Plataforma Solar de Almería

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ANNUAL REPORT 2010

GOBIERNO DE ESPAÑA
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Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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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.

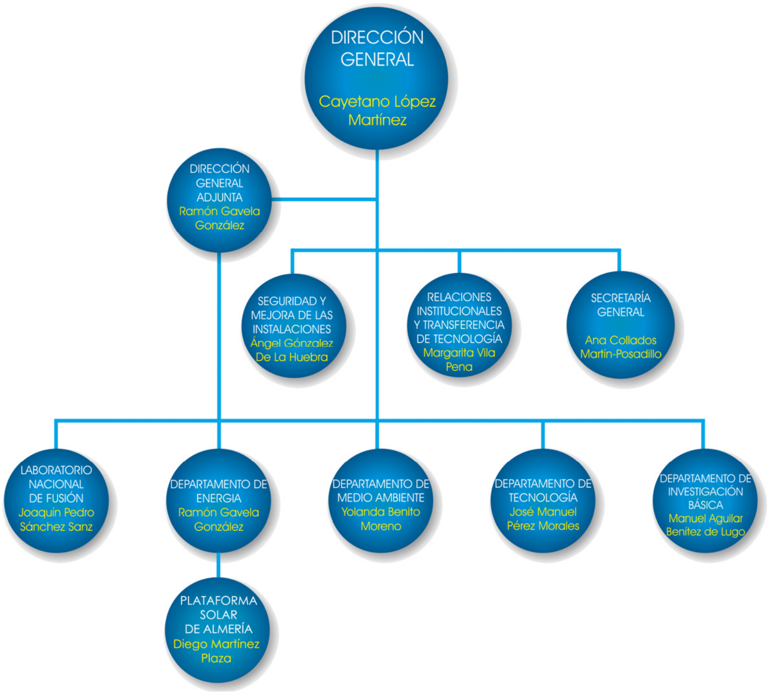


Figure 1.1. Integration of the PSA in the CIEMAT organization

- 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.

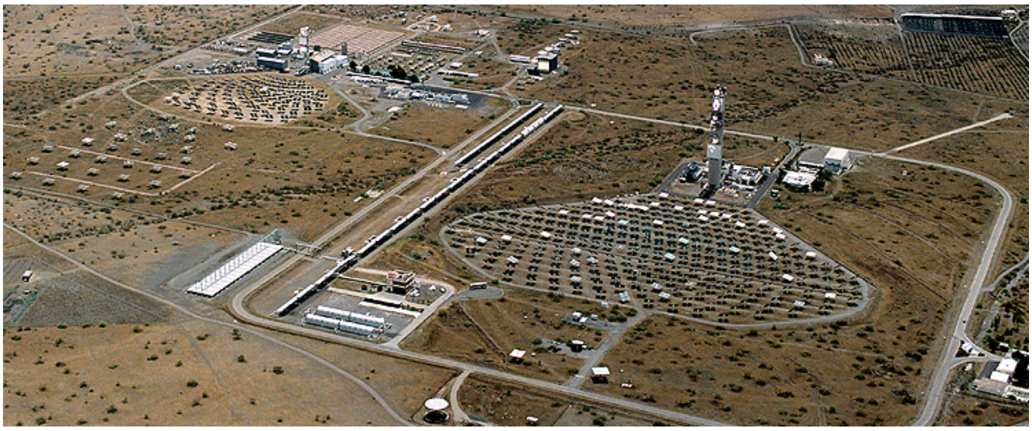


Figure 1.2. Aerial view of the Plataforma Solar de Almería

1.2 Functional Structure

Since 2004, research activity at the Plataforma Solar de Almería has been structured around two R&D Units:

- Solar Concentrating Systems Unit
- Environmental Applications of Solar Energy

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 123 persons that as of December 2010 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 123 persons who work daily for the PSA, 64 are CIEMAT personnel, 19 of whom are located in the main offices in Madrid. In addition, the 9 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, 15 work in operation, 14 in maintenance and 5 in cleaning. The auxiliary services contract is made up of 8 administrative personnel and secretaries, 3 IT technicians for user services, and another 5 persons from the security contract.

