September 2007

Motivation: Direct steam generation in the parabolic-trough collector absorber tubes themselves is a very attractive cost-reducing option for electricity generation with this type of solar collector. To make solar thermal power plants more commercial, they must have heat storage systems that allow electricity production to be disconnected from the hours of sunlight. Thermal storage systems currently available for solar thermal power plants are based on materials that increase in temperature (sensible heat) and are inappropriate for direct steam generation solar systems. That is why a specific solar thermal storage system must be developed for solar fields with direct steam generation.

Purpose: Development of a competitive thermal storage system suitable for solar plants working with direct steam generation in parabolic-trough collectors. Since most of the thermal energy in the steam is released when it condenses, and this is a process that takes place at a constant temperature, the appropriate storage system for this type of solar plants must be based on a medium that is able to absorb heat at a constant temperature. This leads to the need for a thermal storage system based on latent heat, using phase-change materials. Several possible options are being studied for a storage system using phase-change materials, and when the best option has been selected, a prototype storage module with a rated power of 100 kWt and 200 kWh capacity will be built. This module is scheduled to be installed and evaluated at the PSA in 2007.

Achievements 2006: In 2006, the PSA DISS plant interface necessary for connection of the prototype phase-change storage module to be designed and erected in the project was revised. Figure 3.1 below shows the new interface design, which will make it possible to test storage charging and discharging (labeled TES in the figure).

Although the storage prototype to be installed and evaluated in 2007 works at 40 bar, the interface and its associated instrumentation have been designed to work at pressures up to 100 bar. This will make it possible to evaluate future storage models designed for higher operating temperatures (up to 310ºC).

In July 2006, a Collaboration Agreement for development of the data acquisition and control software necessary for this test facility was signed with the University of Malaga. The software developed will allow on-line internet access to test data in real time so they can be quickly evaluated by the other partners in the project without having to be physically present at the PSA.

One of the problems found in 2006 in the DISTOR project was the need to install a steam condenser at the storage module outlet to get the proper bal-

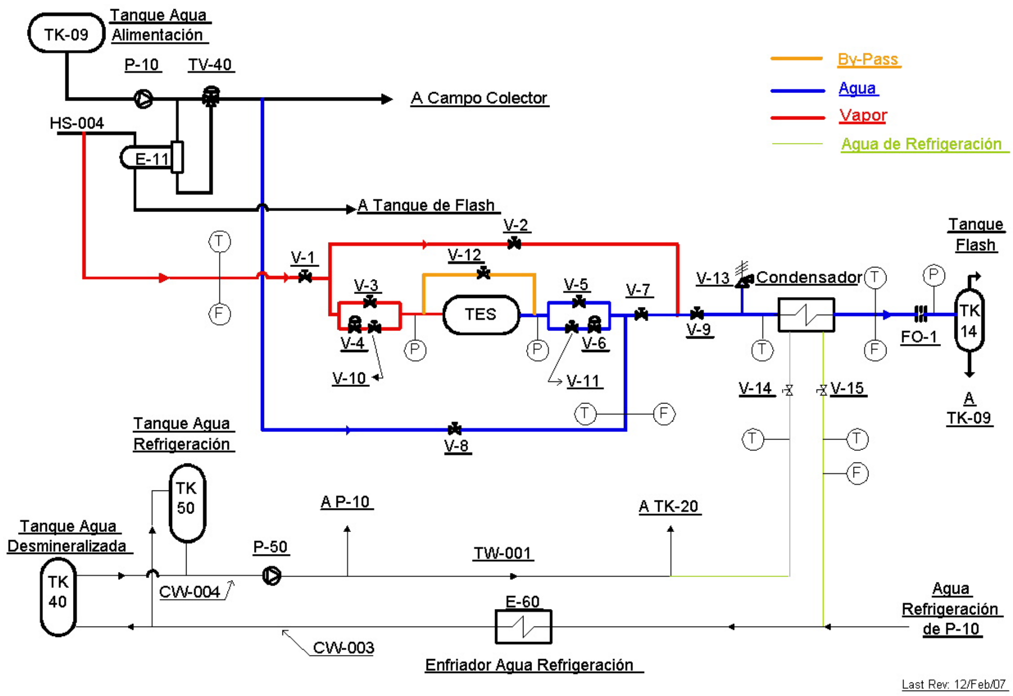


Figure 3.1 Schematic of the interface designed to connect the DISTOR storage module to the PSA DISS experimental plant.

ance of energy during charging and discharging. This condenser is necessary because during discharging, the steam could leave the module without completely condensing, which would make it impossible to find out its specific enthalpy and close the energy balance in the module. In 2006, this condenser was designed and built and erected at the PSA and most of the instrumentation and materials necessary to construct the interface shown in Figure 3.1 have been purchased.

Most of the data acquisition and test monitoring software has been developed, and alarm levels for the various temperature, flow rate and pressure parameters monitored have been defined.

Due to the peculiar characteristics of the storage model to be built for evaluation at the PSA, its design and construction were delayed in 2006, also causing a small delay in the final design of the interface and its construction. Nevertheless, this delay is not a serious risk to project completion as planned before the end of September 2007.

3.2.2 Almería GDV

Pre-commercial solar thermal power plant with direct steam generation

Participants: IBERDROLA, SOLUCAR, SENER, IDAE and CIEMAT-PSA

Contact: Eduardo Zarza, eduardo.zarza@psa.es

Total budget: 18 000 000€.

Duration: January 2006 – December 2008

Motivation: The experimental results in the DISS (1996-2001) and INDITEP (2002-2005) projects demonstrated the technical feasibility for direct steam generation in horizontal parabolic-trough collector absorber tubes, a process known by its initials, DSG. However, the results in the experimental DSG plant erected at the PSA for the DISS project are insufficient to ensure the technical and commercial feasibility of large DSG plants, as the PSA plant has only got one row of collectors and does not have a turbogenerator to convert the steam produced in the solar field into electricity. Therefore, a DSG plant with several parallel rows of parabolic-trough collectors must be built to experimentally verify that the DSG process is commercially feasible.

Purposes: The purpose of this project is the construction of a pre-commercial DGS plant with several parallel rows of parabolic-trough collectors connected to a power block where the steam supplied by the solar field is converted into electricity by a steam turbine and electric generator. This plant will allow study of the interaction among the parallel collector rows, as well as the optimum startup and shutdown processes for large commercial DSG plants. The construction of the DSG plant proposed in this project is necessary before large commercial DSG plants can be safely undertaken.

Achievements 2006: The Spanish consortium that will undertake the construction and evaluation of the DSG plant proposed in this project was consolidated in 2006. During the first half of the year, a business plan was prepared for the 5-MW_e DSG plant designed in the INDITEP project. Because of the peculiar characteristics of this plant (small size, innovative technology, etc.), the study showed that the construction of a 5 MW_e DSG plant would not be commercially profitable. At the end of 2006, it was therefore decided to reduce the plant size from 5 MW_e to 3 MW_e and a preliminary business plan was prepared for the plant, which is not economically attractive either, but the investment and effort required by the partners are significantly less without detracting from the validity of the results for operation of large commercial DSG plants. Based on the results of this study, it was finally decided to build and evaluate the 3 MW_e plant with a budget of 18 million Euros.

The site selected for the construction of the PSA 3 MW_e DSG plant is east of the current site. The land was surveyed and the solar field was redesigned for the 3 MW capacity. Figure 3.2 shows the simplified diagram of the DSG plant that it was finally decided to build. The solar field consists of four parallel rows of ET-100 parabolic-trough collectors with some improvements in the original collector design made at the PSA. Each row consists of ten ET-100 collectors connected in series and has a water/steam separator at the end of its evaporating section and a steam cooler at the inlet of the last collector.

For financial assistance necessary to build this DSG plant, numerous contacts were made with Spanish national and regional government RD&I agen-

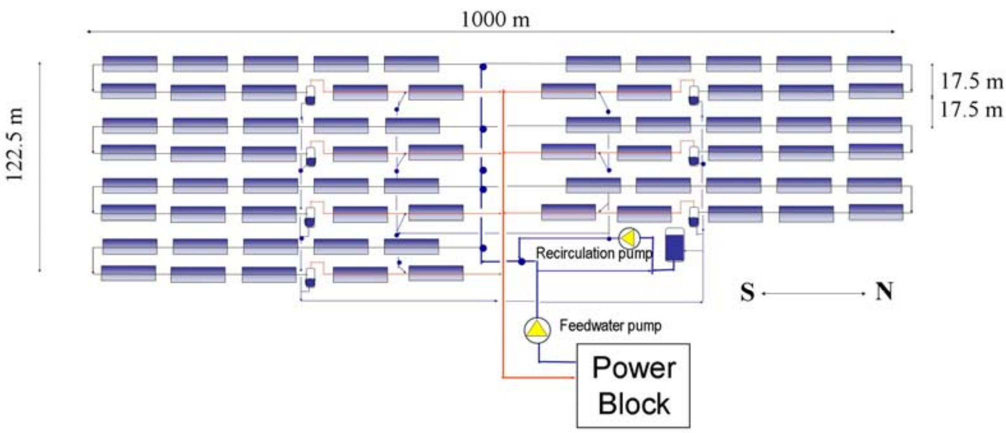


Figure 3.2 Schematic diatram of the 3 MW_e Almería DSG plant.

cies in 2006. Keeping in mind that Spain is currently in the vanguard of the direct steam generation technology, the proposal for construction of the DSG plant attracted strong technological and commercial interest, as it represents the unavoidable step to determining the commercial feasibility of this technology, which promises to significantly reduce the cost of electricity generated by solar thermal power plants with parabolic-trough collectors.

Although its performance is modest, the power block selected for this plant is very robust and simple to operate. Since its operation must be very flexible to study the different startup and shutdown procedures and test control strategies, robustness was considered a higher priority than efficiency.

Among the subjects that will be studied in this plant, apart from the startup and shutdown procedures, are the following:

- Control and regulating procedures for pressure and temperature of the superheated steam produced by the solar field
- Evaluation of behavior of essential components under real operating conditions (ball joints, water/steam separators, coolers and high pressure absorber tubes.
- Secure positions required to ensure proper plant operation in emergency situations and solar radiation transients.

3.2.3 Low-cost absorber tubes

Participants: CIEMAT-PSA, Solucar

Contact: Angel Morales, angel.morales@ciemat.es

Total budget: 750 000 €.

Duration: December 2004 - November 2007

Motivation: One of the most important elements of the parabolic-trough collector is the absorber tube, since that is where the concentrated solar radiation is converted into thermal energy. Due to its high technology, there are only two vacuum absorber tube manufacturerers, Schott and Solel, that currently market this type of solar collector. Because of the scant offer, both the price and the delivery period for these tubes are currently a serious barrier to rapid commercial development of solar thermal power plants with parabolic-trough collectors. Therefore, the development of new absorber tubes with a high quality/price ratio is both very attractive and of interest. CIEMAT has been working on the development of anti-reflective (AR) and selective coatings for use on this type of absorber tube, and has already patented several.

Purpose: Develop new absorber tubes for parabolic-trough collectors, both with (for solar thermal power plants) and without vacuum (for moderate working temperatures) based on the Sol-gel technology developed by CIEMAT for selective and anti-reflective (AR) coatings.

Achievements in 2006: Activities and achievements in 2006 are described below classified in two areas, AR glass films and selective absorbers.

AR films for glass covers

In 2006, we worked on improving the durability of anti-reflective SiO_2 films developed previously for application to glass covers on solar devices. The problems for outdoor durability of this kind of coatings are associated almost entirely with the adsorption of water in hydrophilic pores on the surface, which increases their refraction index. To avoid this process and ensure durability of the films, a method has been developed for replacing the hydrophilic –OH groups on the surface with Si-CH_3 groups, which makes hydrophobic films water-resistant while conserving excellent optical properties.

Accelerated aging studies in a weathering chamber done at the PSA demonstrate the effectiveness of the process, finding variations in solar transmittance of less than 0.8% after 1500 hours at 40ºC and 100% relative humidity while there was more than a 3% drop in transmittance in the untreated anti-reflective films after 200 hours of testing.

High-temperature selective absorbers

In 2006, the optical properties and thermal durability of the high-temperature selective absorber were optimized. Solar absorptance of 0.96 and thermal emissivity at 500ºC of 0.14 were achieved.

No optical or layer-adherence degradation was found in the coating deposited on AISI 304 stainless steel after a two-month thermal durability test in a furnace at 500ºC air temperature.

A pre-industrial procedure for manufacture of the absorber is being developed and it has been observed that better optical properties and more homogeneity are achieved if the films are dried at a certain temperature for a few seconds while the precursor solution sample is being extracted.

To date, the maximum size of flat samples prepared has been 100x100 mm. These samples have had excellent homogeneity and optical properties. Next year, tubes of different diameters up to 500 mm long will be coated.

Publications: [3.1]

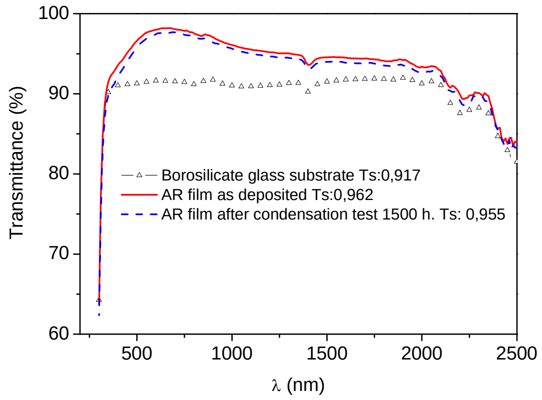


Figure 3.3 Glass transmittance with and without the AR film, before and after 1500 h in weathering chamber

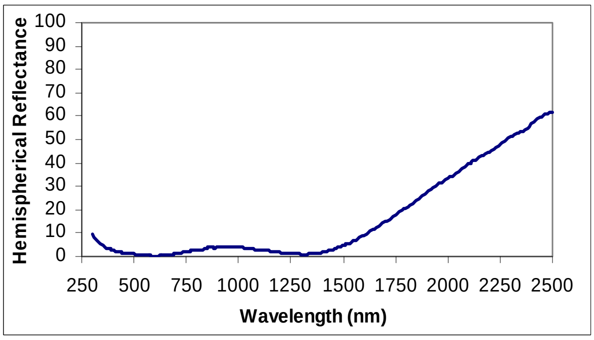


Figure 3.4 Hemispherical reflectance of the high-temperature absorbers

3.2.4 Advanced low-temperature absorber coatings

Participants: CIEMAT-PSA, WAGNER Solar

Contact: Angel Morales, angel.morales@ciemat.es

Total Budget: 161 500 €.

Duration: March, 2005 - June, 2008

Motivation: At the present time a wide variety of solar hot water collectors are available. Although some of their characteristics are different, all of them have in common a working temperature clearly below 175ºC. The selective coatings usually used for these collectors at present are economically manufactured, although their optical and thermal properties are not excellent. Improving the quality of these coatings and their optical properties is of great commercial interest if it can be achieved without significantly raising the cost of manufacture. CIEMAT-PSA has long experience in the field of selective coatings for solar absorbers manufactured using the Sol-gel technique. This experience can be applied to the development of solar absorbers with better properties than those currently used in low-temperature solar collectors without prohibitively raising the cost. Solar collectors with a better selective coating without increasing the price will no doubt rank well on the market.

Purposes: Develop an advanced solar collector absorber with a working temperature below 200ºC manufactured using the Sol-gel technique, which is industrially competitive with currently available low-temperature coatings.

Achievements in 2006: Although a good advanced coating had already been achieved in 2005, its quality/cost ratio was not good enough for commercial applications. Therefore, work done by CIEMAT-PSA on this project in 2006 concentrated mainly on improving the properties of this coating.

A strong effort was devoted to optimizing Cu-Mn spinel deposition, which is the basis of the new absorbent coating developed by CIEMAT-PSA for industrial manufacture. It was attempted to improve coating homogeneity to avoid pore formation by optimizing the substrate cleaning method and solution composition, particularly, the concentration of additives.

Increased additive concentration in the solution composition used for manufacturing the new coating was observed to improve the homogeneity of the films by reducing the amount of undesirable pores formed. The Cu-Mn spinel precursor solution was also optimized, increasing the extraction speed up to 45 cm/min and the SiO_2 anti-reflective layer to 23 cm/min, with a mean solar absorptance of 0.940 and emissivity at 100ºC of about 0.06-0.08.

Accelerated aging tests were performed in a weathering chamber to evaluate the durability of the new coating following the IEA Solar Heating and Cooling Program Task X procedures (Standard ISO/DIS 12952), which include temperature (thermal treatment at 250ºC for 200 hours) and humidity (treatment in 40ºC condensation for 600 hours) requirements. The performance coefficient for the AR layer with Cu-Mn spinels was less than 0.05, and was therefore validated by the standard's criteria.

Publications: [3.2] - [3.3]

3.2.5 FASOL

Design and development of a parabolic-trough thermal collector for process heat

Participants: CIEMAT and, and occasionally, SMBs

Contact: Esther Rojas, esther.rojas@ciemat.es

Funding: 225 000€

Background: Several projects financed by the European Commission (POSHIP, PROCESOL I and II) have shown the enormous potential for solar thermal energy in industrial processes requiring temperatures from 60ºC to 300ºC.

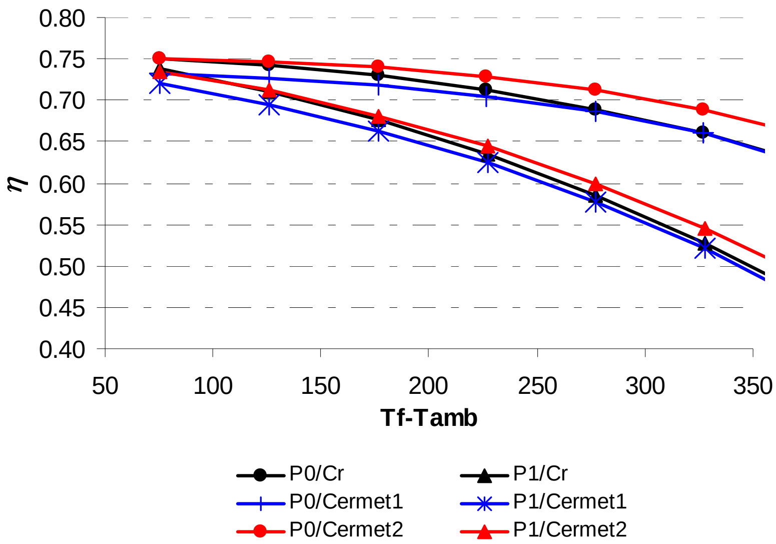
This high potential has not been fully developed to date for various reasons, but for processes over 120ºC, it is mainly because of the lack of suitable commercial collectors with appropriate performance and cost. International enthusiasm for promoting solar thermal energy in industry is evidenced by the startup in 2004 of International Energy Agency Task 33/IV on Solar Heat for Industrial Processes, in which the CIEMAT actively participates.

Purpose: Develop a solar thermal collector that can be integrated in processes having a temperature range between 120º and 300ºC and a cost/efficiency ratio attractive to industry. Because of their similar temperature ranges, this collector will be connectable, not only to industrial processes, but also to double-effect absorbers for air conditioning. To effectively implement the collector developed in the project, it is intended to involve small and medium businesses, both in the development and design of the collector itself, and in the construction of an experimental pilot plant using this collector.

Activities and results in 2006:

The theoretical model developed previously in the Solar Concentrating Unit has been improved by including a simplified flat glass cover over the parabolic reflector. This model, along with the one developed in 2005 for geometric optical performance, optimizes collector characteristics to the temperature required by the criteria of maximum energy performance (see Figure 3.5).

Study of commercial reflective materials and their outdoor stability has continued. During the first quarter of 2006, periodic measurement of an aluminum film on a methacrylate (PMMA) reflector cleaned using a simple methodology that practically returns it to its nominal reflectivity was continued.



	α_{solar}	ε
Cr	0.963	0.186
Cermet 1	0.938	0.12/0.13
Cermet 2	0.955	0.03/0.10

Figure 3.5 Simulation of the influence of absorber optical properties on overall performance of a parabolic-trough collector with a flat anti-reflective glass cover over the reflector and a vacuum ('P0') or atmopheric pressure ('P1') receiver

The disadvantage of this material is its relatively low solar reflectivity (around 77%). Reflectors with aluminum-silver on a metal support have been tested using two different methods, accelerated aging in weathering chambers following the AST G-154-2000 (G-53-95, 1995) standard, and exposing them to outdoor conditions at the PSA. Based on the results found to date, two materials have been selected as candidates for use as the prototype reflector.

All of these results, which it will contribute to a study on economic data and incentives for promoting the use of solar thermal energy in Spanish industry, also fall within the Solar Concentrating Unit's collaboration with IEA Task 33/IV Subtask A ('Evaluation of Industrial Processes and Dissemination of Results').

Publications: [3.4] - [3.5]

3.2.6 Innovative working fluids for parabolic-trough collectors

Participants: CIEMAT, Polytechnic University of Madrid

Contact: Eduardo Zarza, eduardo.zarza@psa.es

Total budget: 950 000 €.

Duration: December 2005 - December 2008

Motivation: Parabolic-trough collector solar thermal power plant technology is currently the most commercially developed, with more than 2.5 million m^2 of collectors in routine operation and a rated power of 340 MW_e. In spite of its commercial maturity, ways to reduce costs and increase performance must be sought to make them competitive with conventional power plants. One of the options for reducing costs and increasing performance is to attempt to find new working fluids for the collectors. To date three different fluids have been studied experimentally, oil, water/steam and molten salt. But there are other possible working fluids that have not yet been studied experimentally.

Purposes: Experimental study of innovative working fluids for parabolic-trough collectors, evaluating their behavior under real operating conditions and analyzing their advantages and disadvantages compared to those currently in use. The first goal is design and construction of a test loop at the PSA for experimentally studying new parabolic-trough collector working fluids.

Achievements in 2006: Activities in 2006 in this project, supervised by Prof. Carlo Rubbia, concentrated on the design and construction of a test loop for evaluating new working fluids under real solar conditions. The system designed consists of:

- Two Eurotrough-type parabolic-trough collectors with only four modules, connected in series in each collector, with a total collector surface of 274.2 m^2 and a length of 50 m. These two collectors can be connected in series or in parallel by a by-pass valve.
- An air cooler able to dissipate the thermal energy supplied by the two solar collectors
- A pump able to supply the wide range of fluid flow rates required by the collectors
- A heat exchanger that transfers the thermal energy supplied by the collectors to a secondary circuit where thermal storage systems may be installed and tested
- A data acquisition and control system for complete loop monitoring

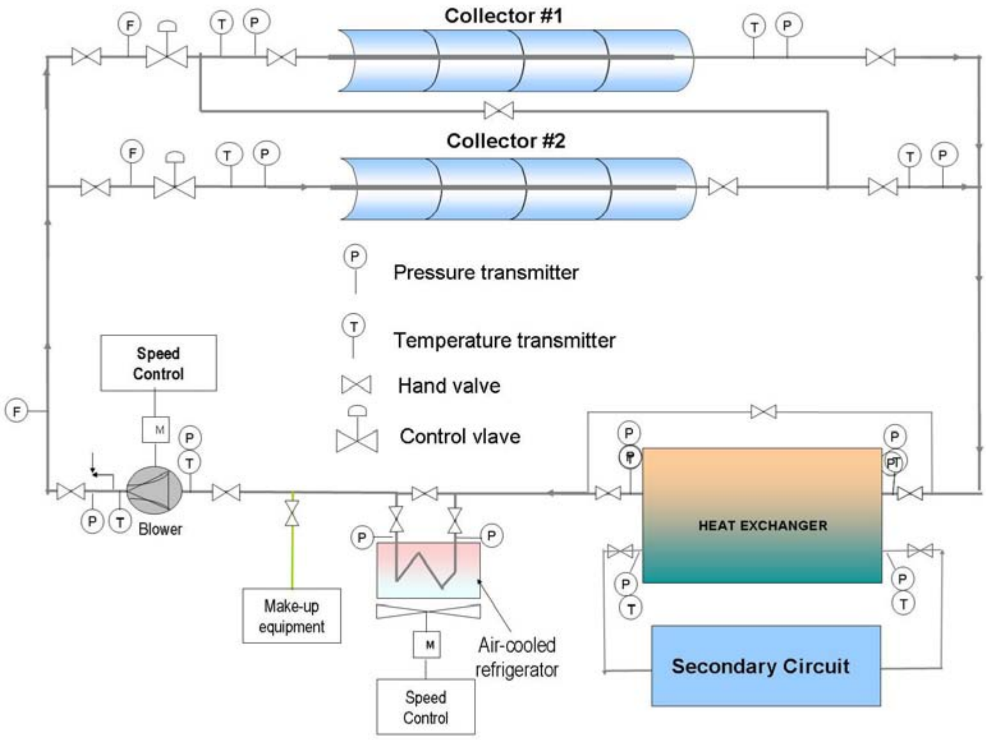


Figure 3.6 Diagram of the innovative fluid test loop

- Automatic control valves for precise, safe variation of collector input flow.
- Hydraulic circuit and accessories able to work at 100 bar/400ºC

Figure 3.6 shows a simplified diagram of the test loop designed for operating flexibility.

This experimental system is to be erected at he PSA on a site north of the DISS plant control room, which will also be used as the control room for the new test loop, since it is so close.

Most of the test loop components were acquired in 2006, and some have been installed, including the two solar collectors. These solar collectors will be provided with an innovative solar tracking system to ensure the integrity of the absorber tubes, automatically taking the collectors out of focus without the need for a UPS in the driver motors if the electrical supply to the drivers should be cut off.

Although some special equipment required was difficult to find, all of the major equipment was purchased in 2006. Underground electrical supply channels were dug and the pneumatic loop for the corresponding DISS plant systems was also laid.

The CIEMAT Engineering Unit used finite elements programming to calculate the stress in the metal absorber tubes in the loop under various operating conditions, verifying that they will able to resist foreseen operating conditions.

3.2.7 Other activities of the medium Concentration Group

In addition to the activities described above, the PSA medium Concentration Group carried out other activities, such as those below:

- Modeling and simulation software development in the TRNSYS environment, improving existing parabolic-trough collector field simulation programs for both the HTF technology and direct steam generation in the parabolic-trough solar collector absorber tubes.
- Evaluation of new components and designs for parabolic-trough collectors. The confidential nature of this type of work prohibits us from providing concrete information on the PSA's work in this area in 2006.
- Diffusion of the parabolic-trough collector technology, by giving lectures and participating in courses on renewable energies. In this field, the most significant contribution of the medium Concentration Group was our participation in the Course on "Solar Concentrating Systems" in Madrid from October 2-11, 2006.
- Consulting services for builders and engineering firms on parabolic-trough technology: The incentives and premiums set by Royal Decree 436/2004 have given rise to a strong commercial interest in solar thermal power plants. This has caused a large number of companies to start exploring the possibility of entering this field of technology. Since the parabolic-trough collector technology is the most commercially mature for solar thermal power plants, it is the technology most of the companies are interested in. As the PSA is the European center of reference in solar concentrating technologies, almost all the companies come to the PSA for information and consultancy. Given the logical limitation of available resources in the Medium Concentration Group, it is sometimes impossible to attend to all of the requests received. It is our desire to be able to increase our human resources to adequately give Spanish industry all of the support demanded of us at this time and which, at present, it is impossible for us to do.

3.3 High Concentration Group

Central Receiver Systems (CRS), after a scale-up and concept demonstration stage, at the end of 2006, are at the gateway of commercial operation. Today, over 10 complete experimental central receiver systems and a wide variety of components (heliostats, receivers, storage subsystems) have been tested worldwide. This accumulated experience has demonstrated the technical feasibility of the concept and its ability to operate at high incident radiation flux (typically between 200 and 1000 kW/m^2), which makes it possible for them to work at high temperatures (between 250ºC and 1100ºC) and gradually be integrated into more efficient cycles, from Rankine cycles with saturated steam to Brayton cycles with gas turbines. It has also been demonstrated that they easily admit hybrid operation in a wide variety of options and have the potential to generate over 4500 equivalent hours per year high-capacity electricity with the aid of thermal storage systems. System efficiency predictions are 20-23% at design point and 15-17% annual.

The high cost of capital is an obstacle to the commercial deployment of its full potential. The first commercial applications that are about to be inaugurated, still have installed power costs of 2500-9000€/kW (depending on storage) and electricity production costs of around 0.16-0.20€/kWh. A reduction in the cost of the technology is therefore essential to increase the number of commercial applications. Aware of this problem, the PSA, as well as participating in the first commercial CRT demonstration plants, maintains a permanent line of research in component and system development for their cost reduction and efficiency improvement.

In 2006, in addition to contributing to SCSU activities, such as improving own R&D capabilities and technological training of third parties, the High Solar Concentration Group, HSCG, performed three basic types of activity:

- System development, which at the present time of commercial deployment of these technologies could be understood as cooperating with the developers promoting the first generation of commercial central receiver solar thermal power plants, such as PS10 (with Solucar-Abengoa) or Solar tres (with Sener).
- Component development for central receiver technology by initiative or collaboration in national (such as AVANSOL) or international (such as HICON-PV or SOLHYCO) projects.
- Improvement of experimental capacities and quality procedures (as IN MEPSOCON)

3.3.1 SOLAR TRES

15 MW_e Molten Salt Solar Thermal Power Demonstration Plant

Participants: SENER Ingeniería y Sistemas, S.A. (E), GHER,S.A. (E), CIEMAT-PSA (E), Compagnie de Saint Gobain, S.A. (F), SIEMENS Aktiengesellschaft (D)

Contacts: Javier Viñals (javier.vinals@sener.es), Juan Ignacio Burgaleta (ignacio.burgaleta@sener.es); Félix M. Téllez (felix.tellez@ciemat.es)

Funding: CEC- DG TREN (ENERGIE Program, Ref.:NNE5/369/2001): 5 M€

Duration: December 2002-December 2007

Background: The Project accumulates the experience of the previous Solar Two project, but also has design innovations, as a consequence of work performed together by Sener and the CIEMAT as well as the technical conditions imposed by Spanish legislation on solar thermal power. The initial Solar Tres project was predesigned to meet the requisites of the Spanish legal frame-

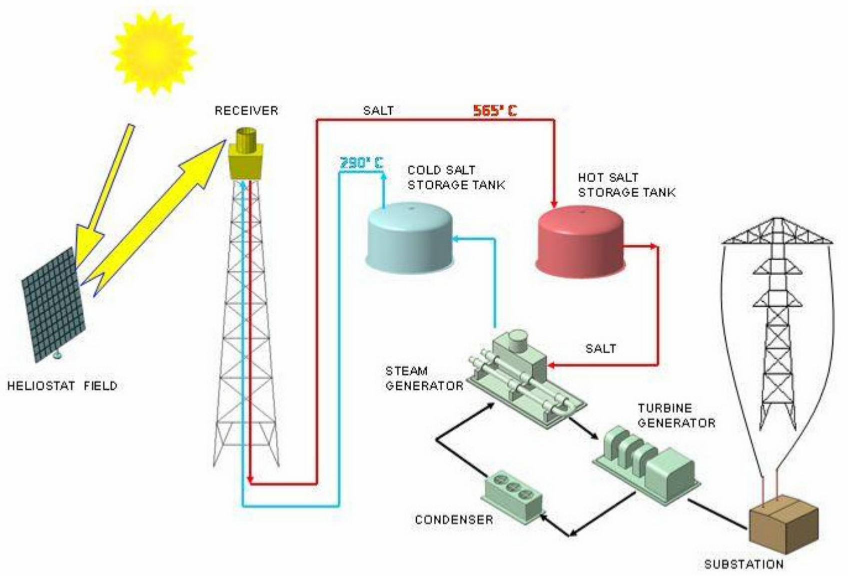


Figure 3.7 Flow diagram of the Solar Tres plant

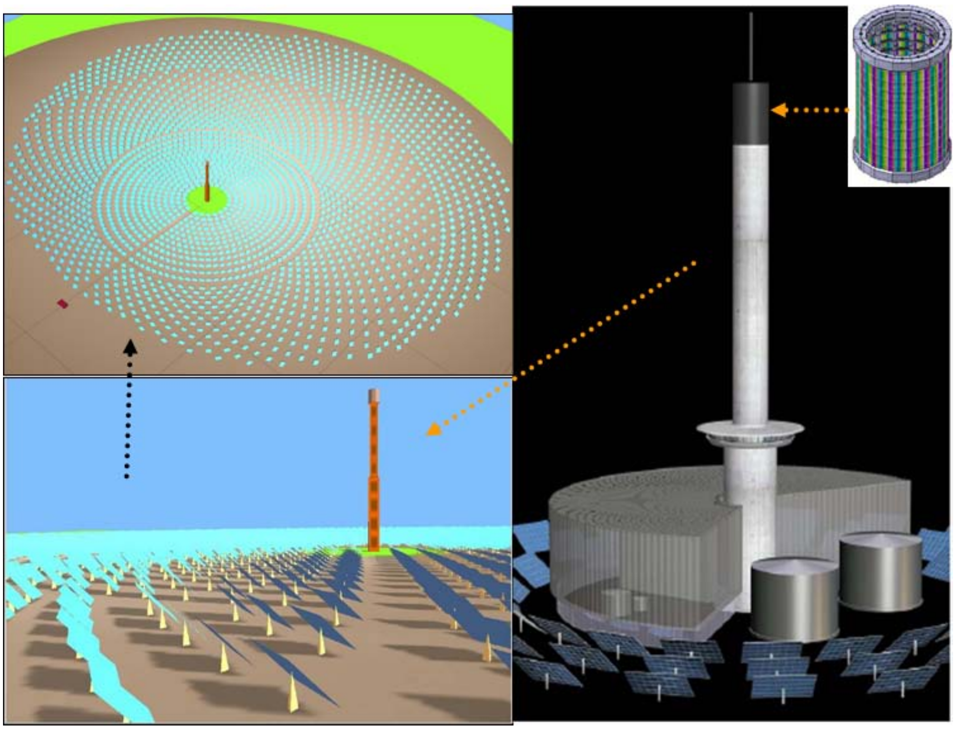


Figure 3.8 Predesign views of the Solar Tres plant

work in 2000. During the development of the project, national legislation on renewable energies underwent some changes, and there were also some changes in partners, which led to reorientation of the project and the promoting consortium. Finally, in 2005, the team was consolidated in an entirely European consortium led by Sener. At the same time, Sener and CIEMAT signed an agreement for the development and evaluation of new heliostat and molten salt receiver concepts and a prototype with better thermal performance, able to operate at higher flux without compromising its durability (see project below).

Purposes: The purpose of the SOLAR TRES project is to build and operate a 17-MW commercial-scale demonstration solar thermal power plant with heliostat field, tower and molten salt thermal storage system. As allowed by recent Spanish law (RD 436/04), the facility will have up to 15% natural gas or LPG, which, which along with the molten salt heat transfer fluid and thermal storage, will make it possible to generate 105 million kWh/year. This electricity will be delivered entirely to the grid under the Special Regime for Electricity Generation established by the above-mentioned decree.

Achievements in 2006: Sener has completed permitting and financing required for the special regime, and it has initiated the suitability and environmental impact studies for the site chosen. Detailed engineering of the main components is well advanced: heliostats, receiver and thermal storage system (Sener), selection of turbine (Siemens); electrical tracing, instrumentation and definition of civil engineering work (Sener), and selection of mirrors for heliostats (Saint Govain). As a task relevant to project progress, Sener and CIEMAT are funding (65% Sener, 35% CIEMAT), and “validating” the Solar Tres receiver design, by building, testing and evaluating a prototype receiver panel. The test plan at the end of 2006 is already well advanced.

Publications: [3.6], [3.7], [3.20]

3.3.2 Development of the molten salt receiver for a solar thermal power plant

Participants: SENER Ingeniería y Sistemas, S.A. (E), PSA-CIEMAT (E); [2 CIEMAT Divisions participate in this project: a) PSA-CIEMAT, b) CIEMAT-Structural Materials Division].

Contacts: Juan Ignacio Burgaleta (ignacio.burgaleta@sener.es); Félix M. Téllez (felix.tellez@ciemat.es)

Funding: Sener (65%) and CIEMAT (35%). Total estimated cost 6 M€, of which 1.5 M€ are for equipment.

Duration: November 17, 2005 to December 31, 2007.

Background: In 2004-2005, Boeing withdrew its offer to build the Solar Tres receiver, compromising continuation of the project in the absence of an alternative commercial offer. In view of this situation, Sener decided to undertake the engineering and development of the molten salt receiver for Solar Tres on its own. Nevertheless, in order to reduce the development risk, it requested CIEMAT assistance in sharing in the design and validation of a tube salt receiver, including design, building and testing a receiver panel prior to the fabrication of the Solar tres receiver, which will consist of 16 such panels. In the second half of 2005, Sener and CIEMAT signed a collaboration agreement for receiver technology validation (with Sener-CIEMAT technology) and definition of operating and control strategies to be applied in solar thermal power plants (starting with Solar Tres).

Purpose: i) Reduce the risk associated with the first own development of a molten-salt central-receiver solar thermal power plant technology, ii) Experimental validation of the Solar Tres receiver design, iii) Review of the selection of materials and geometries to extend the lifetime expectancy of the receiver. The equipment developed for the experiment is almost the complete system, lacking only the turbine and generator. It includes the 4-MW thermal receiver

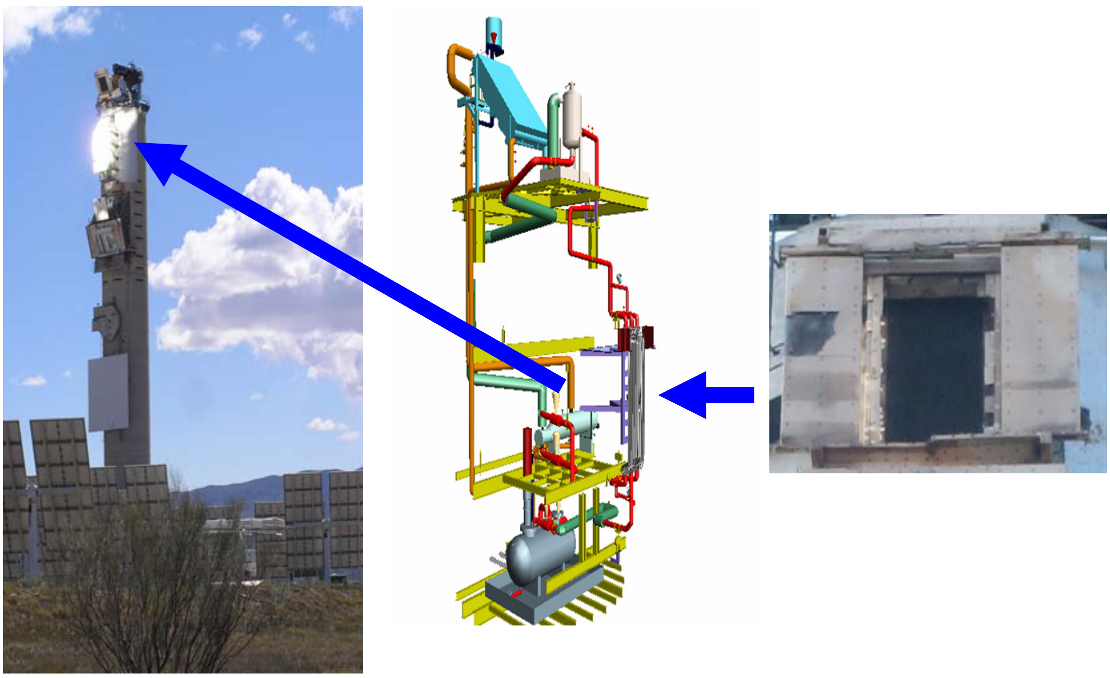


Figure 3.9 Salt Receiver Panel during testing at the 70-m level of the CESA-1 tower; diagram of the experimental device and front view of the receiver panel with side shielding.

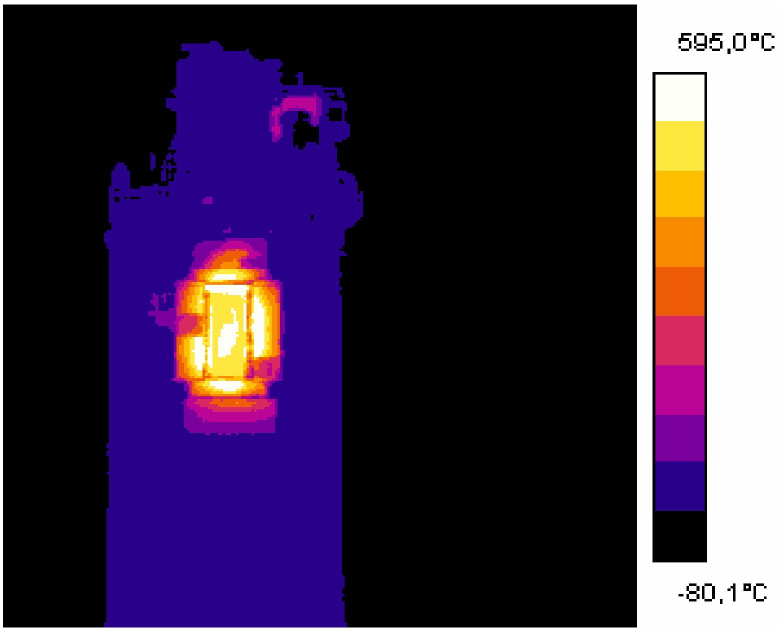


Figure 3.10 Infrarred image of first salt receiver panel tests in the CESA-1 tower.

subsystem, 18-ton molten salt storage tank, 1-MWh evaporator, air condenser, electrical tracing system, tubing, control and measurement system equipped with about 400 sensors.

Achievements in 2006: In the first half of 2006, all of the subsystems in the salt receiver bed and experimental prototype had been completely installed. In the third quarter, the measurement and control systems in the experimental installation were commissioned. Testing began in the fourth quarter, including a final stage operating under very demanding conditions (with solar flux of up to 1000 kW/m^2, salt temperatures of 565ºC and slight temperature differences on the receiver panel.) The first tests with low-flux solar concentration (of about 100 kW/m^2) were performed at the end of 2006.

Alloyed materials for the receiver were also selected after 2000 hours of comparative thermal aging tests (at 750ºC) and seven months of accelerated aging tests in a weathering chamber for outdoor conditions. Selected materials showed good resistance with less than 0.3% loss of absorptivity under both types of aging.

Tests were also made to determine residual impurities in the mixture of salts from different suppliers to decide which will least corrode receiver tubes and ducting.

Finally, to ensure suitability of the solar resource at the selected site, all the information available was analyzed, including recorded measurements, generating a meteorological design sequence using the datasets from the surrounding area and collection and analysis of a year of direct measurements at the site.

Publications: [3.6],[3.7]

3.3.3 PS10

10 MW Solar Thermal Power Plant for Southern Spain

Participants: SOLUCAR (E) Coordinator, CIEMAT (E), DLR (D), Fichtner (D).

Contacts: Valerio Fernández (valerio.fernandez@pssm.abengoa.com); Félix M. Téllez (felix.tellez@ciemat.es)

Funding: The Project has received a 5-M€ subsidy from the European Commission DG TREN ENERGIE Program.(Ref. NNE5-1999-00356), and 1.2 M€ from the Andalusian Government.

Duration: July 2001 to July 2004 (participation of CIEMAT extended by specific Agreement up to plant startup in March 2007).

Background: The PS10 Project, begun in 1999, has had a long history to date and awakens many expectations in the solar community, as it is the first commercial solar tower initiative inside and outside of Spain. For the PSA, the PS10 project is of enormous importance as the obligatory reference that focuses research and technology development and channels feedback from industry, in this case the SOLUCAR company, and a public research organism like the CIEMAT, for definition of joint development strategies for heliostats, advanced concentrators, solar receivers, software codes and tools and thermal storage, all subjects which have generated projects funded by the Ministry of Education and Science PROFIT Program.

Purposes: The main purpose of the PS10 Project (Planta Solar 10) is to design, build and operate a commercial solar thermal power plant with tower and heliostat field system having a rated gross power of 11 MW. This plant has been installed in the municipal limits of Sanlúcar la Mayor in the Province of Seville and is expected to be inaugurated in March 2007.

Achievements in 2006: In 2006, construction and installation were completed and commissioning was begun. During this stage, the PSA-CIEMAT advised Solucar on operating procedures and selection of instrumentation for special variables, such as solar flux infrared measurement during receiver adjustment and testing, etc.