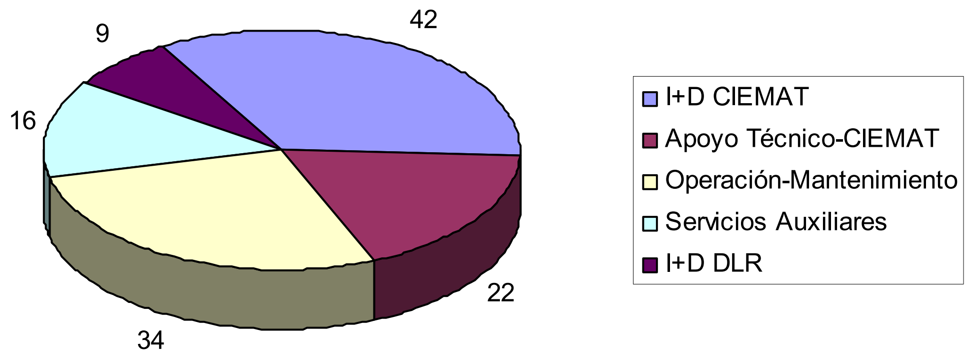


Figure 1.3. Distribution of permanent personnel at the PSA as of December 2009

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 expense budget has an upward trend, in large part due to higher income, both from European Commission project funding, and from the National Plan for RD&I, although the most important factor was the increase in revenues from research contracted by business.

The PSA operating budget in 2010 4.8 million Euros (not including R&D personnel or new infrastructure).

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 VI of this Agreement, which includes the commitment to maintain a permanent DLR delegation at the PSA from 2009 and 2011.

In all, the scope of collaboration in which the PSA moves is remarkably wide. In the international sphere, the PSA actively participates in the International Energy Agency 'SolarPACES' (Solar Power and Chemical Energy) 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 founding 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

Figure 1.4. Photo of the 'CIESOL' Bldg.

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 Paul Scherrer Institute in Zurich (Switzerland) and the CIEMAT itself.

In training activities, there is an agreement with the University of Almería (UAL) for managing joint fellowships and 'ad hoc' 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 Joint Center for Solar Energy Research' called 'CIESOL'.

Apart from the joint projects carried out in several fields of science, this year, the 2nd CIESOL Master's Degree in Solar Energy was given. This one-year Master's degree is listed in the Univ. of Almería's coursework catalog.

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.

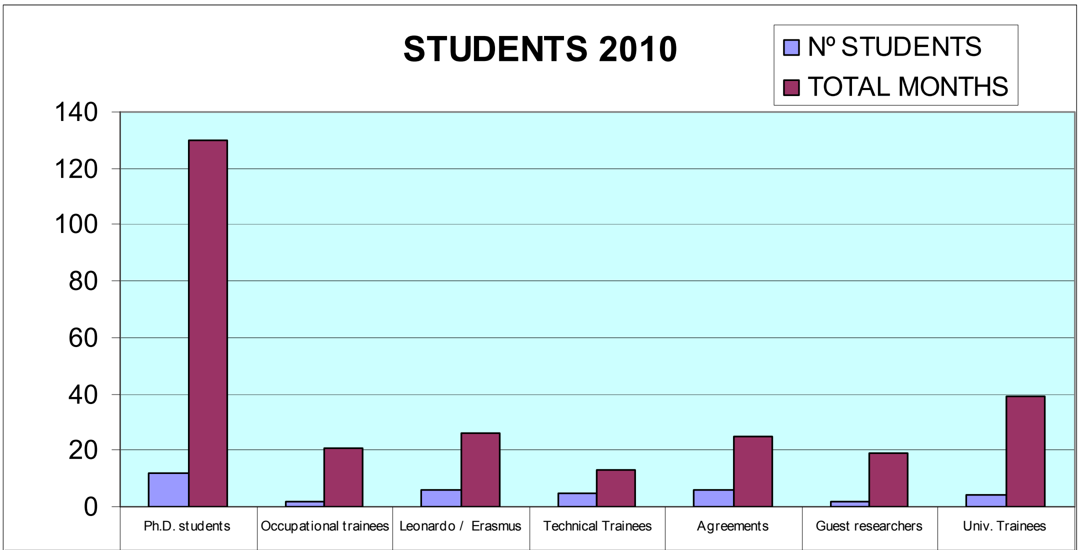
Apart from all these institutional cooperation programs, it should be pointed out that each of the two R&D Units keeps up a stable range of collaboration, including national and international universities, SME and large companies.

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 especially interested in solar thermal electricity technology development and commercialization, for example, IBERDROLA, ABENGOA Solar, GAMESA, SENER, ENDESA, ACCIONA and ECOSYSTEM.

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.



	Ph.D. students	Occupational trainees	Leonardo / Erasmus	Technical Trainees	Agreements	Guest researchers	Univ. Trainees
Nº STUDENTS	12	2	6	5	6	2	4
TOTAL MONTHS	130	20,5	26	13	25	19	39

Figure 1.5. Fellowships in 2008

Very recently, ambitious lines of collaboration have been launched with Maghreb countries, specifically, in agreements signed 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 and COEXPHAL.

In Central and South America there ìs 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

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 joint SolLAB activities is an annual seminar for Ph.D. students from the five different institutions (Doctoral Colloquium). The sixth such seminar, organized this time by the PSA, was held from June 9th to 10th at the PROMES-CNRS Laboratory in Font Romeu (France).

1.6 PSA Access Activities

1.6.1 National Access

Since 2005, the National Plan for R&D has promoted a new line of activity for Spain's Unique Large Science and Technology Infrastructures (ICTS). This line, managed by the Ministry of Science and Education's General Directorate for Science and Technology Policy, annually announces the ICTS 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 ICTS 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 had a very successful response since 2005. In 2010, 21 researchers benefited from this program, enjoying a total of 57 weeks of free access to the various PSA test facilities.

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

1.6.2 International Access: The SFERA Project

SFERA is the acronym for "Solar Facilities for the European Research Area". It is an "Integrating Activity" under the 7th EU Framework's "CAPACITIES" Program. It is a four-year project, officially beginning on July 1, 2009. The CIEMAT coordinates a total of 12 partners and administers a European Commission subsidy of 7.4 M€.

The project's main goal is to advance toward the creation of the "Large European Solar Laboratory", in which all the major institutes working in CSP technology in Europe are participating.

- CIEMAT
- CNRS (PROMES Laboratory, France)
- DLR (Institute of Technical Thermodynamics), Germany)
- ETH (Swiss Federal Institute of Technology Zürich, Switzerland)
- Paul Scherrer Institut (Villigen, Switzerland)
- ENEA (Casaccia, Italy)
- Weizmann Institute (Rehovot, Israel)

The main purpose of the project is to integrate, coordinate and promote scientific collaboration among the main European research institutions working in the field of solar concentrating technology, with special emphasis on large experimental infrastructures for this technology.

It also intends to promote an offer of free access to these infrastructures focused on the scientific community and European industry.

The project is structured in three large blocks.

http://sfera.sollab.eu

Networking: These activities are directed at the creation of stable long-term cooperation among the project partners. It is intended to progress toward shared use of human and material resources, develop common standards and cooperate jointly with European industry and academic and research institutions. Some concrete intercenter activities are organization of courses, workshops, and guest researchers.

Joint research activities: These joint R&D activities are directed at improving test capacities and available infrastructures for experimentation, and thus offer a better service to the scientific community and also to industry, optimizing the use of European R&D resources available.

Access: All of the European institutes that have relevant solar concentrating technology test infrastructures are participating in this project. Through this activity, these activities are made available to the European scientific community. This is done by a mechanism of calls for competitive participation where a committee of independent experts evaluates the scientific quality and feasibility of the proposals received, and granting free access to the test facility requested to the groups that present the projects with the most scientific merit.

Five of the partners offer access to users from other countries through this financing scheme: ENEA, PROMES, WEIZMANN, PSI and the PSA.

This access is managed jointly by annual announcement and with the collaboration of an international experts committee that makes the selection from among the proposals received.

In 2010, five groups of users from other countries used the PSA solar detoxification facility for a total of 20 weeks.