Publications: [3.19]

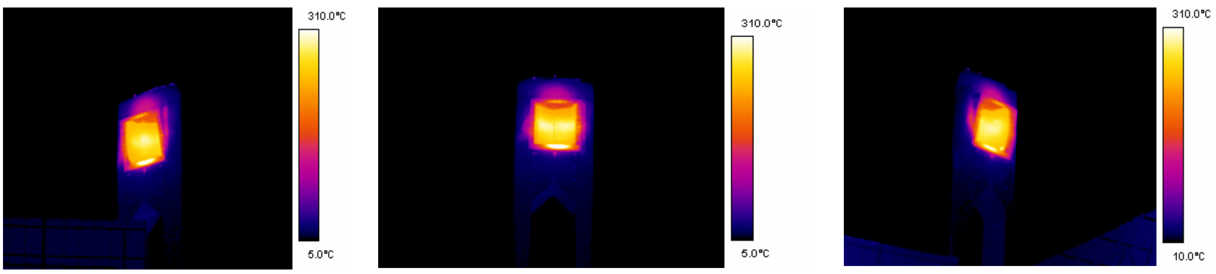


Figure 3.11 Infrared measurement of the PS10 receiver during commissioning (14/12/06) from three field observation points

3.3.4 HICONPV

High Concentration PV Power System.

Participants: Solúcar Energía (coordinator), DLR, Fraunhofer ISE, CIEMAT-PSA, CIEMAT, RWE (D), Ben Gurion Univ. (IL), EDF and Univ. Malta.

Contact: Jesús Fernández Reche (Jesús.fernandez@psa.es)

<u>Funding:</u> European Commission 6th Framework Program (Contract SES6-CT-2003-502626)

<u>Duration</u>: December 2003 to December 2006

<u>Background</u>: The HICON-PV project proposal is based on the use of GaAs multijunction cells which resist high solar flux and have efficiencies near 35%. With the current silicon technology, cells are limited to concentrations of less than 500 kW/m^2 and efficiencies of hardly 20%.

<u>Purpose:</u> Development, manufacture and testing of a concentrating photovoltaic device able to work at solar radiation fluxes of up to 1000 kW/m^2, as a means of developing a concentrating photovoltaic technology at a system cost of 1€/Wp in 2015.

<u>Achievements in 2006</u>: CIEMAT tasks in the project include selection of solar concentrating systems suitable for high photovoltaic concentration, as well as their adaptation to the strict requirements of radiation and temperature flux distribution on the photovoltaic module (in collaboration with DLR); testing and evaluation of the photovoltaic modules in the solar furnace, and development of test standards, procedures and evaluation of concentrating photovoltaic devices.

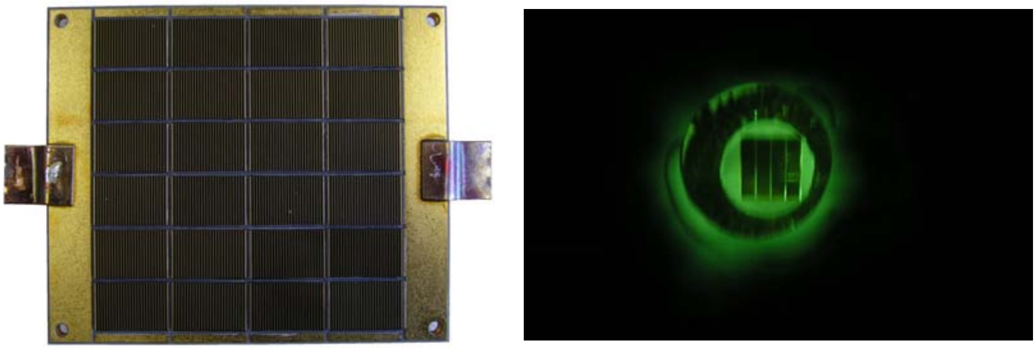


Figure 3.12 CCM Module: 120VDC and 21A and photo during testing at 1 MW/m^2.

2006 was the culmination of the project with testing of the photovoltaic module prototypes developed in the Fraunhofer Institute of Solar Energy. In 2004, PSA project activity concentrated on equipping the solar furnace with all the instrumentation needed for testing the cells developed by the Fraunhofer-ISE in addition to the simulation and optical optimization of several different types of solar concentrators (parabolic, Fresnel or tower). In 2005, all of the new components installed in 2004 were commissioned and several different cells and integrated monolithic modules (MIMs) were tested and characterized, and

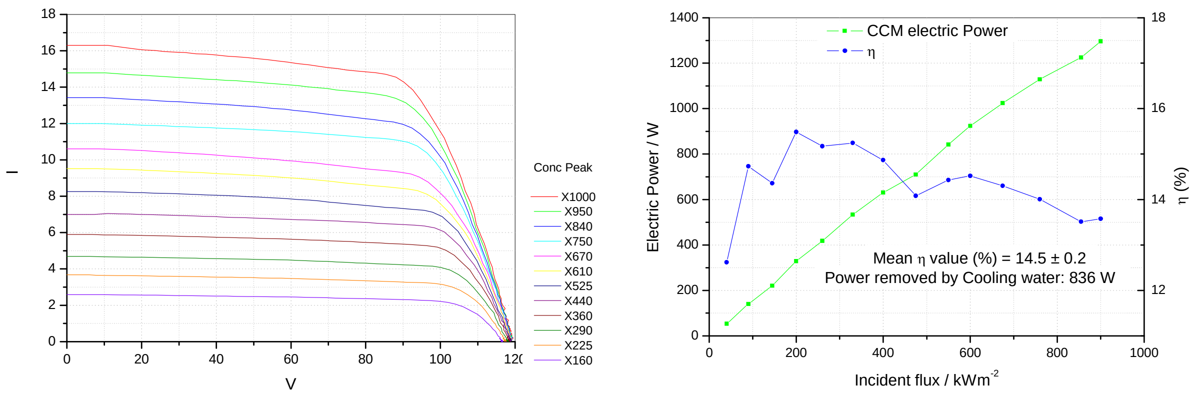


Figure 3.13 IV curves for the CCM tested at different concentrations in the solar furnace; delivered electric potential and effciency curves.

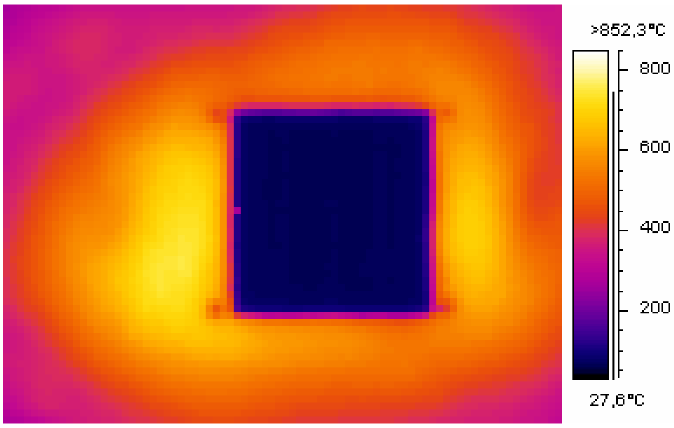


Figure 3.14 Thermogram of CCM surface temperature at 1 MW/m^2 concentration

the thermal behavior of the cooler for the photovoltaic modules proposed by PSE were evaluated. Finally, in 2006, a compact concentrating module prototype (CCM) made up of 5 MIMs connected in parallel, each composed of 4 cells connected in series, was tested. The complete module has a 120 VDC, 21A output at a concentration of 1 MW/m^2. The mean experimental efficiency of the module tested was 14.5%

The module is directly integrated into the cooler which was characterized in 2005. This way, thermal contact between the module and the cooler has improved noticeably and the CCM can be tested continuously without overheating even at high concentrations (1 MW/m^2).

Another activity in the Project had to do with the proposal for an incident solar flux measurement standard for large-surface photovoltaic modules (more than 1 cm^2). As solar irradiance incident on the surface of a photovoltaic module is not uniform, an incident solar flux map must be built up so that the efficiency of the module can be calculated for this flux map. Furthermore, as the intensity of cells connected in series is equal to that of the cell that has the lowest intensity, i.e., the one that is the least illuminated, an incident solar flux measurement protocol must differentiate between cells connected in series or in parallel.

Publications: [3.12][3.18], [3.21]

3.3.5 AVANSOL

Advanced Volumetric Absorbers for High Concentrating Solar Technologies

Participants: Solucar (Coordinator); Fundación INASMET, Univ. Seville and CIEMAT; [3 CIEMAT Divisions participate en this project: a) CIEMAT-PSA, b) CIEMAT-Fusion Materials. National Fusion Laboratory; c) CIEMAT-Structural Materials Division].

Contacts: Cristina Montero (cristina.montero@solucarrd.abengoa.com); Félix M. Téllez (felix.tellez@ciemat.es)

Funding: PROFIT, (CIT-120000-2005-49) : 513 k€

Duration: October 30, 2005 – October 30, 2007

Background: After experiments with about thirty different-sized volumetric receiver prototypes, there are still matters pending that are crucial to the de-

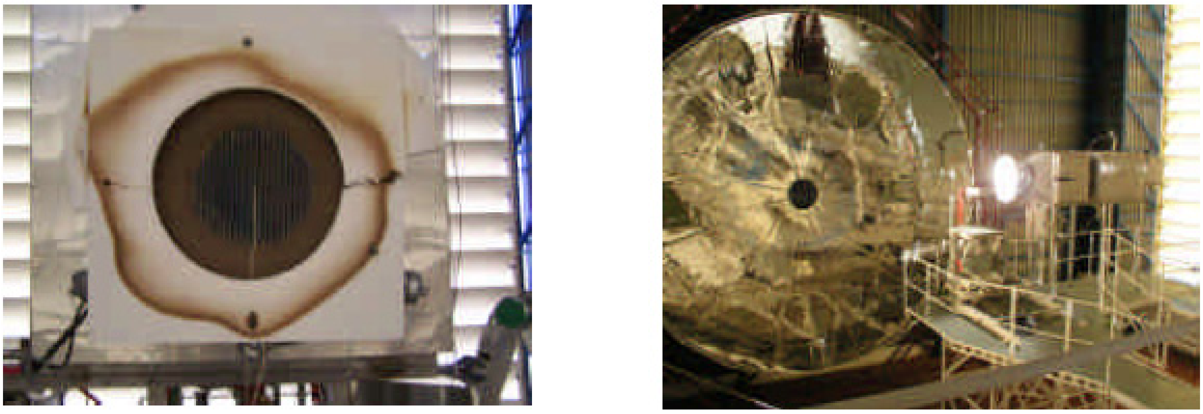


Figure 3.15 SiC volumetric absorber aging test. To analyze microstructural deterioration in this type of material, the concentration on the absorber was raised until small samples of the material started melting at surface temperatures of around 1500ºC.

velopment and industrial application of this type of receiver: i) Durability of materials; ii) Efficiencies observed in volumetric receivers up to now are far from expected performances, the apparent temperatures are similar to maximums and thermal behavior does not adequately reproduce theoretical models; iii) determination of optimum pretreatment techniques of porous materials such as “blackening” for operation at high fluxes and high temperatures; iv) Search for new materials and geometric structures which would allow low-cost thermal performance; v) Scale-up of receiver sizes to around 50 MW_{th} or higher.

Purpose: The AVANSOL project attempts to respond to two main uncertainties in air-receiver technologies: 1) Durability of the volumetric receiver under real operating conditions, and 2) Optimum selection of absorber material and porous geometry. An advanced metal volumetric absorber and another ceramic one (with higher efficiencies, durability and lower-cost) for high-temperature applications between 600 and 800ºC (metal) and between 800 and 1000ºC (the ceramic absorber prototype) were developed to do this.

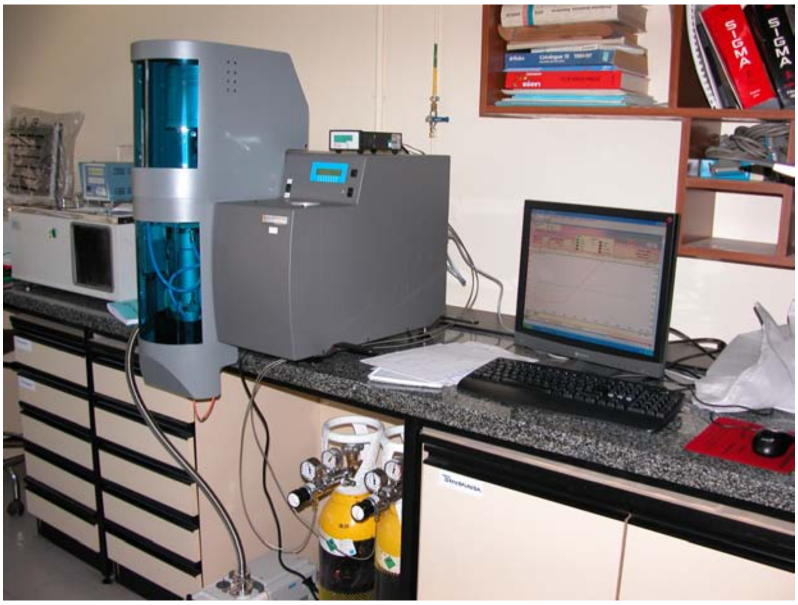


Figure 3.16 Thermogravimetry analysis system for analysis of materials subjected to the combined action of high temperatures and cycles in controlled atmosphere.

Achievements:

- Experimental techniques and installations were perfected: i) a 4000 W lamp for laboratory testing at 100 to 1500 kW/m^2; ii) optical test bench for measuring reflectivity and directional transmissivity of porous absorbers; iii) a cyclic solar thermal testing device to be installed in a parabolic dish at the Plataforma Solar de Almería; iv) acquisition and adjustment of Vickers and Knoop hardness testers (Leco mod. LV700); v) acquisition and adjustment of a thermogravimetry analysis, or thermobalance, system.
- Pretreatment/durability methods were developed for metal absorbers: The durability of two “blackening” techniques were explored, 1) the typical Pyromark paint and, 2) a thermal sprayed metal-oxide coating.
- Volumetric receiver tests in the PSA furnace.

Publications: [3.17]

3.3.6 SolHyCo

Solar Hybrid Power and Cogeneration Plants

Participants: DLR (D, coordinator), TURBEC (I), CIEMAT (E), CEA (F), Ormat (IL), Abengoa (E), FTF (D), Sonatrach (ALG), GEA (PL), Vitalux (BR), and the IIE (MEX)

Contact: Peter Heller (peter.heller@dlr.de);
Thörsten Denk (thorsten.denk@psa.es)

Funding: European Commission 6th Framework Program (Contract 019830)

Duration: January 1, 2006 to June 30, 2009

Background: This project is the heir to the successful REFOS, Solgate and HST projects that developed pressurized receiver solutions for integrating solar heat in gas cycles or combined cycles and demonstrated their capacity to produce electricity in hybrid schemes (with conventional fuel backup) in a 250 kW_e system. This type of solar-hybrid system combines solar energy and fossil fuels, but they are only 100% sustainable if they use biofuels.

Purpose: The main purpose of SolHyCo is to develop a very high-efficiency solar-hybrid microturbine for generation of both electricity and heat, working with concentrated solar radiation and biofuels, and making it a completely renewable system. Another purpose of the project is study of market introduction in sunny countries, in particular, Algeria, Brazil and Mexico.

Achievements in 2006: Tests were planned at two CESA-1 tower test beds, the first at the 60-m level with the 250-kW_e turbine made by the Israeli company, Ormat (Figure 3.17), which had already been very successfully operated in the Solgate project. This turbine is fed by three pressurized air receivers (one tube and two volumetric) with a total thermal power of 1 MW. The kerosene used in the Solgate Project was replaced by 100% biodiesel.

The second is at the 45-m level with a 100-kW turbine from Turbec, an Italian/Swedish firm. For this turbine, a new type of pressurized tube air receiver is being developed, using high-technology “multi-layer tubes”. The tubes have three layers: the outside is very-high-temperature steel, the middle is copper to distribute the heat around the circumference of the tube and the inside is very fine steel to mechanically stabilize the copper layer.

Figure 3.17 Ormat turbine at the 60-m level in the CESA-1 tower

It was originally planned to prepare the Ormat turbine for operation with biofuel in 2006. As the machine had not been operated for two years, before starting it up again, it was run with kerosene to make sure the turbine was in good condition before modifying it. However, the task was harder than originally thought. Some auxiliary components were added as a new monitoring system first, and then continued with a general subsystem control, e.g., for the turbine oil and gear systems, tower communications system – control room, main electric box, fuel lines, fuel metering valve, and water-cooling system with its associated pumps and piping. Finally, it was attempted to start up the turbine. Since the cause of failures could not be determined with the means available at the Plataforma Solar, specialists from Ormat came at the beginning of November. But in spite of about three dozen attempts, they were unable to start up the turbine either. The most likely reason for the problem was that deposits may have formed in the metering valve capillary tubes (Figure 3.18). The valve was sent back to the manufacturer in the U.S. where it was thoroughly cleaned out, some pieces were replaced for its future use with biofuel and it was recalibrated.

In 2007, the Ormat turbine will be restarted, 100% biofuel components will be modified and 100% renewable solar tests performed, and finally the Turbec turbine and the new multilayer tube receiver will be installed at the 45-m level.

Figure 3.18 The Metering Valve (fuel lines disconnected)

3.3.7 MEPSOCON

Measurement of Solar Concentrating Power in Central Receiver Power Plants y Laboratorio de Radiometría

Participants: CIEMAT

Contact: Jesús Ballestrín (jesus.ballestrin@psa.es)

Funding: Spanish Ministry of Science and Technology 2002 National R&D Plan de Industrial Production Program (Reference DPI2003-03788).

Duration: December 2003 to December 2006

Background: At the Plataforma Solar de Almería (PSA), several different systems are used for measuring solar irradiance on large surfaces. The main element in these systems is the radiometer, and measurement of the power of the concentrated solar radiation incident on the aperture of the solar receivers depends on their correct use. The measure of this magnitude is basic to determining the efficiency of the receiver prototypes evaluated at the PSA and to defining future central receiver solar plants.

Purpose: i) Definition of a sensor calibration procedure (calorimeters or flux meters for measurement of concentrated solar flux (in the range of 100-1000 kW/m^2); ii) Modeling and design of a new calorimeter that solves the current deficiencies; Integration of existing concentrated solar radiation power measurement systems for solar receiver evaluation in order to have redundant measurement of this magnitude so its validity is ensured.

Achievements in 2006: Project completion. The most relevant results of the MEPSOCON project were:

1) Procedures for calibration of radiometers for high solar irradiance were defined and put into service. To date there had been no established procedures for calibration of these sensors.
2) A systematic error in high solar irradiance measurement was detection and corrected.
3) Development and improvement of a hybrid radiative power measurement system for large surfaces. This system can be adapted to the different needs of the different types of tests. This year, this system was patented in Spain.

It should be mentioned that this year, the Radiometry Laboratory, where many of the activities in the project mentioned above were carried out, was finished.

This laboratory is currently operating and providing the following services to CIEMAT and other Spanish and foreign entities:

Figure 3.19 New radiometry laboratory

Figure 3.20 Calibration of an IR detector in the laboratory.

- Calibration of high solar irradiance radiometers
- Calibration of mid-temperature IR sensors

A black body can be used as a source of thermal radiation for reference and calibration of IR devices (infrared chambers and pyrometers) that use thermal radiation as a means of determining the temperature of a certain surface. It is also used as an irradiance reference for calibration of radiometers.

The Radiometry Laboratory has two reference black bodies. The MIKRON M330 black body can provide any temperature between 300 and 1700ºC with ±0.25% accuracy and a resolution of 1ºC. Its emissivity is 0.99 in a 25-mm-diameter aperture. The MIKRON M305 black body can also provide any temperature between 100 and 1000ºC with the same accuracy and resolution. Its emissivity is 0.995 in a 25-mm-diameter aperture. Both have a PID control system and the temperature is checked by a high-precision platinum thermocouple.

Publications: [3.8][3.9][3.10][3.11][3.12][3.13][3.14][3.15][3.16][3.17]

3.4 Solar Fuels and Solarization of Industrial Processes Group

Production of different energy vectors other than electricity that allow seasonal storage and transport of solar energy, as well as integration in industrial process that must be adapted to integrate the solar share in its most endothermic stages, are emerging activities at the PSA coordinated by the Solar Fuels and Solarization of Industrial Processes Group. In the first case related to solar fuels, thermochemical hydrogen production is without doubt the process where most effort has been concentrated. Recent interest in hydrogen as an energy vector in the transportation industry and the doubtless attractiveness of its clean production using solar energy have made the PSA give special interest to adapting high-temperature solar concentrating technologies to their application to mass production of hydrogen. The activity is covered by two European projects, (INNOHYP and HYDROSOL), a project funded by the PROFIT program (SOLTER-H), a project funded by the research program of the Community of Madrid (PHISICO2) and a project with significant industrial support from Petróleos de Venezuela (SYNPET). These projects are supplemented by participation in two technological network initiatives on the subject, one of them European called SUSHYPRO and the other international, called THESIS, sponsored by the International Partnership for the Hydrogen

Economy (IPHE). The application of the solar concentrating technologies to high-temperature industrial processes is another field of enormous importance, which at the PSA is channeled through the SOLARPRO project.

3.4.1 Hydrogen Production

Like its European, American and Japanese counterparts, the CIEMAT, as a national energy research laboratory, is promoting its own hydrogen technology development program. The weight and goals of the hydrogen production part of this program are impressive. In spite of all the uncertainties and challenges posed by the so-called hydrogen economy, it is evident that public R&D programs are going to give more and more significant support to hydrogen. The main CIEMAT goal in this field is research and development of efficient, competitive hydrogen production methods using authochtonous energy sources, leading to the implantation of the hydrogen economy in Spain, in both transportation and stationary consumption. The PSA is the basic instrument for developing hydrogen production processes using the abundant solar resource available in our country and the excellent knowledge of solar concentrating technologies applicable to reactors operating at temperatures over 1,000ºC. Activity is concentrated in two lines of action (Figure 3.21).

- Development of fossil fuel decarbonization processes and technologies giving them added value by solar gaisification, with special attention to low-quality carbonacious materials.
- Pre-commercial demonstration of the technical and economic feasibility of water-splitting for hydrogen production in thermochemical cycles with concentrated solar energy.

These lines of R&D are complemented by participation in international forums and work groups, feasibility studies and roadmaps such as INNOHYP

Roadmap for thermochemical hydrogen production (INNOHYP Project: Innovative High Temperature Routes for Hydrogen Production)

Participants: CEA (F) coordinator, CIEMAT (E), Empresarios Agrupados (E), ENEA (I), DLR (D), Univ. Sheffield (UK), JRC-Petten (UE), CSIRO (Australia).

Contact: François Le Naour, francois.le-naour@cea.fr

PSA Contact: Manuel Romero, manuel.romero@ciemat.es

Funding: Proyecto cofinanciado por la CE. Presupuesto total: 617 k€. Presupuesto CIEMAT: 55 k€.