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 sunbelt 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:

- 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
- The FRESDEMO "linear Fresnel" technology loop.
- The "Innovative Fluids Test Loop" for parabolic-trough collector systems

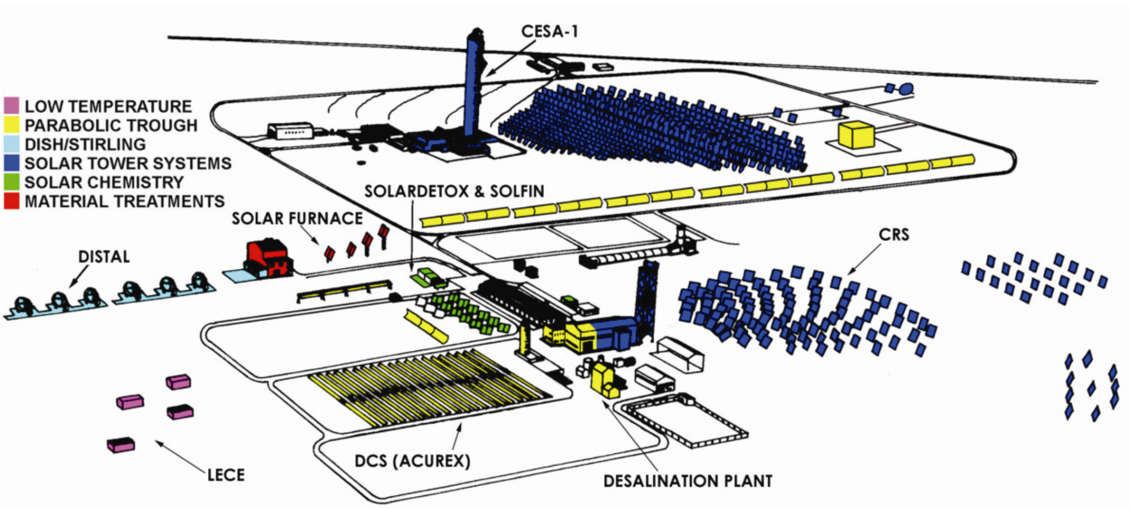


Figure 2.1. Location of the main PSA test facilities

- 6-unit DISTAL dish/Stirling facility.
- A 60-kW_t solar furnace for thermal materials treatments.
- A solar chemistry facility for solar detoxification applications consisting of a parabolic-trough loop with two-axis tracking and three CPC photoreactors for different types of trials.
- Laboratorio de Ensayo Energético de Componentes de la Edificación (Laboratory for Energy Testing of Building Components) (LECE).
- The ARFRISOL Building, an integral part of the "Unique Strategic Project" of the same name, which is a container-demonstrator for advanced energy savings and efficiency technologies in building.
- Meteorological station forming part of the "Baseline Surface Radiation Network" (BSRN).

These test facilities are complete with fully equipped specialized laboratories.

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, was promoted by the Spanish Ministry of Industry and Energy and inaugurated in May 1983 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

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

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 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 good working condition due to a strategic program of continual mirror-facet replacement and drive mechanism maintenance and replacement.

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, achieving a peak flux of 3.3 MW/m^2. 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.
- A multipurpose test facility for new receiver concepts at 75 m.
- A volumetric air 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.

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 conceived to demonstrate continuous electricity generation, 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 units manufactured by Martin-Marietta. A second field north of it has 20 52-m^2 and 65-m^2 second-generation supporting heliostats manufactured by MBB and Asinel.

The original CRS heliostat field was improved several years ago with the conversion of all of its heliostats into completely autonomous units powered by photovoltaic energy, with centralized control communicated 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.

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 thermochemical applications.

The second test platform is at the top of the tower at 43 m, and houses an enclosed room with crane and calorimetric test bed for the evaluation of small atmospheric-pressure volumetric receivers, and solar reactors for hydrogen production. The tower infrastructure is completed with a 600-kg-capacity crane and a 1000-kg-capacity rack elevator.

Figure 2.3. An autonomous heliostat in the CRS field

The facility's calorimetric test bed 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 characterize the concentrated solar radiation flux map 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-

Figure 2.4. Aerial View of the CRS Facility

resolution CCD camera records the image. After its exhaustive treatment, the total power can be integrated, and the rest of the magnitudes of interest, such as peak flux or statistical energy distribution parameters on the receiver can be calculated.

2.3 Linear focusing facilities: DISS, HTF, Innovative Fluids Loop and FRESDEMO and CAPSOL

The PSA has several linear-focusing solar collector facilities, both parabolic-trough and Fresnel. Many of these experimental installations, such as the innovative fluids test loop or the DISS plant, are the only one of their kind, 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 HTF Test Loop

The HTF test loop, which was erected in 1997 based on an LS-3 collector, which was later disassembled, and an ideal facility for evaluating parabolic-trough collector components under real solar energy operating conditions. The facility is appropriately instrumented for measurement and monitoring of the following components: .