Duration: September 1, 2004 – December 31, 2006

Motivation: The accelerated development of the so-called hydrogen economy must unavoidably be through innovative technologies for its mass production without contaminating emissions and at competitive prices. The use of themrochemical cycles that achieve thermal decomposition of the water molecule in consecutive redox stages is extraordinarily attractive, but requires the use of a clean, inexhaustible energy source, such as solar energy. The number of thermochemical cycles analyzed in the literature is enormous, but most of the options have only been studied theoretically or at the most at laboratory scale. The interest in a roadmap is to compile the information available on the various processes and propose joint master lines of action in the European arena.

Purpose: The INNOHYP-CA (Innovative high temperature routes for Hydrogen Production–Coordinated Action) Project is a Concerted Action funded by the European Commission 6th Framework Program, the purpose of which is a review of the state-of-the-art in innovative mass CO_2-emission-free thermochemical hydrogen production [3.22] The project goals are:

- Assess the state of the art in mass high-temperature hydrogen production processes
- Rank these technologies with regard to conventional fossil fuel processes.
- Define the need for research and propose priority activities for a European roadmap
- Create a platform for sharing and coordinating results of research in these processes, in collaboration with the International Partnership of Hydrogen Economy.

Results achieved in 2006: The project began in September 2004 and finished in December 2006, so during this last year, the work program was completed and the final report was sent into the European Commission. The results of the project have been presented at a Seminar for diffusion that took place in Brussels on November 29' 2006. The state-of-the-art review offers a selection of promising processes, grouped in three categories (Figure 3.22): Decarbonization transition processes, first-generation and alternative or second generation, water-splitting processes. The roadmap includes development of pilot plants for transition processes by 2015 using solar methane reforming technologies, solar gasification of carbonaceous materials and carbothermal reduction of zinc oxide. During the same period, lab-scale development would be carried out in order to undertake pilot plants from 2015 to 2020 for SI, Westinghouse, mixed Ferrite and high-temperature electrolysis water splitting technologies. In a third stage, development would culminate in the more technologically demanding alternative cycles, such as the ZnO/Zn cycle or the

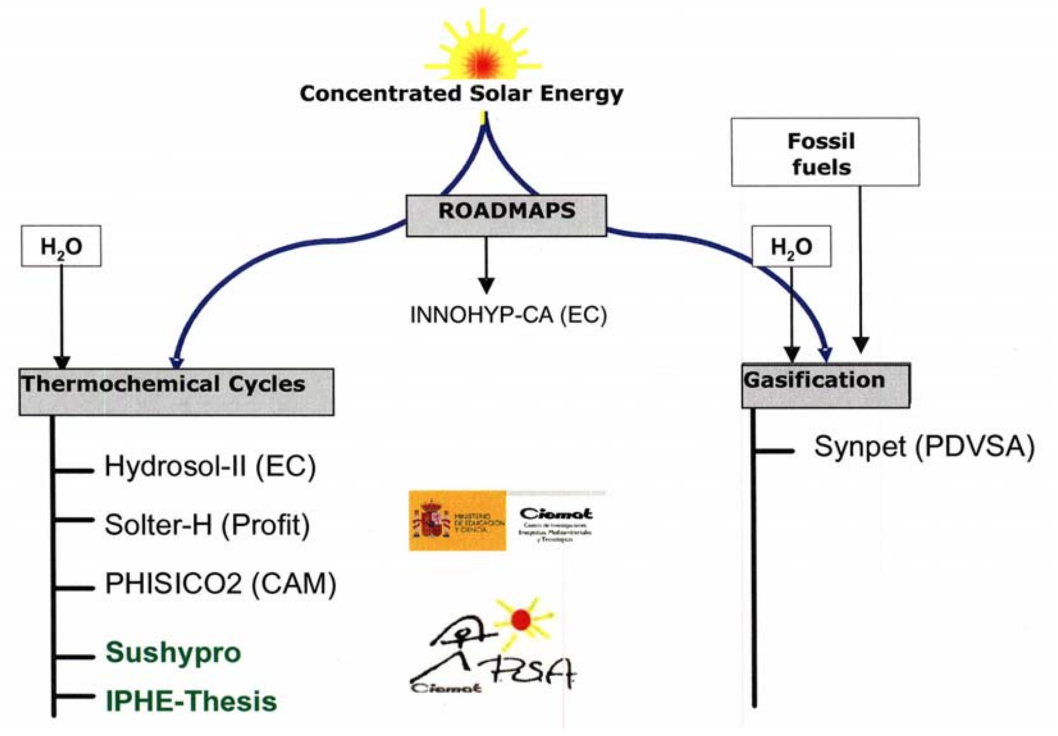
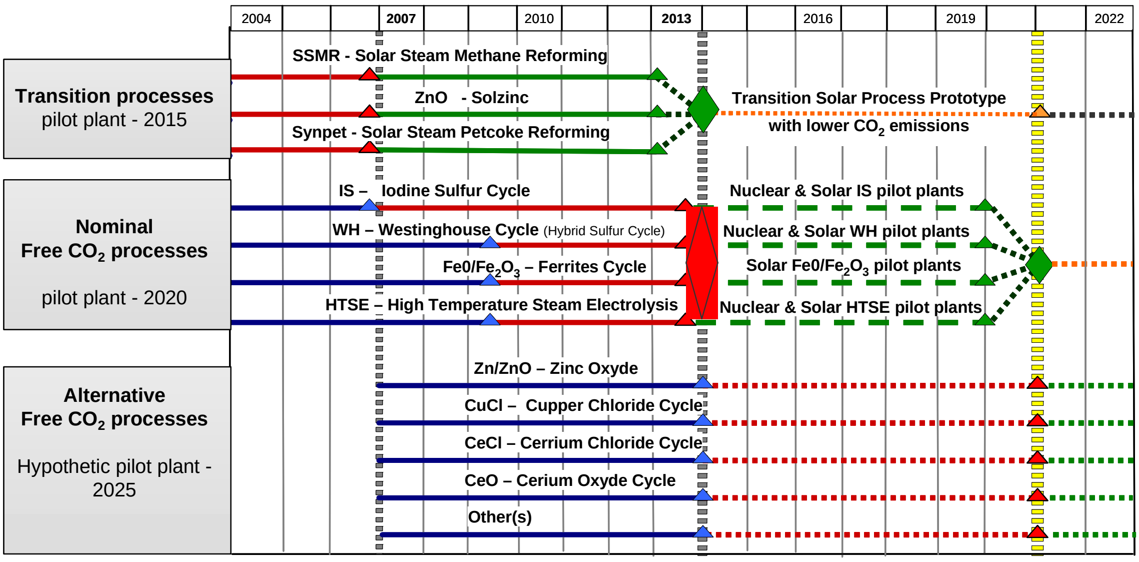


Figure 3.21 Lines of thermochemical hydrogen production activity and projects at the PSA

less known CuCl and Ce Cl, which would hypothetically go into pilot plants around the year 2025. The roadmap incorporates parallel development of horizontal R&D activities in materials, components such as high-temperature heat-exchangers and test benches.

Publication: [3.22]



Source: INNOHYP

Figure 3.22 Main high-temperature thermal hydrogen production processes retained for development for a future hydrogen economy .

Solar petcoke gasification (SYNPET)

Participants: El proyecto de gasificación solar de coque de petróleo es una colaboración entre la empresa Petróleos de Venezuela (PDVSA), el Instituto Tecnológico de Zurich (ETH) y CIEMAT.

Contact: Juan Carlos de Jesús, dejesusjc@pdvsa.com

PSA Contact: Manuel Romero, manuel.romero@ciemat.es

Funding: Project funded by partners majority by PDVSA.
Total budget: $6,950 k. CIEMAT budget: $1.940 k

Duration: September 1, 2002 –de December 31. 2007

Motivation: Solar coal gasification is a pathway of great interest for the transition to the hydrogen economy. In conventional industrial gasification, the energy necessary to heat the reagents and for the reaction is supplied by burning a large amount of raw material, whether by direct internal combustion or indirectly by external combustion. In internal combustion, as applied to autothermal reactors, the product gas is contaminated, while in external combustion, as applied in fluid-bed reactors, the thermal performance is lower due to irreversibilities associated with indirect heat transfer. Alternatively, the advantages of supplying solar energy for the process heat are multiplied by three: 1) the calorific value of the raw material is increased; 2) the product gas is not contaminated by combustion subproducts; and 3) air pollution is avoided. Furthermore, direct irradiation of the reagents provides a very efficient means of heat transfer directly to the chemical reaction where the energy source is needed, avoiding the limitations imposed by heat exchangers.

Solar gasification of coke without combustion can be represented in a simplified by the reaction:

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

Gasification of 1 mol of C requires approximately 1 mol of C as the source of energy supply. That is why substitution of fossil energy by solar energy supply reduces CO_2 emissions by about 50%.

Purpose: The main purpose of the SYPET project is to develop a specific solar gasification process for coke and waste from extra-heavy oil processing in the Faja del Orinoco. The development is specifically finding the thermodynamic and kinetic parameters of associated reactions, and selection of particle sizes and residence times, design of a solar reactor with a quartz window and its scale-up and testing in a 500 kW installation located at the top of the PSA CRS tower.

Results achieved in 2006: After demonstrating the technical feasibility of the process in previous years, in 2006, testing concentrated on selecting the optimum coke particle size to be gasified and testing a method of injecting the material. Finally, it was decided to feed a slurry of coke particles and water. The practical advantages of using a slurry are asociated with eaier transport and injection of the solid reagent and with system scale-up. In 2006, experimental testing was done using a petcoke slurry feedstock. Figure 3.23 shows the effect of particle size and stoichiometry of the slurry on chemical conversion. A higher H_2O/C in the slurry favors reaction kinetics, but at the cost of higher flow rates and lower residence times, resulting in lower conversion rates. The mean conversion achieved was 48% and the maximum was 87%, using particles with diameters of less than 80 µm.

The results have served to complete the design and construct a 500-kW reactor, as well as for preheating system and heat rejection definition. The Synpet-500 facility will be erected and tested at the PSA in 2007.

Publication: [3.23][3.24][3.25][3.26][3.27]

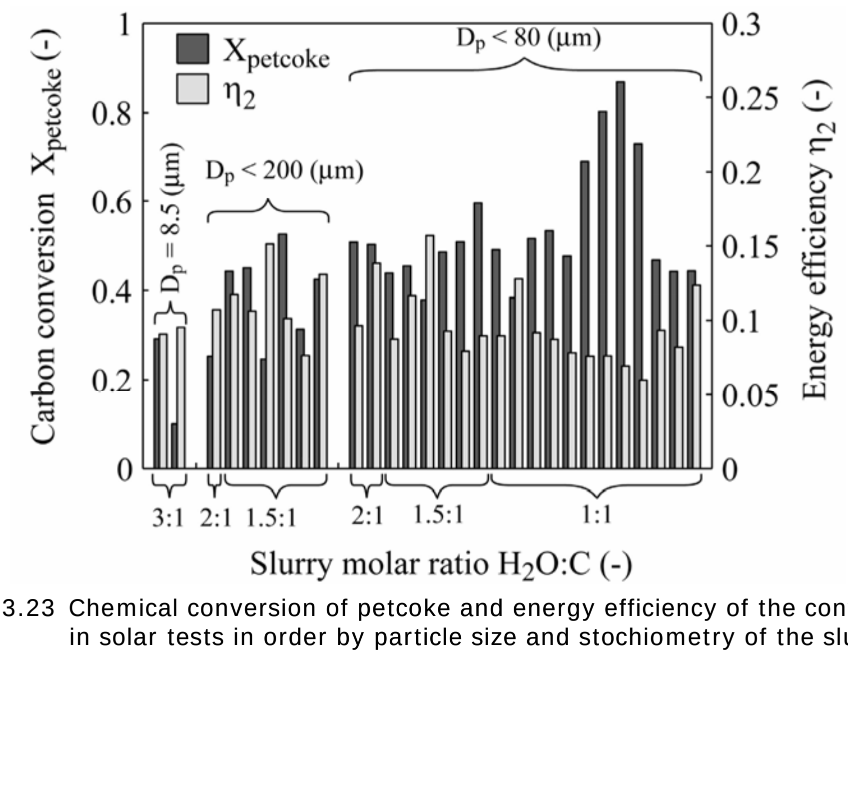


Figure 3.23 Chemical conversion of petcoke and energy efficiency of the conversion in solar tests in order by particle size and stochiometry of the slurry.

Generation of hydrogen from high-temperature solar thermal energy (SolterH Project). PROFIT Project.

Participants: Hynergreen and CIEMAT.

Contact: Cristina Rodríguez; cristina.rodriguez@hynergreen.abengoa.com

PSA Contact: Alfonso Vidal, Alfonso.vidal@ciemat.es

Financiación: Cooperative Project funded by the MEC PROFIT program. Total budget: 987k€. CIEMAT budget not including personnel: 286k€

Duración: January 1, 2004 – December 31, 2008

Motivación: Thermochemical cycles are the processes we believe will be a great mid-term solution for mass clean hydrogen production from solar energy. Electrolysis is the hydrogen production benchmark for water-splitting. With 35% performance in the electric conversion and 70% in the electrolyzer, we would be talking about efficiencies of around 25%. With advanced technologies, this value could hardly surpass 32%. Although the use of nuclear energy is limited in thermochemical processes to around 900ºC, this is not true of solar energy. Solar concentrating technologies make flux of over 5 MW/m^2 and temperatures over 200 K possible at a reasonable cost. This enables other more efficient two-stage thermochemical cycles with metal/oxide redox reactions to be approached. The smaller number of stages is fundamental for solarization of the process and its adaptation to the fluctuation inherent in the solar resource.

Stage 1 (solar): $M_xO_y \rightarrow xM + \frac{y}{2}O_2$

Stage 2 (non-solar): $xM + yH_2O \rightarrow M_xO_y + yH_2$.

The use of mixed oxides (based on iron) makes it possible to lower the temperature considerably, since the hydrogen generating stage is based on artificial creation of gaps in the oxide structure, increasing the avidity for this material. Therefore, the Solter-H Project concentrates on developing technologies based on the use of mixed ferrites as the optimum candidates for thermochemical hydrogen production.

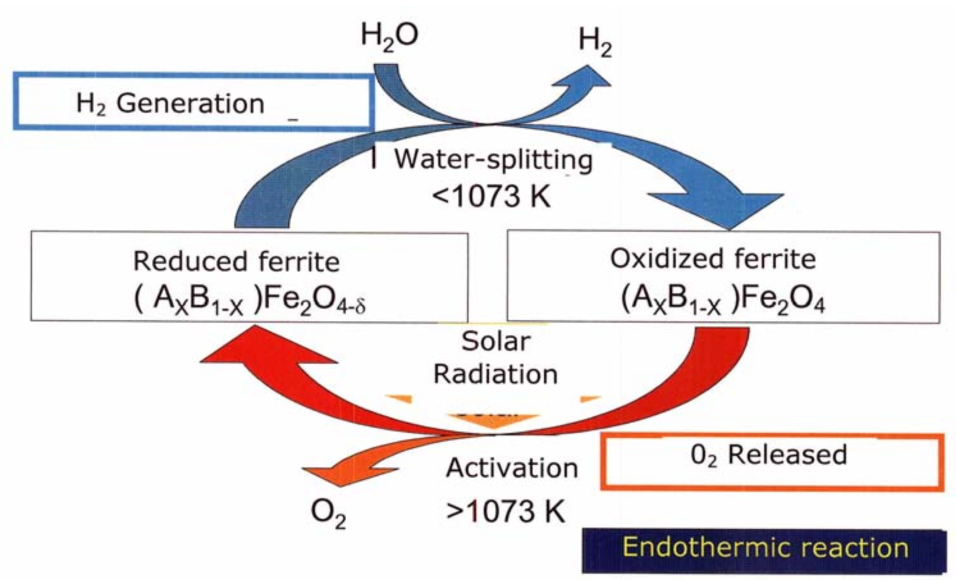


Figure 3.24 Schematic diagram of the ferrite cycle for H_2 production selected in the SOLTER project.

Purpose: The main purpose of the SolterH project is to demonstrate the usefulness of binomial renewable energies – the hydrogen vector, specifically of solar thermal energy, and its use in clean renewable hydrogen production by appropriate use of an unlimited, abundant resource such as the sun. The final purpose of this project is the design, development and evaluation of a high-temperature solar thermal hydrogen generation system, with an important milestone at the end of the project in the testing of a 5 kW reactor in the PSA solar furnace. During the first stage of the project in 2004-2005, different possibilities of meeting technical and economic criteria were studied, evaluating the advantages and disadvangates of each. We could summarize by saying that the SOLTER-H Stage I clearly demonstrated the use of simple cycles at high operating temperatures that allow variations in the energy supply without undergoing any significant decrease in efficiency as good candidates for our needs. The mixed oxides (ferrite) cycle has all of the qualities for being an ideal cycle, that is, simplicity and relatively high temperatures, although it had the disadvantage of a lack of reliable operating data.

Results achieved in 2006: In the second stage of the project, commissioning of the experimental device was begun and the first tests with synthesized materials were done by the CSIC Instituto de Catálisis y Petroleoquímica through a supply contract. These activities consisted of preparing and synthesizing ferrites, the design of a particle injection system and reactor characterization. Batch mode testing has demonstrated H_2 production using these materials for the first time in our laboratories. The batch tests did not allow us to come to a clear conclusion concerning the technical feasibility of this process, since tests could not be performed under the best conditions. At the present time, work is underway to incorporate a particle reactor for the next tests that will calibrate process feasibility better.

Clean Hydrogen Production: CO_2-free Alternatives (PHISICO2 Project)

Participants: Universidad Rey Juan Carlos, CSIC, INTA, REPSOL, HYNERGREEN y CIEMAT.

Contact: David Serrano; david.serrano@urjc.es

PSA Contact: Manuel Romero, manuel.romero@ciemat.es

Funding: Cooperative Project fianced by the 4th PRICIT-Regional Science and Technology Plan of the Community of Madrid. Total budget: 1,000k€. CIEMAT budget not including personnel: 240k€

Duration: January 1, 2006 – December 31, 2009

Motivación: Coordinate and make available to all involved, the research efforts and capabilities of groups from different institutions (URJC, CSIC, CIEMAT, and INTA) in the study and development of different clean hydrogen production processes, that is, CO_2-emission-free, using renewable energies as the primary energy source for its generation. Two companies in the energy sector (REPSOL YPF and HYNERGREEN) have shown their intereste in monitoring the results and participate actively in the project. It is worth mentioning that CIEMAT participation in this project is not only through the group at the PSA, but also by the Chemistry Division and the Fusion Materials Laboratory Unit. Hydrogen production processes included in this project are photo-electrolysis of water, thermochemical cycles and decarbonization of natural gas. In addition to contributing to the scientific-technical development of these alternatives, this project is intended to evaluate their mid-to-long-term technological and economic feasibility and their ability to reduce CO_2 emissions from more conventional hydrogen production systems, such as gasification and steam reforming.

Purpose: The basic purpose of the project is to study clean hydrogen production processes in order to advance in the solution of its current technological and economic limitations key to being able to carry out a future transition to the hydrogen economy. The alternatives included in this project are characterized by avoiding formation of CO_2 as a coproduct of hydrogen and using renewable resources to provide the energy consumed in the formation and release of hydrogen.

1. Hydrogen production from water by photodecomposition
2. Hydrogen production from water by solar thermochemical cycles
3. Hydrogen production from natural gas by catalytic decarbonization
4. Comparative analysis of the above possibilities

Results achieved in 2006: Although CIEMAT participates in several of the subprojects, its main dedication is to Subproject 2, related to thermochemical hydrogen production. CIEMAT activity in PHISICO2 is largely complemented by activities and developments in the Solter-H project. In 2006, the scientific effort concentrated on the synthesis, physical-chemical characterization and thermogravimetric testing of mixed transition-metal oxides to identify their efficiency in hydrogen production, especially at optimum process temperatures in order to select the most suitable for solarization. Work was also done on assembly of a laboratory test bench. Synthesis, physical-chemical characterization and thermal reduction of $Mn_xNi_{1-x}Fe_2O_{4-\delta}$ in a thermobalance, were also done by varying Ni/Mn between 0 and 3. Wet synthesis Ni, Fe and Mn nitrates was performed by the Pechini method from. In all cases, thermogravimetric tests were made with different heating ramps using nitrogen, helium or air as the carrier gas. Air would be best from the point of view of industrial scale-up, since it would avoid the use of an inert gas with the resulting cost

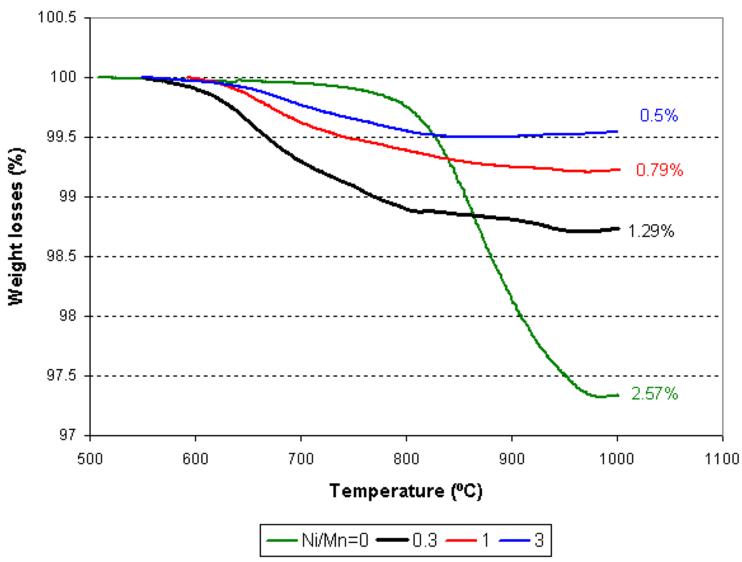


Figure 3.25 Activation stage weight loss testing done in the thermogravimetric balance, with weightloss over temperature for mixed ferrite $Ni_xMn_{1-x}Fe_2O_4$ samples (with nitrogen carrier and heat ramp of 20ºC/min)

reduction in hydrogen generation, because the oxygen separation stage for reuse of the inert gas would then not be necessary. The final goal is for the process temperature in the activation stage to be no higher than 1200 K, as the radiation loss increases with temperature by a power of four. TGA/DTA have shown that using nitrogen as the gas carrier, weight loss in the ferrites can be clearly attributed to partial reduction of magnetite. Weight loss and activation temperature increase when the Ni/Mn ratio decreases, being 0.5% to 700ºC and 2.57% at 900ºC for Ni/Mn=3 and 0, respectively Figure 3.25. Although in 2006, hydrolysis testing with hydrogen production has still not been done, the results found in the activation stage (oxygen desorption) have been very promising, with theoretical estimates leading to expect hydrogen production of around 1 to 3 mg H_2/g ferrite in the water-splitting reaction.

Publication: [3.28]

Solar Hydrogen via Water Splitting in Advanced Monolithic Reactors for Future Solar Power Plants (Hydrosol-II).

Participants: APTL (GR), DLR (D), CIEMAT (E), STC (DK), Johnson Matthey (RU).

Contact: Christos Agrafiotis; chrisagr@cperi.certh.gr

PSA Contact: Maria Jesús Marcos, mj.marcos@ciemat.es

Funding: Cooperative project funded by the EC 6th Framework Programme. Total budget: 4,230 k€. CIEMAT Budget: 647 k€.

Duration: December 1, 2005 – December 1, 2009

Motivation: Solar Thermochemical hydrogen production faces the great challenge of accomplishing solar concentrating technology and reactor scale-up to be able to operate at several MW power. Undoubtedly, this will be the central receiver technology, or the heliostat field with tower, which is the only one that can be adapted for this use. At the present time, there are developments, many of them tested jointly by the DLR and the CIEMAT at the PSA facilities, which allow volumetric receivers to operate at temperatures above 1000ºC. The motivation for the Hydrosol-II project is the confidence in being able to transfer the experience accumulated in materials development and systems with catalytic matrices using SiC with monolithic channels that were validated successfully during the SOLAIR project. The impregnation of these ceramic matrices with mixed ferrites will make it possible to use the volumetric of receiver/reactor concept for hydrogen production. The possibility of using this monolithic reactor with ferrites attached to a substrate greatly facilitates separation of oxygen from the hydrogen by using alternating charge and discharge stages.

Purpose: The second phase of this project (Hydrosol-II) began in November 2005, and its purpose is demonstration in a 100 kW reactor at the Plataforma Solar de Almería of H_2 production from mixed Zn ferrites impregnated on SiC ceramic matrices. The innovation in this design is the use of an intermittent charge-discharge operating mode. The endothermal stage is performed with solar illumination so the high-flux solar radiation in the focus generated by a heliostat field is moved alternately from some matrixes to others to allow the H_2 to be charged.

The quantitative project goals are:

Solar Reactor / Receptor Operating Goals	
Water-splitting temperature	800-900 °C
Regeneration stage temperature	≤ 1200 °C
Water-to-hydrogen conversion	≥ 90 %
Number of operating cycles	≥ 50
Hydrogen/regeneration production stages	Simultaneous in twin reactors
Mid-to-long-range goals	
Solar hydrogen production cost in 2006	≤ 12 cents/kWh
Solar hydrogen production cost in 2020	≤ 6 cents/kWh

Results achieved in 2006: In 2006, the CIEMAT concentrated mainly on defining the pilot plant, which is to be installed in the PSA CRS-SSPS tower on the 32-m level platform, where the dual reactor system, and peripheral measurement and control systems will be located. The housing designed for the system and a support structure for the test bench, as well as selection of supply lines, wiring, auxiliary gases and steam generator. One of the most important tasks has been defining a heliostat-field aiming strategy for simultaneous operation of loading and discharging reactors. After analysis and simulation with FiatLux, it was found that it is possible to select CRS field strategies that reproduce all of the flux and power conditions necessary for the regeneration, water-splitting and reactor heating stages, which are:

	FLUX	*TOTAL POWER*
REGENERATION	**360 kW/m²**	**70 kW**
WATER-SPLITTING	**110 kW/m²**	**20 kW**
HEATING	**500 kW/m²**	**100 kW**

The test bench includes a dual system with two reactors as shown in Figure 6. In order to achieve the regenerating and water-splitting conditions simultaneously, it was necessary to optimize the separation between the two apertures. The most unfavorable conditions are when one of the reactors is heating (500 kW/m^2) and the other is splitting water (110 kW/m^2). It has been determined that a separation of 1.3 m is enough to keep the two reactors working independently.

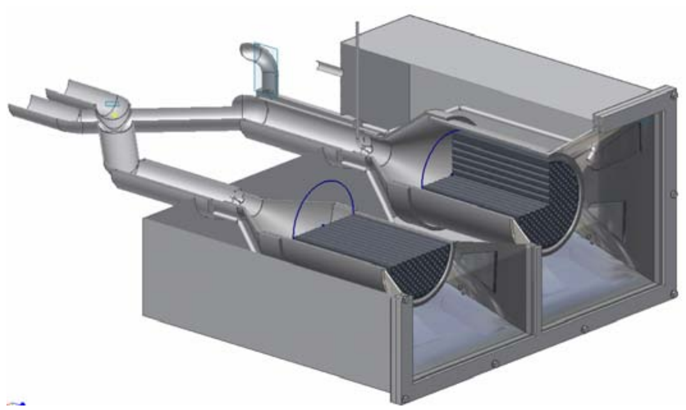


Figure 3.26 Detail of the housing device for the activation and hydrolysis reactors used in Hydrosol-II

3.4.2 SolarPRO

Materials surface treatment and sintering. Development of a concentrated solar radiation heat supply system; testing and characterization of its application to various high-temperature production processes and waste elimination.

Participants: CIEMAT, Univ. Sevilla, Instituto de Tecnología Cerámica, Polytechnic Univ. Cataluña

Contact: Diego Martínez; diego.martinez@psa.es

Funding: Ministry of Science and Technology National R&D Plan (2003-2006). Total budget: 370.6 k€. CIEMAT Budget 176.6 k€.

Duration: November 15, 2003 – November 14, 2006

Motivación: Solar thermal energy is the renewable energy which, because of its characteristics, must take on a relevant role in industry, as it provides, either directly or through transfer to a fluid or absorber material, the thermal energy necessary for many industrial processes, and can supply solar process heat at different temperatures.

The industrial processes that usually require the largest energy share are those that take place at high temperatures. For the future implantation of the solar thermal concentrating technology in high-temperature industrial processes, a strong boost for research is required and for each particular process, its technological feasibilitiy must be demonstrated, adapting the design and production parameters.

Purpose: The purpose of SolarPRO is to demonstrate the technological feasibility of using solar thermal energy as the energy source in high-temperature industrial processes. The processes studied in this project are classified in two basic groups:

- Industrial production processes
- Waste treatment processes

The first such processes selected are the following:

Table 3.1 First processes selected

Ceramic industy processes		
Drying of raw pieces	100ºC < T <200ºC	Drying chamber with volumetric receiver
Third firing for certain types of decoration	800ºC < T <900ºC	
Baking of ceramic tiles	850ºC < T <1150ºC	Baking chamber with volumetric receiver
Powder metallurgy processes		
Metal sintering	T~ 1000ºC	Controlled atmosphere chamber
Waste treatment processes		
Elimination of heavy metals from contaminated soils	T< 630ºC	Solar rotary furnace

Results achieved in 2006: During this project, three different innovative reactors were designed, developed and constructed simultaneously using different technologies, as well as prototypes and test devices for specific applications. At the same time, data acquisition and control programs were developed and

Figure 3.27 Fluidized bed reactor in operation in the PSA Solar Furnace

facilities were improved, reactors were put into operation and characterized, and each of the different processes studied in 'SolarPRO' was tested.

The current status of the different processes is:

- Ceramic processes: a processing plant with an open volumetric receiver was developed for drying and baking ceramic tiles, complete drying cycles were performed on ceramic tiles and tiles were baked at mid-temperature (850ºC), with higher temperature cycles, and 'third firing' tests expected to be undertaken shortly.
- Waste treatment: preliminary testing for thermal desorption of contaminated soils in the fluidized bed reactor, which provides homogeneous sample treatment. In 2007, new tests were carried out in the solar rotary furnace.
- Powder metallurgy treatments: metals were sintered in a controlled atmosphere using a fluidized bed reactor (acquired with ERDF funding awarded at the same time as this program and jointly designed with the CENIM). Due to the characteristics with which it was designed, it is possible to work inside the solar fluidized bed reactor in a controlled atmosphere, using concentrated solzr energy. This made it possible to use it without fluidizing as a controlled atmosphere chamber, in which process heat over 800ºC was achieved in air and various gases, applicable to thermal treatments such as sintering.

Therefore, SolarPRO has made it possible to:

- Demonstrate the technological feasibility of using solar termal energy as the energy suplí in different high-temperature industrial processes.
- Identify possible new processes that can use the solar energy supply.
- Acquire experience and sufficient know-how to undertake a second preindustrial-scale phase of the project.

Furthermore, two collaboration agreements related to this project were signed with two different institutions for the development of new processes and reactors for materials treatment by concentrated solar energy:

- Specific collaboration agreement between the Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT) and the Centro Nacional de Investigaciones Metalúrgicas (CENIM), called "Thermal treatment of metals by concentrated solar energy and characterization of solar concentrators" (2006-2008).
- Specific collaboration agreement between the Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT) and the Polytechnic University of Madrid, called "Feasibility study on the use of solar concentrated radiation to make aluminum foam" (2005-2007).

Publicación: [3.29][3.30][3.31]

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4 Environmental Applications of Solar Energy and Evaluation of the Solar Resource Unit

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4.1 Introduction

2006 was an important year of consolidation for the Environmental Applications of Solar Energy and Evaluation of the Solar Resource Unit, which has been gradually but continuously enlarged in recent years, and its activity now encompasses the following lines of research:

- Solar water detoxification and disinfection
- Solar gas detoxificación
- Solar seawater desalination
- Characterization and measurement of solar radiation

In 2006, the Unit signed and negotiated and actively participates in 7 new European contracts and one national project, *Consolider*. Two of these projects are also coordinated by the Unit. This has also meant a considerable increase in the Unit's staff, especially the number of Ph.D. research students. As of December 31, 2006, there was a staff of 23 people as follows: 6 permanent researchers, 6 contract researchers, 7 Ph.D. research students (3 of them not Spanish) and 4 laboratory technicians. From a budgetary point of view of, the Unit's income has increased slightly above the average of previous years.

The setting for this continual increase in activity is one of growing interest of institutions, research programs and a multitude of businesses, for solar energy water applications, specifically, and environmental applications in general.

This interest is clearly justified by the conviction of many of the gravity of local, Spanish and worldwide water problems. Given the equally important issue of energy and the need to evolve toward sustainable non-oil energy models, the clear conclusion arrived as is that tomorrow's water problems (all signs point to their being much more severe than they are now), are not going to be solved with today's energy. Since, furthermore, in those places where these problems are the most critical, there is usually a good level of solar irradiation, the development of innovative technologies is something that is not only already appropriate, but absolutely indispensable. The development of this type of technologies is the Unit's basic goal.

The main activities carried out in 2006 in each of the various groups and lines of research, and the technological development mentioned above are described below.

4.2 Water Detoxification and Disinfection Group

Recent concern for pollution and other environmental matters have led to a search for new and more efficient methods for eliminating water pollution. Among them, the use of solar radiation as a resource for developing physical and chemical processes appears today to be a promising treatment method for toxic pollution and water disinfection.

2006 has been an especially relevant year for the "Water Detoxification and Disinfection" Group, as it has meant significant consolidation of the activities that have been ongoing for 15 years. This was confirmed by the start up in 2006 of four European projects (European Commission 6th Framework Programme), and another three National R&D Program projects, in addition to the National Plan for Access, which due to its scientific and economic importance could be considered to have the relative weight equivalent to various national projects. It is worth mentioning that among these, one of them pertains to the Ingenio 2010 Program (CONSOLIDER), MEC project of excellence offered for the first time in 2006 and only 15 of which have been awarded to science in all of Spain. The group is involved in the only CONSOLIDER project devoted to water treatment. Details on each of them are given in the following pages.

It should be mentioned that this is the most activity (and most demanding) in the history of the group. Scientific production in 2006 can be summarized as follows: 2 Ph.D. dissertations defended (supervised by members of the group), 4 Ph.D. dissertations underway, 12 articles in journals in the impact index (22 more accepted or in review) and 29 communications at 9 international congresses (12 of them oral or invited). This is expected to increase in the next few years as a result of all the projects that are beginning now.

4.2.1 FOTODETOX

Elimination of persistent pollutants by advanced oxidation.
http://www.psa.es/webesp/projects/fotodetox/index.html

Participants: Univ. of Almería Dept. of Chemical Engineering; Polytechnic Univ. of Valencia Dept. of. Textile Engineering; CIEMAT-PSA (coordinator).

Contact: Dr. S. Malato, sixto.malato@psa.es

Funding: National RD&I Plan, MEC. CIEMAT budget: 80 K€ + 1 FPI Ph.D. Fellowship.

Duration: December 2003 – December 2006

Motivation: Treatment of water containing pesticides by combined biological and photocatalytic treatment.

Purposes:

1) Pilot-plant solar photocatalytic (photo-Fenton and TiO2) treatment of water containing pesticides. Find optimum operating parameters.
2) Study of biodegradability using monospecific bacteria cultures (selected from among those commonly used in WTPs) in pesticide-polluted water partly treated by photocatalysis. Evaluation of the bacteria strains that are the most active in biodegrading pollutants.
3) Development of predictive models for biodegradability of water partly treated by photocatalysis.
4) Study of the biodegradability (using real activated sludge from WTPs) of pesticide-polluted water partly treated by photocatalysis.
5) Development of a bioreactor specially adapted to this kind of water partly treated by photocatalysis.
6) Predesign of a solar photocatalytic water treatment plant for pretreating water containing persistent pollutants and make them compatible with municipal WTP input requirements.

Objectives achieved in 2006:

The objectives set for 2004 and 2005 were met (see PSA Annual Reports 2004 and 2005), and during 2006, work was mainly related to Objectives 4, 5 and 6.

Biological processes are among the simplest and economical treatment techniques available, and it therefore makes good sense to combine them with photo-Fenton, since the degradation of non-biodegradable pollutants is normally coupled with both reduced toxicity and increased biodegradability. Our proposal is a combination of quick analysis techniques (COD, TOC, toxicity) that would assist in making a decision as to which parameters to use for estimating or measuring the biodegradability of water. Once the plant is in continuous operation, just one of the above parameters might even be enough for an experienced operator to make this decision.

Below we propose a working methodology for fast techniques to predict when water is biodegradable. One of these parameters is called "Average Oxidation State" (AOS), which can be calculated by the following equation, where TOC (Total Organic Carbon and COD (Chemical Oxygen Demand) are expressed in moles of C L^{-1} and O_2 L^{-1}, respectively.

$$AOS = 4x\left(\frac{COT - DQO}{COT}\right)$$

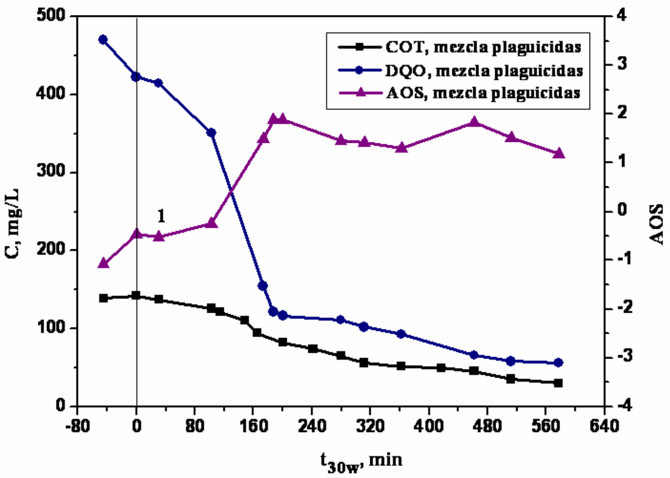


Figure 4.1 Degradation of a pesticide mixture (50 mg/L each) by foto-Fenton at 20 mg/L Fe2+

The AOS varies with treatment time and indicates the degree of oxidation of the organic compounds in the water. When applied to Advanced Oxidation Processes, it can be used to determine the best moment for transfer to a biological treatment. Figure 4.1 shows that after a first period in which the AOS grows quickly, it reaches a stage at which it slows down considerably, suggesting that the chemistry of the intermediate compounds generated does not vary significantly. Therefore, biodegradability must be reached before or at precisely the moment when the AOS stabilizes.

Obviously, the above conclusions, [see 4.14, 4.21, 4.27] are insufficient to ensure the biodegradability of water pretreated by solar processes. Specific methodologies must be applied to evaluate the real biodegradability. But as these are slow (days or weeks), it is a good idea to select the samples for their application from toxicity, COC and TOC data, which are the fastest measures (minutes or hours) using the above-mentioned strategy. The methodology developed in the project has been followed to evaluate two different types of water (one industrial and the other containing pesticides on the EU "Priority Substances" List) with results that validate its use [4.26, 4.33]. From the overall analysis of results, the predesign of a solar photocatalytic (photo-Fenton) water treatment plant has been undertaken, to treat water containing persistent pollutants and make it compatible with bioreactor inlet requirements. In this case two alternatives are proposed. On one hand, discharge into a WTP, or else hook up the photoreactor to a biological reactor in series. Figure 4.2 shows the second of these options This other option would discharge the output effluent from the neutralization tank into a WTP.

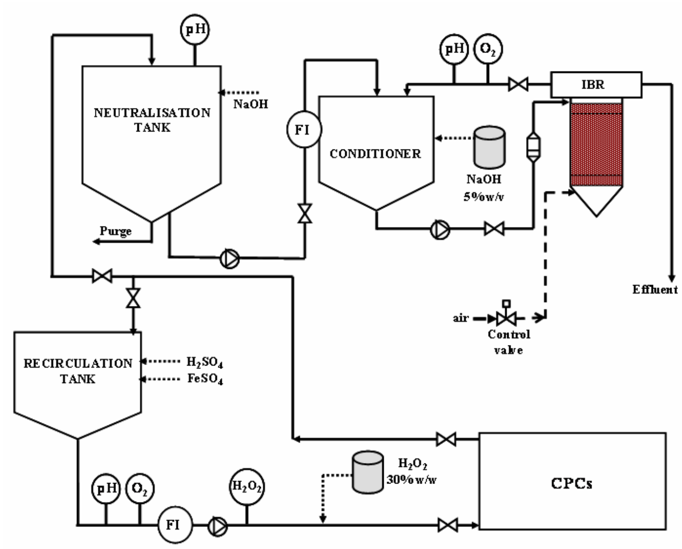


Figure 4.2 Conceptual design of photo-Fenton (solar radiation using CPC-type collectors) treatment of toxic and/or persistent waste water hooked up to biological treatment in a fixed-bed reactor

4.2.2 CADOX

A coupled advanced oxidation-biological process for recycling of industrial wastewater containing persistent organic contaminants

http://www.psa.es/webeng/projects/cadox/index.html

Participants:	CIEMAT-PSA (Coord., E). Ecosystem S.A. (E), AUSOL Lda (P)., Univ. Autònoma de Barcelona (E), INETI (P), Trailigaz Compagnie Générale de l'Ozone (F), Janssen Pharmaceutica N.V. (B). EPFL (CH), DSM Deretil S.A. (E).
Contact:	Dr. S. Malato, sixto.malato@psa.es
Funding:	EC (Energy, Environment and Sustainable Development Programme); 1,200 k€ (+ 260 k€ of Switzerland).
Duration:	February 2003 – July 2006

Motivation: One of the most alarming problems plaguing water resources is the accumulation of hard-to-degrade anthropogenic compounds, because there are no adequate techniques for treating chronic or severely toxic substances. The inability of traditional biological methods to do so makes new treatment systems necessary. Ever-stricter pollution control legislation has intensified the search for solutions in the field of water treatment technologies.

In this context, it has been demonstrated that partial oxidation of these harmful substances by AOPs (Advanced Oxidation Processes) can appreciably increase the biodegradability of water containing them. But in spite of this, the cost of such treatments continues to be expensive (tens of €/m^3). The use of AOPs as a pretreatment for biological treatment, which is usually much cheaper, may be an attractive option. In the same sense, the AOPs that can be carried out by a cheap renewable energy source (the Sun) can also contribute to solving the problem.

Purposes: The CADOX project, which ended in July 2006, was framed in this EU water treatment context. Practically all of the goals set at the beginning of the Project were achieved (see PSA Annual Report 2003).

Figure 4.3 General view of the demonstration plant installed during the CADOX project at the DSM-Deretil facilities in Villaricos, Almería.

Objectives achieved in 2006: The project's main achievements may be summarized as follows:

- TiO_2 photocatalysis and the photo-Fenton process (AOPs) are two treatment methods suitable for decontaminating water containing soluble pesticides. They also substantially improve biodegradability.
- The photo-Fenton process is suitable for decontaminating water containing chlorinated solvents (such as dichloroethane, dichloromethane and chloroform) which are not adequately treated by TiO_2 or ozone (other treatment methods tested during the CADOX project). Furthermore, at no time is biodegradability improved by AOPs, and treatment must continue until complete elimination.
- New solar collectors with larger-diameter absorber tubes have been developed for photocatalysis, allowing the amount of catalyst necessary to be reduced.
- The technology developed in the CADOX Project can be adapted to very different types of nonbiodegradable waste water, but always with prior specific studies in each case.
- A combined ozonization, photo-Fenton and biotreatment demonstration plant was designed, erected and tested. The combination of the different processes was demonstrated and a detailed economic study was carried out.
- The total cost (including investment, operation, etc.) per m^3 treated effluents containing 1 kg/m^3 (approx. 2.0 g COD/L) of resistant compounds is around 7€/m^3. The cost for water containing smaller organic loads would be significantly lower.
- The results of a Life Cycle Analysis (LCA) show the best results for solar photo-Fenton. The results of comparison with traditional technologies like adsorption in activated carbon are clearly more favorable for the solar technology.
- The process developed can be applied not only to water containing pesticides (phosphorated, chlorinated, carbamates, etc.), but also phenols and chlorophenols, chlorinated solvents, aromatic and polyaromatic hydrocarbons, biocides, dyes, etc.

4.2.3 PhotoNanoTech

Nanoparticle Photozyme Applications for Water Purification, Textile Finishing, Photodynamic Biomineralization and Biomaterials Coating

Participants: Sofia University (coord., BLG), Bulgaria; CIEMAT-PSA (ES), Politec. Univ. Cataluña (E), Univ. Minho (P), Univ. Kaiserslautern (D), Univ. Torino (I), Specialni polimeri Ltd. (BLG), Tinfer (E), Colorcenter (E), Tecnologie Biomediche (I), Inotex spol s r.o. (Rep. CH) y Perca Ltd. (BLG).

Contact: Dr. S. Malato, sixto.malato@psa.es

Funding: EC, 6th FP. Nano-biotechnologies: Using nature as model for new nantotechnology-based processes; 1,720 k€. CIEMAT Budget: 350 K€.

Duration: Pending contract signature

Motivation: This project plans such interesting innovations as materials coatings for use in medicine to enable compatibility with cells and tissues by the addition of specific photozymes to minimize rejection, modify tissues by adding specific photozymes to imitate the behavior of chlorophyll in plants (selective adsorption of photons of certain solar spectrum wavelengths) to improve whiteness, brightness, color and tone, modify tissues to enable self-cleaning exclusively by exposure to solar radiation, take advantage of the antenna effect for decontamination and disinfection of water and, above all, of soils, and materials that favor photodynamic biomineralization to improve regeneration of bones and even bone implants.

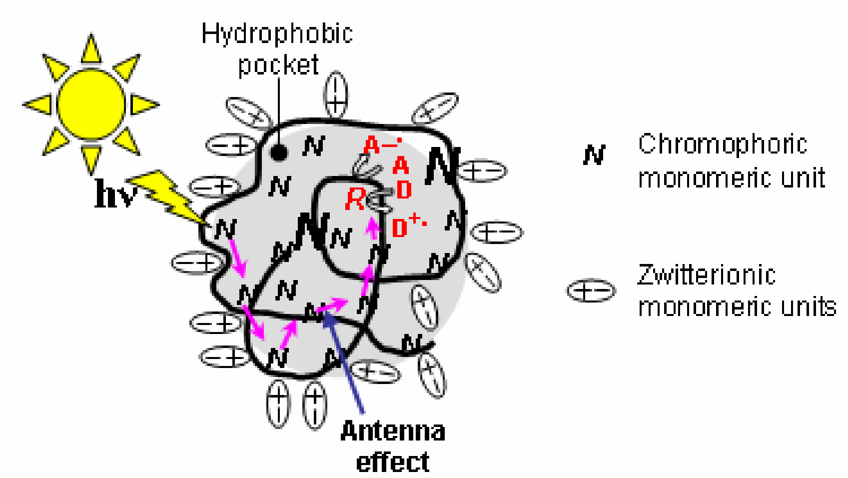


Figure 4.4 Conceptual illustration of light capture and formation of singlet oxygen in photozyme nanomicels (R is a unit of anthracene acting as a reactive center)

Purposes: The PhotoNanoTEch project is intended to develop new "photozymes", amphiphilic copolymers containing comonomers with chromophorous groups) using zwitterionic comonomers, and demonstrate their potential for innovation in the following applications: (i) solar photocatalytic treatment and disinfection of polluted water; (ii) treatment of whiteners in the textile industry; (iii) development of biomineralization processes and (iv) development of new biomedical coating materials with no inflammatory response. The last three photozyme applications are completely innovative and have not been explored up to now.

Objectives achieved in 2006: The work in the project has not yet begun since it was evaluated and approved by the European Commission 6th Framework Program in 2006 under its thematic priority "Nanotechnologies and Nanosciences, knowledge-based multifunctional materials, and new production processes and devices".

4.2.4 INNOWATECH

Innovative and integrated technologies for the treatment of industrial wastewater. http://www.innowatech.org

Participants: CNR - Istituto di Ricerca Sulle Acque (I), Aachen Univ. Technol. (D), Tech. Univ. Delft (NL), Swedish Env. Res. Inst. Ltd (S), Cranfield Univ. (UK), Swiss Fed. Inst. Tech. (CH), CIEMAT-PSA (E), Norw. Inst. Wat. Res. (N), SolSep BV (NL), Bayer Material-Science AG (D), ITT Wedeco (D), Austep S.r.l. (I), Albaida S.A. (ES), AnoxKaldnes (S), Water Innovate Ltd (UK), DHV (NL), Adv. Wastewater Manag. Centre (Aus).

Contact: Dr. W. Gernjak, wolfgang.gernjak@psa.es
Dr. Antonio López, antonio.lopez@ba.irsa.cnr.it

Funding: 6th FP. Global Change and Ecosystems.; 2.750 k€. CIEMAT Budget: 350 K€.
Duration: November 2006 – October 2009

Motivation: Granulated aerobic biomass, combination of advanced oxidation processes and biological treatment and integration of membrane processes are all considered high-potential innovations for development of industrial process wastewater treatment. These technologies will be applied to different industrial effluents (lixiviates, pharmaceuticals, pesticides, paper industry, etc.).

Purposes: (i) Study and increase the performance of promising options for industrial wastewater treatment, such as, e.g., aerobic granulation, membrane contactors and chemical membrane reactors. (ii) Advance in both fundamental knowledge and technology. (iii) Evaluate economic and ecological sustainability of these technology options. (iv) Develop integrated solutions tailored to the requirements of the final user, valid in different industrial sectors and favoring their implementation to increase competitiveness in the EU water industry. (v) Transfer the knowledge developed to potentially interested final users inside and outside the scope of the project.

Project organization is shown in Figure 4.5. The scientific research and technological development tasks are concentrated in Work Packages WP1, WP2 and WP3. These work packages are complemented by life-cycle and lifetime cost analyses, the results of which should be solutions designed for concrete cases of waste water in different sectors of industry. This work will be done in Work Package WP4. Two additional work packages (WP5 and WP6) complete the project. The CIEMAT-PSA is the coordinator of WP2. The research task of the CIEMAT-PSA concentrates on widening the existing knowledge on combining the solar photo-Fenton process with biological treatments. It is intended for treatment of waste water severely polluted by pesticides, formulation agents and industrial pharmaceutical waste, increasing knowledge of how the structure of the pollutant affects the evolution of severe toxicity

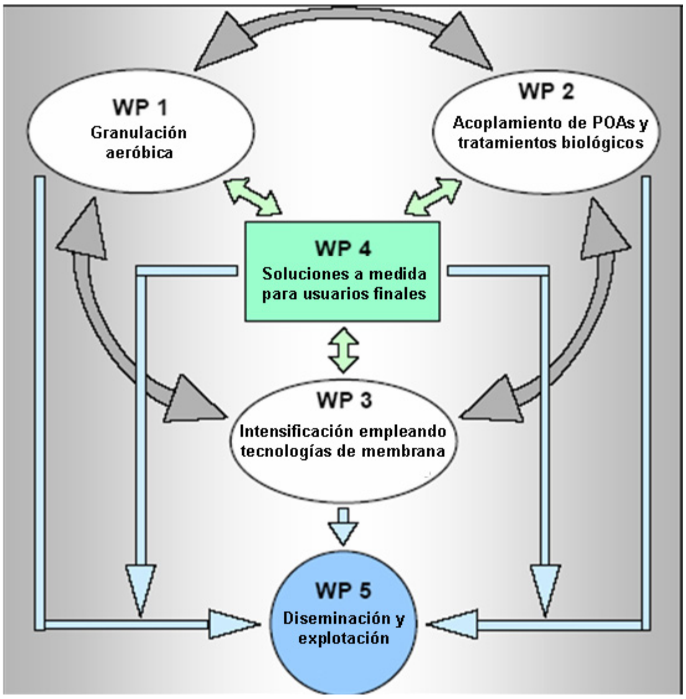


Figure 4.5 INNOWATECH project structure

and biodegradability of the effluent, new automation methods and process control, and evaluating the influence of effluent salinity.

Objectives achieved in 2006: The project began in November 2006, and has not yet generated relevant results.

4.2.5 SODISWATER

Solar disinfection of drinking water for developing countries or emergency situations. http://www.rcsi.ie/sodis/

Participants: RCSI (Coord., IR), UU (UK), CSIR (S. Africa), EAWAG (CH), IWSD (Zimb.), CIEMAT-PSA (ES), UI (UK), ICROSS (Kenya), USC (E).

Contact: Dr. Kevin McGuigan, kmcguigan@rcsi.ie
Dr. Pilar Fernández-Ibáñez, pilar.fernandez@psa.es

Funding: EC, 6th FP. Specific measures in support of international co-operation "INCO". 1,900 k€. CIEMAT Budget: 350 K€.

Duration: September 2006 – August 2009

Motivation: The main purpose of this Project is to demonstrate that the SODIS technology ("Solar Disinfection) for solar-only disinfection of drinking water is an effective tool against diseases communicated by domestic water (in developing countries) and as an aid in natural disasters. Solar disinfection is a water depollution technique that commonly uses transparent plastic bottles full of water exposed to direct solar radiation for 6-8 hours. This process reduces the levels of fecal contamination of 1 million bacteria per ml to zero in less than 1.5 hours and is completely effective in treatment of pathogens responsible for such diseases as cholera, dysentery, typhus, giardiasis, salmonellosis, gastroenteritis and poliomyelitis. The only clinical test to date for this technology, carried out in a community in Kenya, has demonstrated that children under 5 years of age who drank SODIS-treated water were 7 times less likely to contract cholera than those who did not. There are no limitations to SODIS applications in high solar radiation areas (e.g. Africa), and its cost is practically nil as the only material required is transparent plastic bottles.

Purpose: The project is basically focused on Sub-Saharan Africa. Its strategic objectives are the following:

- Demonstrate SODIS as a suitable and effective technique for making contaminated water fit for human consumption in small communities in developing countries that do not have easy access to "safe water". Its application is equally effective in natural catastrophes or accidents that place access to drinking water in jeopardy.
- Test and evaluate strategies for changing behavior and spreading information about SODIS as a drinking water treatment technique in zones with different sociocultural profiles.
- Communicate the results of project research through international aid organizations (to developing countries and victims of catastrophes) so SODIS is recommended as a quality measure for intervention meeting water treatment standards (e.g., filtration, chlorination, desalination, etc.).
- Development of a series of technological improvements in the SODIS process, based on the use of ultraviolet disinfection dose indicators, solar-radiation activated photocatalysts and solar collector modules (CPCs). to be used depending on socio-economic conditions

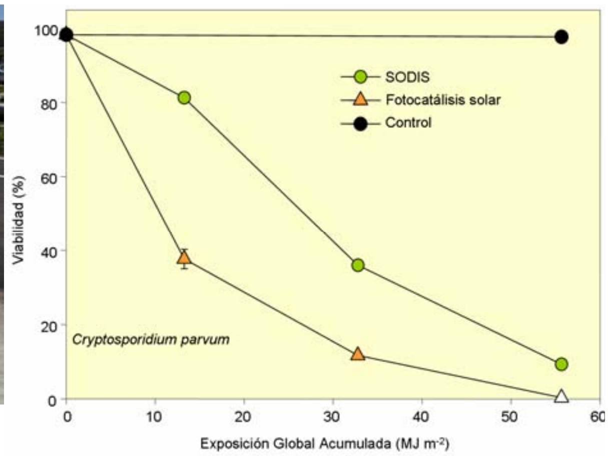


Figure 4.6 Solar photoreactor prototype for water disinfection (left). Degradation of Cryptosporidium parvum oocysts by SODIS and solar photocatalysis with supported TiO_2 under natural solar radiation at the Plataforma Solar de Almería (right, [4.4])

The scientific project objectives are: (i) Study the effect of the consumption of water treated with SODIS on health in four African countries; (ii) analyze the relationship between water disinfected by SODIS and certain health markers (morbidity due to diarrhea and dysentery, weight loss, loss of life, growth rates, productivity, etc.); (iii) demonstrate the effectiveness of the SODIS technique on a domestic scale and its acceptance as a disinfection method; (iv) evaluate the effectiveness of SODIS for certain viruses, protozoa, helminthes and bacteria. The CIEMAT-PSA will work mainly in the design and construction of a low-cost solar reactor prototype, research and development of a dosimetric UV radiation sensor for continuous-flow system control, evaluation of all the technological improvements related to the reactors and radiation sensors under real radiation conditions with appropriate model microorganisms and cost analysis.

Objectives achieved in 2006: To design the final prototype,a prototype solar reactor for water disinfection already existing at the PSA facilities will be used (Figure 4.6 left). Figure 4.6 right shows the degradation of C. Parvum oocysts in water during SODIS experiments at the PSA, and improvement of deactivation by a catalyst (TiO_2 Degussa P25) supported on an acetate film [4.4].

4.2.6 FITOSOL

Elimination of phytopathogens in water by photocatalysis: application to disinfection and reuse of nutritive solutions in recirculating hydroponic culture.
http://www.psa.es/webeng/projects/fitosol/index.html

Participants: Dept. of Vegetal Production /Univ. Almería; CIEMAT-PSA (coordinator).

Contact: Dr. Pilar Fernández-Ibáñez, pilar.fernandez@psa.es

Funding: National RD&I Plan, MEC. CIEMAT : 117 K€ + 1 FPI Ph.D. Fellowship.

Duration: October 2006 – September 2009

Motivation: The reason for this project is the destruction of phytopathogenic microorganisms with solar photocatalytic treatment (using an insoluble semiconductor such as titanium dioxide and photo-Fenton), avoiding the use of

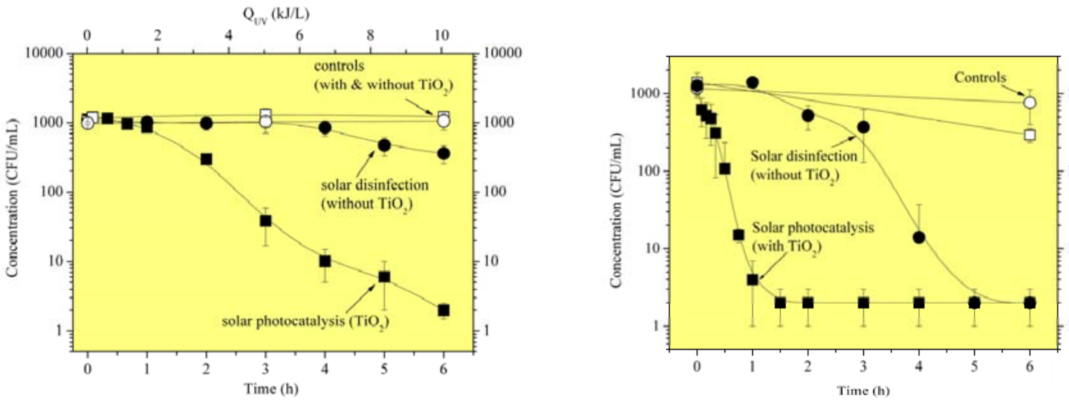


Figure 4.7 Degradation of Fusarium equiseti spores (left) and Fusarium verticillioides (right) by solar irradiation and solar photocatalysis with TiO_2 in suspension (35 mg/L) under natural solar radiation at the Plataforma Solar de Almería (right [4.5]).

conventional chemical disinfectants (toxic and nonbiodegradable compounds) which contribute a certain level of undesirable toxicity to the nutritive water solution. Photocatalytic treatment Effectiveness of the photocatalytic treatment will be evaluated using models present in horticultural crops in the Spanish Southeast: *Pythium aphanidermatum*, the cause of root rot and hypocotyl rot, which leads to wilting in cucurbits, *Phytophthora parasitica*, which causes root rot and tomato end rot, *Fusarium oxysporum f.sp*. radicis-cucumerinum, fungi excluding zoosporangium (water mold), which causes significant losses wherever it appears and Olpidium bornovanus, vector of the melon necrotic spot virus (MNSV) on melon and watermelon plants. Experimental confirmation of capacity for photocatalytic disinfection of these pathogens will be done in the laboratory and at pilot scale, in the solar reactors at the Plataforma Solar de Almería facilities. Finally, the results will be tested in a crop in non-recirculating systems typical at the University of Almería experimental facilities.

<u>Purposes:</u>

- Laboratory study of elimination of model phytopathogenic microorganisms in crops in non-recirculating nutritive solution by solar photocatalysis with TiO_2 (in suspension and supported) and with photo-Fenton.
- Design and construction of a pilot solar reactor for disinfection of water with the above-mentioned phytopathogenic microorganisms for application in the reuse of water used in recirculating hydroponic cultures.
- Evaluation of the results of treatment of phytopathogens in water from photocatalysis using model phytopathogens from different types of crops normally grown without soil.
- Demonstration of the feasibility of photocatalysis for disinfection of polluted water from nutritive solutions in hydroponic cultures will be carried out in the laboratory and at pilot scale in the solar reactors at the facilities of the Plataforma Solar de Almería. Finally, the results will be tested in a recirculating hydroponic crop typical of the University of Almería's experimental facilities.

<u>Objectives achieved in 2006</u>: The first experiments on solar photocatalytic degradation with TiO_2 and solar inactivation without catalyst were carried out at the PSA with *Fusarium equiseti* spores. "Batch" reactors are used for this without concentration with natural solar irradiation times of 6 hours on perfectly clear days. The results show an important effect of the solar radiation on the viability of the *F. equiseti* spores. The use of titanium dioxide (P25) as a catalyst shows a noticeable improvement in disinfection efficiency (Figure

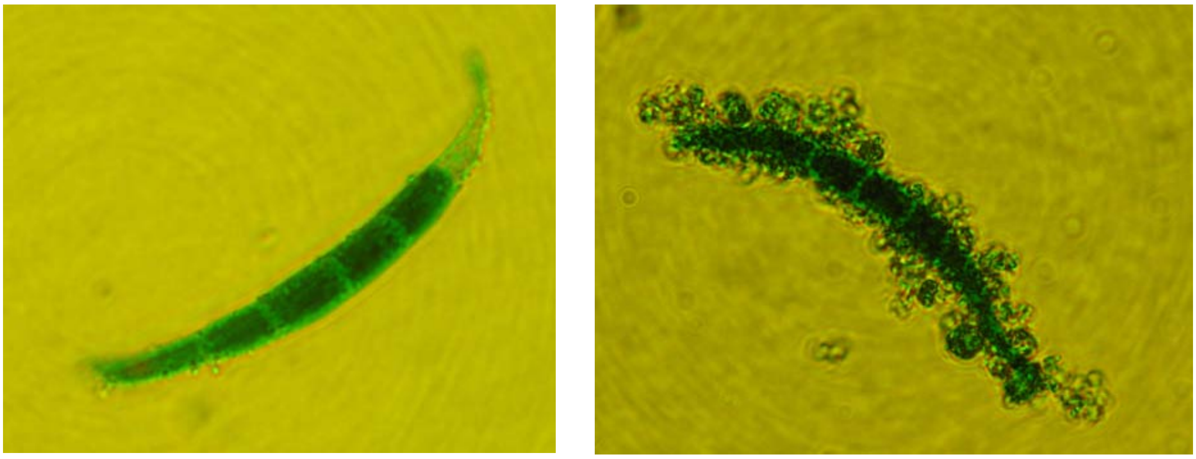


Figure 4.8 Image of Fusarium equiseti macroconidia dyed with malachite green with phase contrast optical microsope (x1000), before (left) and after 5 hours of photocatalytic treatment (right) (dcha.) [4.5].

4.8). Optical microscope observations of the spores of this phytopathogenic fungus during testing showed a clear tendency to adsorption of TiO_2 particles and aggregates on its surface.

4.2.7 National Plan for Access to the PSA.

Participants: Instituto de Catálisis y Petroleoquímica, CSIC (Madrid), Univ. Autónoma de Barcelona, Univ. Santiago de Compostela, Polytechnic Univ. Valencia (2), Universidad de Barcelona

Contact: Dr. Manuel I. Maldonado. mignacio.maldonado@psa.es

Funding: National RD&I Plan, MEC. CIEMAT budget in 2006:

Duration: 2005 – 2007

Motivation: As CIEMAT directives are to promote knowledge of renewable energies in Spanish society, in 2006 it made available to the scientific community the PSA facilities and consulting services of its technical-scientific staff through the MEC "Improvement of Large Scientific Installations and Access in the Framework of National Program of Scientific and Technological Research Equipment and Infrastructure" program (http://www.mec.es/ciencia/jsp/plantilla.jsp?area=instalaciones&id=21).

Purpose: The basic purpose is to provide access to the largest number of researchers possible, Ph.D. students, research trainees and senior researchers in National Plan projects. The Water Detoxification and Disinfection Group also intends for this program to increase collaboration with existing in Spanish research groups, identify new partners for future projects, contribute ideas from visitors and motivate us to maintain and improve the facilities.

Objectives achieved 2006: Researchers selected by the external evaluation committee belonging to Spanish research groups have achieved the following results:

Polytechnic Univ. Valencia (UPV), Ana García Ripoll. Scale-up to pilot plant size of photocatalytic photo-Fenton degradation of the pesticides, Laition® and Metasixtox®. Detoxification of mixtures of four commercial pesticides were studied, comparing the different methods for determining the toxicity and/or biodegradability of the effluent. These results, along with others found previously, form the basis of a publication that is being jointly written by the

PSA and the UPV entitled, ““Decontamination of aqueous solutions containing four commercial pesticides by means of solar-driven photo-Fenton process”.

Polytechnic Univ. Valencia (UPV), Antonio Arqués Sanz. Scale-up to pilot plant size of photocatalytic photo-Fenton degradation of the pesticides, Laition® and Metasixtox®. Results found with the toxicity/biodegradability methods used at the PSA (Zahn-Welles, MicroTox) were analyzed and compared with those used by the UPV (inhibition of activated sludge respiration and DBO5 and respirometry).

Instituto de Catálisis y Petroleoquímica-CSIC. Cristina Adán Delgado. Increase in biodegradability and elimination of persistent contaminants in aqueous effluents by oxidation. The photo-efficiency of titanium dioxide (TiO_2) doped with Fe synthesized by reverse microemulsion with the commercial Degussa P-25 TiO_2 applying both catalysts to aqueous solutions of ethidium bromide. It was demonstrated that incorporation of ethidium bromide in the molecular structure of the TiO_2 particle does not improve ethidium bromide photodegradation efficiency achieved with commercial Degussa P-25 TiO_2.

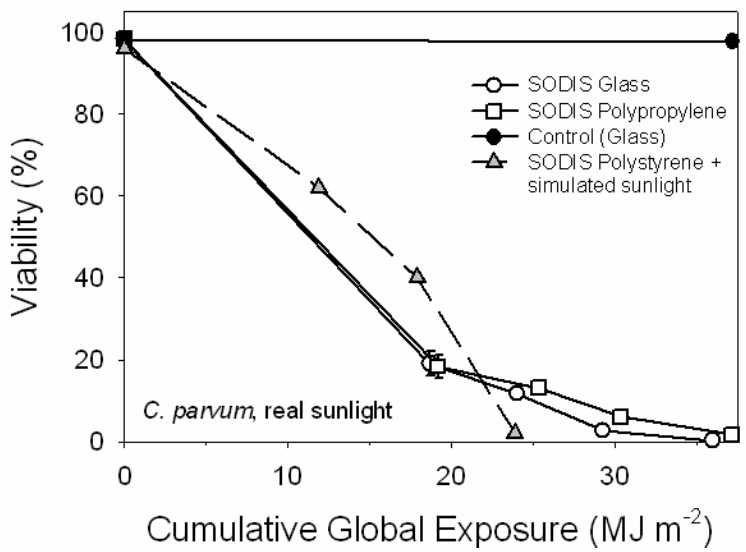


Figure 4.9 Comparison of solar inactivation of C. parvum oocyst suspensions in borosilicate glass and polypropilene bottles exposed to real sunlight

Univ. Santiago de Compostela. Fernando Méndez Hermida. Study of solar-only inactivation (SODIS) of infective *Cryptosporidium* sp. Inactivation of C.parvum oocysts in water with natural solar radiation was demonstrated, and solar photocatalysis with supported TiO_2 was shown to improve these disinfection results [4.4].

Univ.Autónoma de Barcelona (UAB). Julia García Montaño. Pilot plant degradation of reactive azodyes by solar-assisted photo-Fenton. Two commercial azodyes, Procion Red H-E7B and Cibacron Red FN-R, both representative of the textile industry, were studied in a combined photo-Fenton/biological treatment. With only 225 mg l^{-1} of H_2O_2 (Cibacron Red) and 65 mg l^{-1} of H_2O_2 (Procion Red) the dye solutions became sufficiently biodegradable to discharge into the bioreactor [4.2].

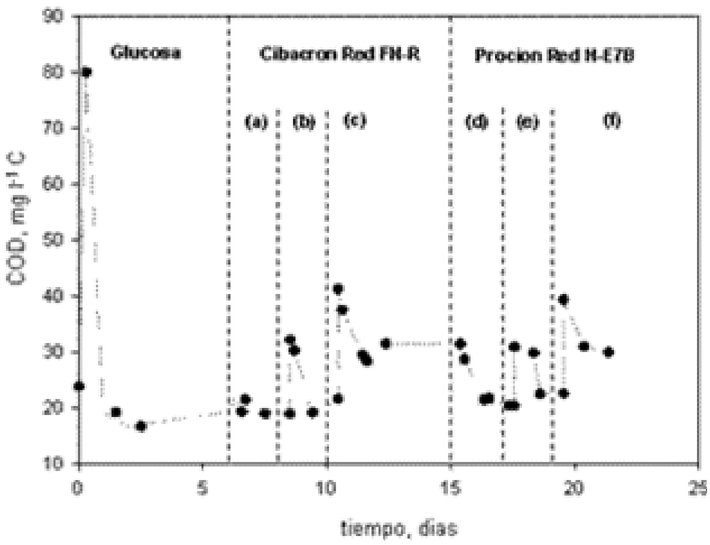


Figure 4.10 Operation of the bioreactor after photo-Fenton pretreatment. 250 mg l-1 Cibacron Red FN-R with different H2O2 doses (a) 250 mg (a) 250 mg l-1, (b) 225 mg l-1, (c) 200 mg l-1. 250 mg l-1 Procion Red H-E7B with different H2O2 doses (d) 80 mg l-1 (e) 65 mg l-1 (f) 50 mg l-1

Univ. of Barcelona (UB). Jordi Bacardit Peñarroya. Combined photochemical/biological treatment of biorecalcitrant water. Study of change in scale and control methods. In the laboratory (UB) experiments were designed to study the influence of the most characteristic parameters of this process: hydrogen peroxide dose, iron (FE^{2+}) dose and temperature. Based on the results, experiments were designed at the PSA conforming to the conditions of interest for study (Table 4.1). In this case, the temperature id not change and 4-chloropenol (4-CP) was used. The strongest influence, as expected, is the H2=2 dose. A large fraction produces more degradation and a better biodegradability of the resulting degradation compounds. Furthermore, it was demonstrated that with very low iron doses, the H_2O_2 is used more efficiently.

Table 4.1 Designs of experiments performed at the PSA

Exp.	$[4\text{-CP}]_0$ ppm	$[Fe^{2+}]_0$ ppm	$[H_2O_2]_0$ ppm	coded		Temperature °C	initial pH
				Fe^{2+}	H_2O_2		
1	200	10	500	0	+	27	2.8
2	200	10	400	0	0	27	2.8
3	200	10	300	0	-	27	2.8
4	200	2	300	-	-	27	2.8
5	200	20	300	+	-	27	2.8
6	200	20	500	+	+	27	2.8
7	200	2	500	-	+	27	2.8

4.3 Gas Phase Detoxification Group

The main objective of this group is the development of efficient systems for the treatment of polluted air streams using preferentially solar radiation as energy source. Although adsorbents and combustion catalysts have been also used for this purpose, the group activities are focused on the development of photocatalytic processes for air purification. In this way, the design of most efficient supported photocatalyst constitutes one of the major priorities of this research. Regarding the nature of the pollutants a significant effort has been devoted to the abatement of volatile organic compounds (VOCs) and inorganic molecules toxic and malodorous like H_2S, but the inactivation of airborne microorganisms is also approached. Therefore, the results obtained in these investigations are aimed to provide solutions for the problems of both industrial and workshops emissions and the indoor air quality.

4.3.1 Development of alternative preparation methods for high-efficiency photocatalytic materials

Participants: CIEMAT (PSA-DER) and ICP-CSIC (Spain).

Contact: Dr. B. Sánchez; benigno.sanchez@ciemat.es

Funding: MCYT Spanish Ministry of Science and Technology. Total project funding: 75 k€ (Jan. 2005 – Dec. 2007).

Background: Gas treatment requires photocatalysts fixed on a substrate shaped as open structures, which allow treating high flow rates without dragging the photoactive components. In addition, the support should be transparent to the UVA radiation used for activation of the photocatalyst in order to make the most effective use of incident photons. However, available photocatalysts do not fulfill all these requirements.

Purpose: The aim of this project is to satisfy the growing demand for versatile high-activity supported photocatalysts for the efficient elimination of air pollutants like Volatile Organic Compounds (VOCs). Novel TiO_2-film photocatalysts (formed by anatase or anatase-rutile mixtures), and other semiconductors such as SnO_2 or ZrO_2 and noble metals will be supported on substrates different compositions and morphologies (ceramic, metallic, polymeric).

TiO_2 will be synthesized by a sol-gel procedure which guaranties low-temperature formation of anatase nuclei, and consequently, at a temperature

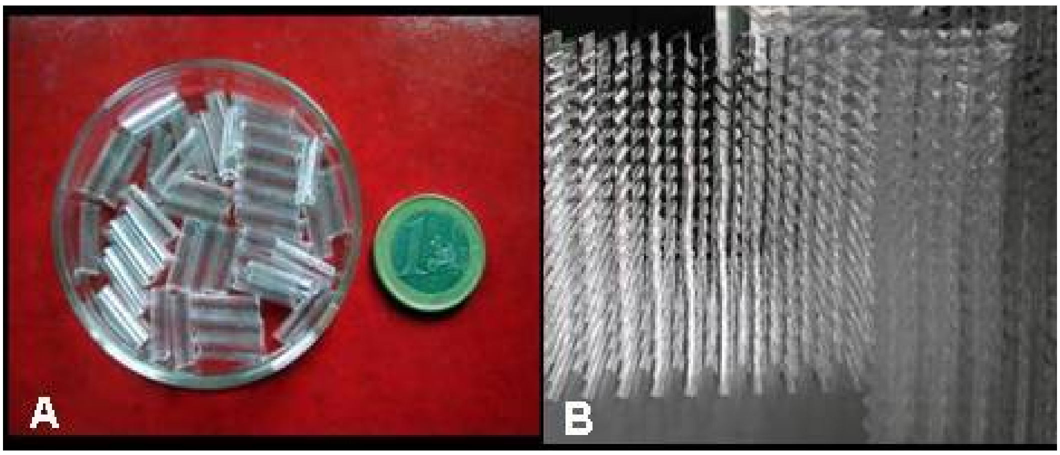


Figure 4.11 Some examples of the supports used to deposit TiO_2 on A) borosilicate glass tubes; B) polymeric monoliths

adequate for coating sensitive substrates. In addition stabilized suspensions of commercial powdered TiO_2 will be also used for comparison. Dip-coating and an innovative electrospray deposition technique will be utilized for photo-catalysts preparation. Photocatalytic activity and catalyst stability with each of the different preparation variables will be studied for the degradation of three representative organic pollutants: trichloroethylene, toluene and formic acid.

Achievements in 2006: CIEMAT activity during this period was mainly focused on the synthesis of TiO_2-coated materials of different porosity and transparency: non-porous transparent supports, like borosilicate glass and organic polymers (PET, cellulose acetate), and opaque ceramic substrates (natural magnesium silicate plates calcined at different temperatures, which were prepared in the ICP-CSIC), which present mesoporosity.

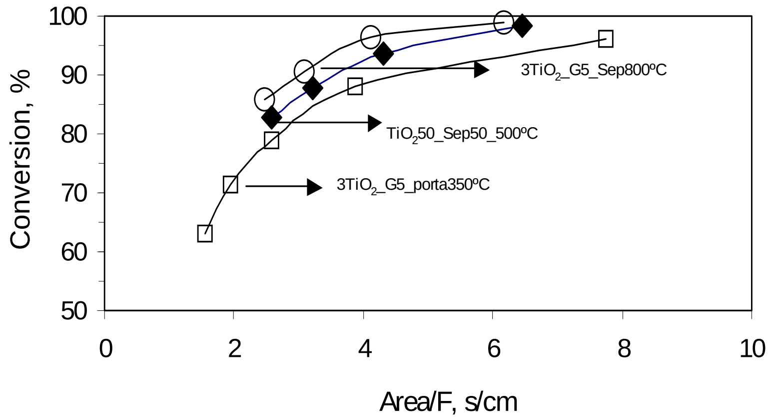


Figure 4.12 Trichloroethylene conversion as a function of the illuminated area to flow ratio (Area/F) for three different photocatalysts: TiO_2 coating on the silcate, a 50:50 W/w TiO_2/silicate mixture and a TiO_2 layer on a glass plate. Initial pollutant concentration 10 ppmv

An example of the of the efficiency of the obtained materials is shown in Figure 4.12, which compare the performance of the same TiO_2 deposited as layer on a porous ceramic or on a dense glass plate, with a bulk photocatalyst formed by a mixture of TiO_2 and silicate. These results reveal that porosity is beneficial for the TCE degradation but the TiO_2 coating is more efficient, very likely due to a better exposure to the light. On the other hand, TiO_2 sol-gel deposited on transparent supports, like those shown in Figure 4.11, have also proved to be very efficient for VOC abatement. Nevertheless, polymeric supports may suffer radiation damage and several strategies to increase their durability have been tested, including the formation of a SiO_2 protective barrier layer.

4.3.2 (DETOX-H_2S)

Development of a new system for the elimination of air borne toxic and corrosive compounds generated in sewage treatment plants

Participants: CIEMAT, ICP-CSIC, ICV-CSIC and UNED (Spain); USACH (Chile) and Univ. of Wisconsin (USA).

Contact: Dr. B. Sánchez; benigno.sanchez@ciemat.es

Funding: CAM funded project, cost shared: 700 k€

Duration: January 2006 - December 2009

Background: This work concerns the development of a new system for treatment of dangerous and toxic substances, such as H_2S, mercaptans, etc., which cause the malodorous sewage plant emissions that make these installations socially unacceptable. Besides, these emissions can contribute to the corrosion of the instruments, causing a relevant economical in the wastewater treatment facilities.

Purposes: Develop a photocatalytic treatment system activated by sun light or UVA lamps that operates under real process conditions.

- Develop an adsorption treatment system that allows retention of the noxious components of the atmospheres found in wastewater treatment plants.
- Based on the results of both systems, a new mixed photocatalysis-adsorption system will be developed. This combined reactor should take advantage of the synergies between both processes, enhancing the efficiency of each system. The achievement of these goals should lead to a drastic reduction in the volume of the costly and irritant chemicals currently used to control these emissions, and consequently a safer environment for the plant workers will be created.

Achievements in 2006: During this first year of the project, the main effort focused on the selection of high-efficiency, durable supported photocatalysts. Different UV-transparent carriers were initially selected and sol-gel-coated TiO_2. In parallel, several adsorbents based on high-strength surface materials (silicates, carbon…) were prepared by extrusion as either plates or monoliths.

Photocatalytic degradation was studied as a function of the flow rate, H_2S concentration and humidity. Results show that high conversion of H_2S can be achieved with adequate operating conditions. Figure 4.3 illustrates the effect of humidity on the conversion of some of the photocatalysts assayed. One significant finding is that following several hours of irradiation, SO_2 can be detected in the outlet stream, revealing that H_2S is not only transformed into sulfate, but can also be oxidized into SO_2. The selectivity of H_2S photodegra-

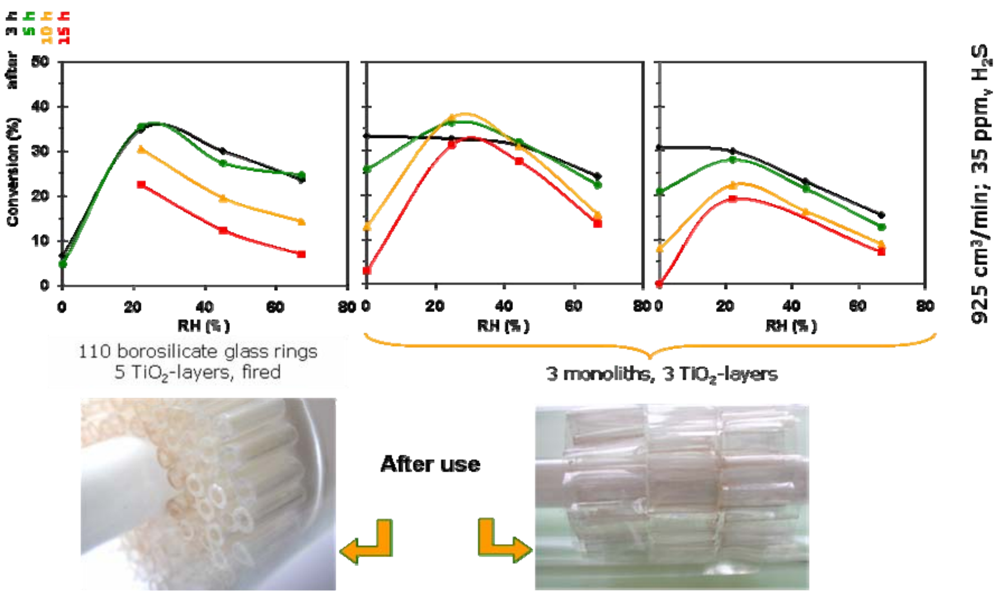


Figure 4.13 Conversion as a function of relative humidity, using glass rings and polymeric monoliths as TiO_2 catalyst supports.

dation has a significant impact on the overall efficiency of the process, because sulfate builds up on TiO_2 causing a progressive deactivation of the catalyst. However, preliminary studies have shown that regeneration can be achieved simply by washing with water. A considerable research effort has been devoted to optimizing the different variables affecting the washing procedure. In this respect, the influence of pH, stirring speed, temperature and time have been systematically investigated. The results indicate that increased temperature and alkalinity of the solution improve the solubility of the adsorbed sulfate and facilitates regeneration of the photocatalysts. Finally, the stability of the materials was studied under exposure to sunlight and in a weathering chamber using standardized procedures. Initial results show that the polymeric support suffers significant loss of transmission in the UVA and become brittle due to damage from solar radiation. Consequently, the search for new ways to protect these supports and to increase their durability will be approached during the next stages of the project.

4.4 Solar Desalination Group

In the section on activities corresponding to solar desalination, the noteworthy increase in activity since 2006 should be especially emphasized. Desalination processes are appearing as a totally necessary alternative in the face of surface water shortages and over exploitation of aquifers in many areas of the globe. As desalination is an energy-intensive process, in the current context of continually rising energy prices and the ever-growing water requirements due to a large number of factors, but, above all, to worldwide population growth, the development of solar desalination processes and technologies is fully justified. Proof of it is the growing interest, not only by a large number of companies, but also by institutions. For example, suffice it to say that the European Union 7th Framework program launched at the end of 2006, has included the subject of solar desalination as a topic of research under Energy for the first time.

Another fact to be emphasized in this area of research is that a considerable part of the activity underway focuses on applications in the Mediterranean Region in general and North African countries in particular. This fact has allowed us to enlarge the spectrum of Unit collaboration significantly, by adding a large number of North African institutions, universities and companies to the traditional European and Latin American areas of collaboration. This Mediterranean environment of collaboration will continue growing in the future as new initiatives and activities currently being negotiated are taken on.

4.4.1 AQUASOL

Enhanced Zero Discharge Seawater Desalination Using Hybrid Solar Technology

http://www.psa.es/webeng/aquasol/index.html

Participants: CIEMAT-PSA (Coord., E). Inabensa-Solúcar (E). Aosol (P). National Technical University of Athens (GR). INETI (P). Cajamar (E). Hellenic Saltworks (GR). Com. Regantes Cuatro Vegas (E). Entropie (F).

Contact: Dr. J. Blanco, julian.blanco@psa.es

Funding: EC (Energy, Environment and Sustainable Development Programme); 1,500 k€.

Duration: March 2002 – February 2006

Motivation: Seawater desalination is one of the possible solutions to the severe water shortage problem that our planet is going to undergo during the first half of this century, a problem which is not exclusively in developing countries, as the appearance of persistent seasonal droughts are more and more frequent in some regions of developed countries.

In spite of all of the advances of the last few decades, seawater desalination technologies continue being intensive fossil-fuel consumers. In the present world framework, with growing instability of oil market prices and environmental demands derived fro compliance with the Kyoto Protocol, sustainable desalination must unavoidably be arrived at through improved efficiency of the technologies involved as well as the use of renewable energy resources. The AQUASOL project faces both options by using solar thermal energy as the renewable energy resource and contributes to increasing the thermal efficiency of the multi-effect distillation process. The environmental impact of the desalination process has also been reduced by recovering the salt contained in the brine.

Purposes: The main goal of the AQUASOL project is the development of a hybrid solar/gas seawater desalination technology based on multi-effect distillation (MED) which also meets the principles of energy efficiency, low cost and zero discharge.

Objectives met in 2006: The implementation of the different subsystems was completed during this period and their testing under real weather conditions was begun at the PSA facilities (MED Plant, heat pump and solar field) and the Greek saltern Hellenic Saltworks on the Island of Lesbos (Solar Dryer).

The AQUASOL system has three different operating modes depending on the origin of the thermal energy:

- Solar-only mode: the thermal energy supply to the first effect of the distillation plant comes exclusively from the solar collector field.
- Fossil-only mode: the double-effect heat pump supplies all of the energy required by the distillation plant
- Hybrid mode: the energy supply comes from both the heat pump and the solar field. Two different operating philosophies are considered: in the first the heat pump works continuously 24 hours a day supplying the minimum 30%, while in the second it starts up and stops, depending on the solar resource availability.

The operating and maintenance experience with the AQUASOL system has been shown to be highly reliable, with no important problems being recorded during testing. The solar collector field has demonstrated an average daily efficiency (ratio between the thermal power delivered to the storage tanks and the global solar radiation incident on the tilted surface of the collectors) of 48%. The plant performance factor (kg distillate produced per 2316 kJ thermal energy supplied to the system) in solar-only mode is over 10.

As a result of evaluation of the new absorption heat puma after the first tests, it was decided to change the initial configuration of parallel flow to series flow, to improve the controllability of the equipment, especially during transients. After this modification, the unit showed excellent behavior, increasing the plant performance factor from 10 to over 20, which is a 100% increase in thermal process efficiency. In hybrid mode, it should be mentioned that the absorption pump showed strong thermal inertia, mainly due to the fact that the maximum power delivered by the steam boiler is much more than required by the pump under stationary conditions. The best results were

Figure 4.14 Double effect (LiBr-H2O) absorption heat pump

therefore with the heat pump working continuously with a minimal contribution of 30%.

Sensitivity analyses have shown that plant size plays a fundamental role in determining the final price of water desalinated by the AQUASOL technology. To reduce the impact of solar field and heat pump amortization on the cost of the the water, plants would have to have capacities above 6,000 m^3/day at a price of 1.55€/m^3, which could be reduced to 0.93€/m^3 for 12,000 m^3/day plant [4.48 a 4.54].

MEDESOL – Seawater desalination by innovative solar-powered membrane-distillation system. http://www.psa.es/webeng/projects/medesol/index.html

Participants: CIEMAT-PSA (E), Universidad de La Laguna (E), Acciona Infraestructuras S.A. (E), Aguas de las Cuencas Mediterraneas, S.A. (E), Aosol (P), Universität Stuttgart (D), Tinep S.A. de C.V. (MX), Centro de Investigación de Energía – Universidad Nacional Autónoma de México (MX), Kunglika Tekniska Högskolan Stockholm (S), Scarab Development AB (S), Iberinsa S.A. (E).

Contact: Dr. J. Blanco, julian.blanco@psa.es
Dr. W. Gernjak, wolfgang.gernjak@psa.es

Funding: 6th FP. Global Change and Ecosystems.; 1,375k€. CIEMAT Budget: 417K€.

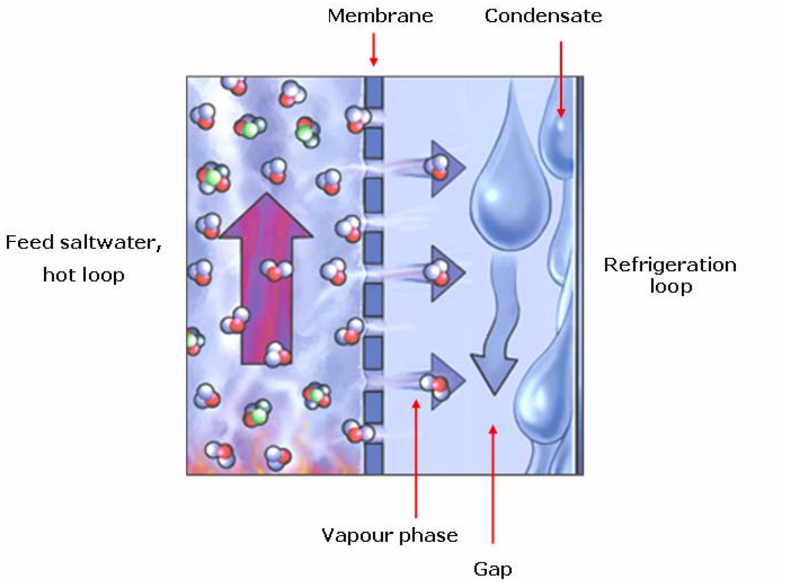
Duration: October 2006 – September 2009

Motivation: Develop membrane-distillation processes in which the power supply comes from low temperature (60-100ºC) solar collectors. This process is very innovative and has a high potential for application, especially for desalination units with small to medium distillate production capacities (0.1–50 m^3/day). Its robustness and simplicity are the main characteristics of this technology, making it ideal for self-sufficient systems in remote areas.

Purposes: (i) Study the membrane-distillation process to increase the system's efficiency; (ii) develop efficient heat recovery system concepts; (iii) develop and/or improve different individual system components, such as an improved solar collector and a heat exchanger with innovative surface treatments is intended to minimize fouling; (iv) develop a system with a capacity of several cubic meters per day; (v) develop an autonomous system with capacity of several hundred liters per day.

The principle of the process is shown in Figure 4.15. Steam goes through a hydrophobic membrane due to the difference in steam pressure on the two sides of the membrane. This difference in steam pressure is generated by keeping different temperatures on both sides. This way, the steam goes through the membrane from the hot side to the cold side, where it condenses and is collected as highly-pure distillate. The condensation heat is released inside the distillation module by the membrane to the cooling fluid which does not come into direct contact with the distillate. The distillation module is therefore made up of four compartments (see also the diagram below):

- Channel for hot water to be desalinated
- Hydrophobic membrane
- Channel for air, where the steam condenses
- Channel for cooling with cooling fluid



(Courtesy of Xzero, Suecia)

Figure 4.15 Principle of the membrane process

OSMOSOL – Desalination by reverse osmosis with solar thermal energy. http://www.psa.es/projects/osmosol

Participants: Univer. La Laguna (Coord., E). CIEMAT-PSA (E). Univ. Rovira i Virgili - CREVER (E)

Contact: Dr. J. Blanco, julian.blanco@psa.es
Dra. L. García, mlgarcia@ull.es

Funding: MEC (National Plan for Scientific Research, Development and Technological Innovation 2004-2007); 70 k€ (CIEMAT).

Duration: December 2005 – December 2008

Motivation: Desalination is an intensive energy consumer; in reverse osmosis seawater desalination systems, this consumption is around 3.5 kWh/m^3. Taking into account that 2 10^6 m^3/day are distilled in Spain, the need for developing sustainable and economically feasible desalination technologies is unquestionable. The solar reverse osmosis plants in operation to date are based on photovoltaic technology. The use of solar thermal energy for this process would enable better use to be made of the solar resource and less environmental impact once the problems of waste involved in the use of batteries required for photovoltaics is eliminated.

Purposes: The main goal of the OSMOSOL project is the development of an innovative technology based on solar thermal energy applied to the reverse osmosis desalination process which complies at the same time with the principles of environmental sustainability and economic feasibility. To do this it is intended to use thermal energy collected and concentrated in a solar device to feed a thermodynamic cycle based on a fluid that evaporates at a relatively low temperature and which, hooked up to a turbo-compressor system, allows direct transformation of the thermal energy into mechanical energy required by the osmosis process.

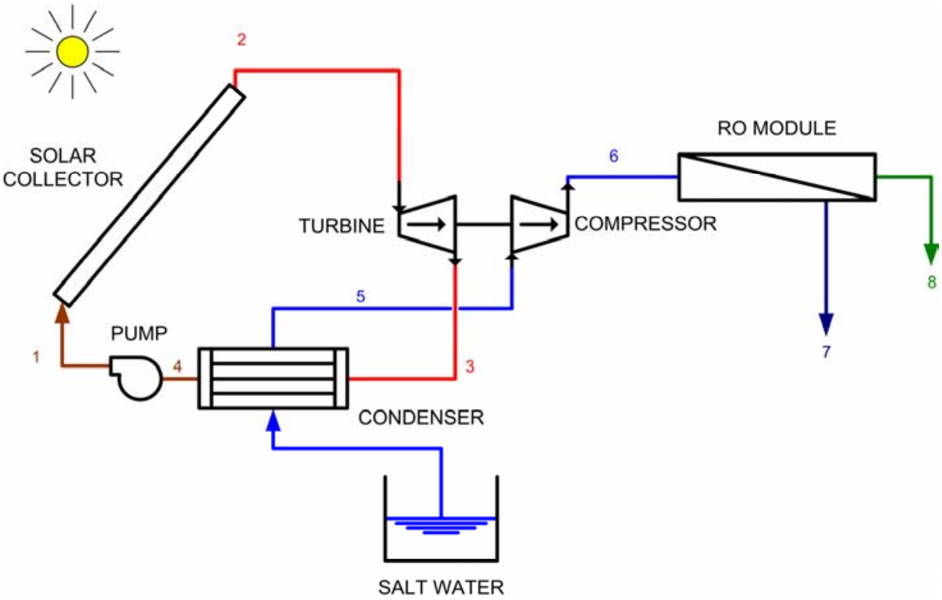


Figure 4.16 Generic reverse osmosis system hooked up to a solar driver

Objectives met in 2006: During the first year of the project, low and medium-temperature solar thermal collectors were thoroughly reviewed from the point of view of their application to desalination processes.

Once certain solar organic Rankine cycles had been selected, we proceeded to choose from among the solar collectors compiled in the previous activity, those which best adapted to the conditions delimited by the thermodynamic cycle mentioned above. Four stationary solar collectors and two parabolic-trough collectors meeting the technical and functional specifications were preselected for analysis of the solar power cycle, which was done employing up to 22 different working fluids.

4.5 Characterization of Solar Radiation

In 2006, activities related to the study and characterization of Solar Radiation concentrated on participation in projects related to:

- Measurement of solar radiation.
- Study of the spectral distribution of solar radiation
- Satellite imaging for calculating solar radiation

The most relevant actions in this line of activities are described below. Las references and publications associated with this activity may be found in Section 4.6 [4.55 to 4.67].

4.5.1 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.**

Figure 4.17 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 for its use, and finally, in 2005, perfecting these tools and implementing filters.

2006 was the first year the station was completely in service, although there were some important incidents, such as lightning striking and leaving it inoperable for several days.

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 com-

Figure 4.18 Damage by lightning. The anemometer at the top of the mast was knocked off

mercial 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 2006, this data base was not modified, but numerous external enquiries have been received. At the present time, the whole application (requests for PSA, CEDER and satellite data) has 455 users:

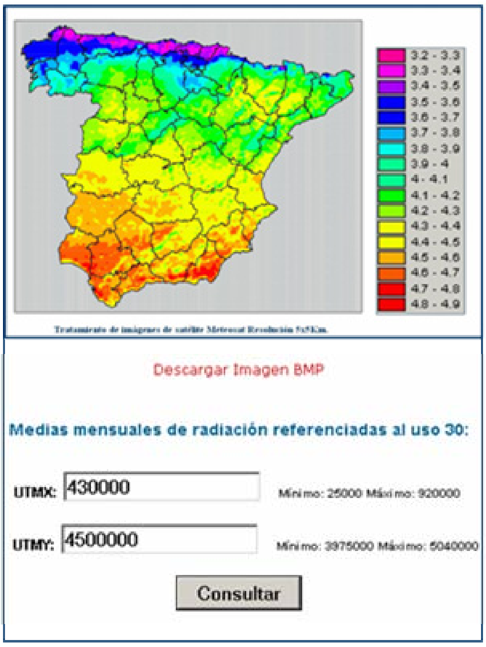


Figure 4.19 Access to solar radiation calculated from satellite images

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

- 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.
- 52 PSA/CIEMAT users with access to average minute data (mean, minimum, maximum and standard deviation) of variables recorded at the measurement stations.
- 399 outside users with access to hourly and daily data from measurement stations.

Table 4.2 List users of PSA Website radiation databases

Universidad Rey Juan Carlos I	Universidad de Almería	Arlas Investment
SunTechnics SL	Enecolo	Universidad de las Palmas de Gran Canaria
ENDESA Generación	Sener	TDT-ER S.L.
Instituto de Astrofísica de Andalucia	Universidad de Córdoba	Universidad Nacional del Santa - Peru
CSIC	Systaic Ibérica S.L	Solartecnik
New Technologies Global Solutions	Isoen Ingeniería	IPEnergia
ITSMO94	Univ. de La Rioja	Enerteam
ECOSOL ENERGY NEDERLAND	Mubadala	Neosolar
GRUPO ISOLUX CORSÁN, S.A.	Universidad de Valencia - Facultad de Ciencias	NIPSA
Universidad de Granada	Universidad de La Laguna	PwC
EREDA -Energías Renovable	SNELL SERVICIOS	Biot
UNED	Neo Energía	Sunergy
ENERFIN SOCIEDAD DE ENERGÍA	Samca	DLR
MICROBEAM, S.A.	GE&PE	Universida de Vigo
CENIM	Alatec	Avant Solar
Cosentino s.a.	Apiaxxi	Geonica
Universidad de Alcalá	INVERSIÓN MAS DESARROLLO	Sunergy
Proyecto MBA	Avenia	INGSEMAT Ingeniería SL
Arquitectural	Solarpack	EPURON
AURANTIA	Promocion Solar	Universidad de Antioquia-Colombia
TU Dresden, Institute of ...	GRUPOSOLAR S. L.	Grupo Enersolar XXI, sl
CASA	CAP	GRUPOGESOLAR
Instituto de Energía Solar. ETSI Telecomunicación	Eolica Navarra	Proinlosa
Bromos	Ingeniería Solándalus S.L	AGNI
Hidroges	Estudio-arquitectura Arquired	Corp. ZIGOR
COENA	Universidad Castilla la Mancha	ETIFA
Universidad de Málaga	Fh-swf Nexgo	OFFICE PROYET S.L.
CITHE	Albiasa Solar SL	KinTech Ingeniería S.L.
Fuente Olen S.L	Berger Erneuerbare Energia	Universidad de Sevilla
Energia alternativa Direc	Soluziona	Energías Renovables Albacete
Innova Italy	Enerpal Madrid	Enertec
ETECAM	ICTA-Universida Autonoma Barcelona	Conmasa
German Meteorological Service DWD	Servirap	Wagner Solar S.L
Isofon	Sadar Energias	Ger 2004, sa
Urbaser	INITEC INFRAESTRUCTURAS	Universida de Jaen
Soelca	Solucar R&D	Gas Natural
Prosolia	IES-UPM	Gamesa Solar
Voltwerk energias nuevas	Milenio Solar	Iberinco
SOLAR POWER Globalum	Unisol	Elixe enginyeria
INDUSTRIAS VÁZQUEZ	Pgi grup	Enerfin
Tragsa	Universidad de alicante	Universidad Salta - Argentina?
BG-Capital	Neo Energía	Sitecma
Sustainable Bioenergy	Energías Renovables Almería ENERPAL	ATON Alternativas Energética
Oplima Portugal	Saguntina de climatización	

4.5.2 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]”. The main goals of this project were:

<u>Development of automatic spectral measurement filtration and classification methodologies</u>

Starting with the operation of the PSA spectroradiometer, there is now an extensive solar spectral radiation database. 2 of these spectra are recorded

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

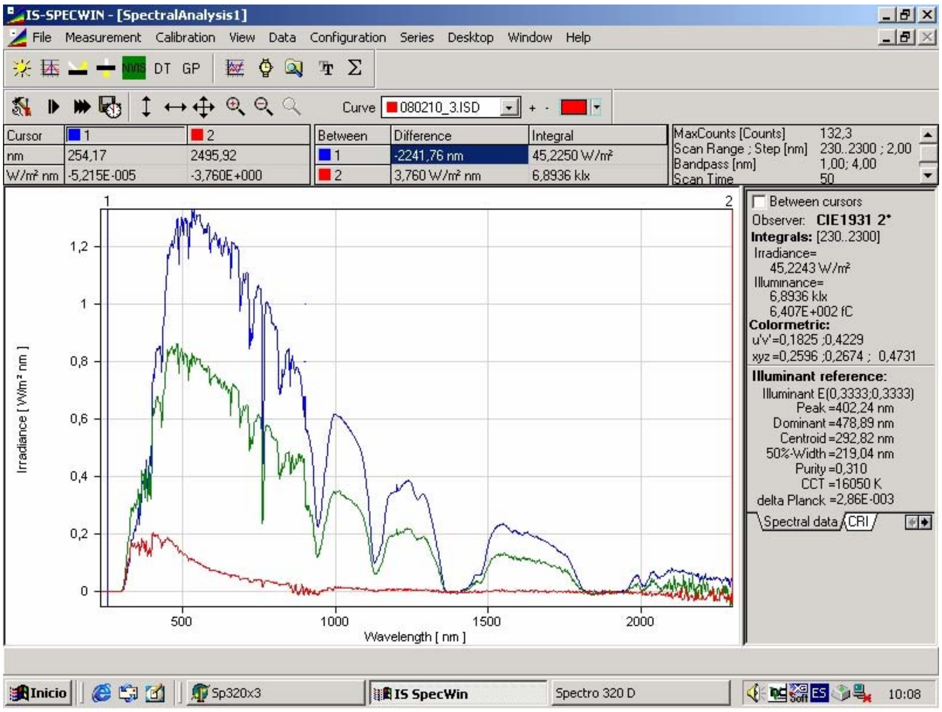


Figure 4.21 Spectral measurements recorded at the PSA.

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 data are 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, 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.

4.5.3 Projects in Collaboration with Companies Building Solar Power Plants

Since 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.

In 2006, 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

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 is therefore being 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.

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Figure 5.1 Logo designed for the 25th Anniversary of the PSA

5 Events

Diego Martínez Plaza

Without doubt, the most important event this year was the celebration of the Plataforma Solar's 25th anniversary.

In fact it was on September 21, 1981 when the SSPS (Small Solar Power Systems) plant was inaugurated in a ceremony with international repercussion. This SSPS plant was the result of an effort driven by a consortium of nine countries under the umbrella of the International Energy Agency: the United States of America, Belgium, Sweden, Switzerland, Greece, Austria, Italy, Germany and Spain.

Figure 5.2 SSPS inauguration ceremony, 1981

The SSPS plant would later be joined with the Spanish CESA-1 (Central Electrosolar de Almería), inaugurated in 1983, to form what we know today as the 'Plataforma Solar de Almería'. On the occasion of this anniversary, there were a series of educational activities as well as a 'Celebration Day' for all the personnel which was attended by some very well-known persons.

The cultural activities consisted of a photography contest, and as an educational activity in the schools, an essay contest and another on general knowledge on a local TV channel.

Figure 5.3 Winner of the 1st prize in the photography competition

The 'Celebration Day' took place on October 28th, and was highlighted by the presence of the Minister of Education and Science, Mercedes Cabrera Calvo-Sotelo, and the Secretary of State for Universities and Research, Miguel Ángel Quintanilla Fisac.

Figure 5.4 The Minister addressing the public at the event

Figure 5.5 The Minister (right) and Secretary of State (left) visiting the PSA facilities

The DLR (German Aerospace Center) also contributed to making it a great day with the attendance of several of their highest officers, with special mention due to Mr. Günther Hamacher, member of their Board of Directors.

The ceremony was the perfect setting for acknowledging the dedication of workers who, like the PSA, had been in service for 25 years. The Director General of CIEMAT, Dr. Juan Antonio Rubio Rodriguez, gave them the award designed for the occasion in a memorable ceremony.

Figure 5.6 Presentation of 25-year service awards

Scientific congresses

The '13th SolarPACES Symposium' took place in the Seville School of Engineering from June 20-23, 2006. This symposium is considered the congress of the 'concentrating' solar community.

This year the Plataforma Solar staff was particularly involved, serving on the Scientific and Organizing Committees and a large number in attendance. The organization was done jointly by the Seville School of Engineering (main campus) the 'PROTERMOSOLAR' association and the PSA-CIEMAT.

This Symposium was especially successful, with over 400 participants. This is because of the high point of maturity that solar thermal electricity is experiencing in Spain. In fact, the Organizing Committee designed the distribution of sessions in such a way that June 21st, "Industry Day", was devoted exclusively to the current industrial interest in these technologies. The sessions included a round table in which the main companies involved in the construction of the first commercial solar thermal power plants in Spain participated. To complete the day's activities, SOLÚCAR offered a visit to the PS10 plant in Sanlúcar la Mayor (Seville), which will be the first commercial plant to enter in service delivering solar thermal power to the Spanish electricity grid.

Figure 5.7 A Symposium session in the Auditorium of School of Engineering

Figure 5.8 'Industry Day' round table discussion

Figure 5.9 Visit to PS10 by Symposium participants

Participation in trade fairs and congresses

As in the previous two years, in 2006, the PSA-CIEMAT participated in the 3rd Renewable Energies and Water Technologies Fair, organized by the Almería Chamber of Commerce, and held in Almería. PSA activities were presented in a joint DLR-CIEMAT stand.

This year, the International Congress on Renewable Energies and Water Technologies (CIERTA) was also held in parallel. The fair is growing from year to year and we would like to think that continued PSA support has contributed to its increasing importance.

Figure 5.10 The stand jointly presented by CIEMAT and DLR

Figure 5.11 The Andalusian Government's Counsilor for the Environment, Fuensanta Coves, visited the PSA stand

Up to now the fair has been held biannually, however, an agreement has been arrived at with the Chamber of Commerce of Rabat for joint organization by the two chambers of commerce, alternating an annual fair between the two venues.

Other visits

On February 2nd, we were visited by the Minister of Education and Science, María Jesús Sansegundo, accompanied by the Director General of Technology Policy, Carlos Alejaldre Losilla.

Figure 5.12 The Director General of CIEMAT welcoming the Minister to the PSA

Figure 5.13 The Minister was especially interested in the direct steam generation facility

There was also much interest by Germany in this important year for our Center. Matthias Machnig, the Ministry of the Environment and Nuclear Safety (BMU) Secretary of State visited us on July 21st, accompanied by a group from the Ministry, Hans-Josef Fell, Green Party member of the 'Bundestag', and Dr. Hans Müller-Steinhagen, Head of the DLR Institute of Technical Thermodynamics from which the solar energy staff depends.

Figure 5.14 The German BMU Secretary of State, Matthias Machnig visiting the PSA

Antes de finalizar el año, aún hubo tiempo para recibir otra visita ilustre. En este caso el Sr. Ministro de Industria, Comercio y Turismo, D. Joan Clos i Matheu, visitó nuestras instalaciones el 9 de noviembre acompañado del Sr. Consejero de Innovación, Ciencia y Empresa de la Junta de Andalucía, D. Francisco Vallejo Serrano.

The Minister was particularly interested in the cost of solar thermal electricity generation and possible technological alternatives for reducing their price.

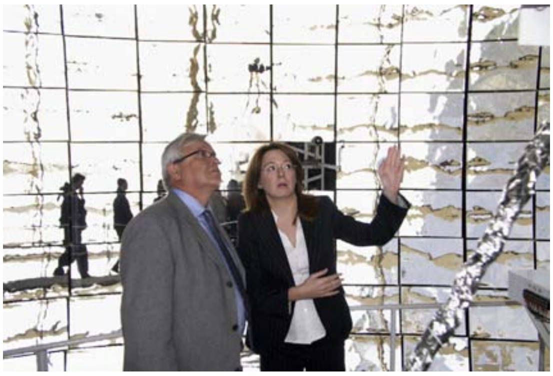

Figure 5.15 The Minister visiting the Solar Furnace

Figure 5.16 The Minister and the Counsilor recieving the press at the end of their visit.

6 List of Acronyms

AMES	Environmental Applications of Solar Energy Unit (PSA)
AOP	Advanced oxidation process
AOS	Average oxygen state
BMU	German Ministry for the Environment and Nuclear Safety
BOD	biological oxygen demand
BSRN	Baseline Surface Radiation Network
CAM	Caja de Ahorros del Mediterráneo
CCM	compact concentrating module
CEA	Atomic Energy Commission (F)
CEDER	Centro de Energías Renovables - CIEMAT
CHA	Spanish German Agreement
CIEMAT	Centro de Investigaciones Energéticas Medioambientales y Tecnológicas
CIERTA	International Congress on Renewable Energies and Water Technologies
CIESOL	CIEMAT-UAL Mixed Center for Solar Energy Research’
CNRS-PROMES	Centre National de la Recherche Scientifique – Processes, Materials and Solar Energy Laboratory
COD	chemical oxygen demand
CPC	Compound parabolic concentrator
CREVER	Centre of Technological Innovation in Heat Upgrading and Refrigeration - University Rovira i Virgili (E)
CRT	central receiver technology
CSIC	Consejo Superior de Investigaciones Científicas
CSIR	Council for Scientific and Industrial Research (Reo, S. Africa)
DER	Renewable Energies Dept. (CIEMAT)
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (D)

EAWAG	Swiss Federal Institute of Aquatic Science
EC	European Commission
ENEA	Agency for New Technology, Energy and the Environment (I)
ETHZ	Federal Polytechnic Institute of Zurich (CH)
EU	European Union
FP	EC Framework program
FPI	Ph.D. research fellowship (Formación de Personal Investigadora)
ERDF	European Regional Development Fund
GPS	global positioning system
ICP-CSIC	Instituto de Catálisis y Petroleoquímica -CSIC
ICROSS	International Community for Relief of Starvation and Suffering
ICV-CSIC	Instituto de Cerámica y Vidrio - CSIC
INCO	Programme for RTD Cooperation with third countries and international organisations
INETI	Instituto Nacional de Engenharia (P)
IPHE	International Partnership for the Hydrogen Economy
LCA	Life Cycle Analysis
LPG	Liquid petroleum gas
LSI	Large Scientific Infrastructures
MCYT	Spanish Ministry of Science and Technology
MEC	Spanish Ministry of Education and Science
MED	Multi-effect desalination
MIM	Monolithic integrated modules
MNSV	melon necrotic spot virus
NEAL	New Energy Algeria
PDVSA	Petróleos de Venezuela, S.A.
PET	Polyethylene terephthalate
PMMA	Polymethyl methacrylate
PSA	Plataforma Solar de Almería
PSI	Paul Scherrer Institute
PTC	Parabolic-trough collector
RCSI	Royal College of Surgeons in Ireland
SBP	Schlaich, Bergermann und Partner
SEM	Scanning electron microscope
SI	sulfur-iodine cycle
SMBs	Small and medium businesses
SODIS	Solar disinfection

SolLab	Alliance of European Laboratories on Solar Thermal Concentrating Systems
SSPS	Small Solar Power Systems Project
TCE	trichloroethylene
TOC	Total organic carbon
UAB	Univ. Autónoma Barcelona
UAL	Univ. Almería
UB	Univ. Barcelona
UNED	National Univ. for Distance Education (E)
UPS	Uninterrupted power system
UPV	Polytechnic Univ. Valencia
USACH	Univ. Santiago de Chile
UU	Univ. Ulster
UV	Ultraviolet
VOCs	volatile organic compounds
WMO	World Meteorological Organization
WP	Work package
WTP	Water treatment plant
WTPs	Water treatment plants
ZSW	Zentrum für Sonnenenergie und Wasserstoff Forschung (D)

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