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:

- Parabolic-trough collector mirrors

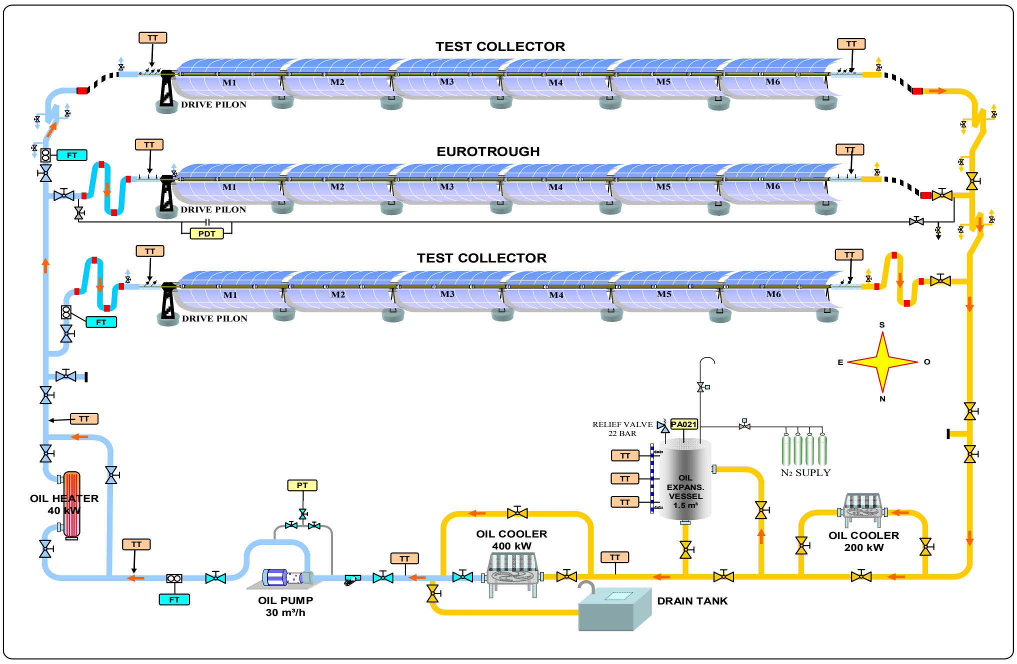


Figure 2.5. Diagram of the "HTF Loop" parabolic-trough solar collector test loop facility

- Parabolic-trough collector absorber tubes
- Parabolic-trough collector prototypes (up to 75 m long)
- New connector prototypes for parabolic-trough collectors
- Solar tracking systems

The facility consists of a thermal oil closed circuit connected to half of a EUROTrough-II parabolic-trough collector, with a total solar collecting surface of 274 m^2, and with connections for two more collectors with a maximum length of 75 m, all east-west-facing, which allows the number of hours per year when the solar radiation incident angle is under 5º to be increased. The thermal oil used in this facility (Syltherm 800) has a maximum working temperature of 420ºC and a freezing point of -40ºC.

The oil circuit in this facility has a maximum working pressure of 16 bar and is made up of the following components:

- 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.

The original LS-3 collector was replaced by the first EUROtrough-II collector prototype developed by a European consortium with the financial aid of the European Commission. Under this project, the new parabolic-trough collector was designed, built and erected at the PSA, and evaluated under real operating conditions. It is not only suitable 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. This collector is currently used for evaluating new absorber tubes.

2.3.2 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. It was the first facility built in the world where two-phase-flow water/steam processes in parabolic-trough collectors could be studied under real solar conditions.

The facility consists of two subsystems, the solar field of parabolic-trough collectors and the power block (BOP). In the solar field, feed water is preheated, evaporated and converted into superheated steam at a maximum pressure of 100 bar and maximum temperature of 400ºC as it circulates through the absorber tubes of a 700-m-long row of parabolic-trough collectors with a total solar collecting surface of 3,838 m^2. The system can produce a nominal superheated steam flow rate of 1 kg/s. In the power block, this superheated steam is condensed, processed and reused as feed water for the solar field (closed loop operation).

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

Facility operation is highly flexible and can work from very low pressures up to 100 bar. It is also equipped with a complete valve system allowing the solar field to be configured for recirculation (perfectly differentiated evaporation and superheating zones) or Once-Through (the intermediate water-steam separator and the recirculation pump located in the solar field are not used

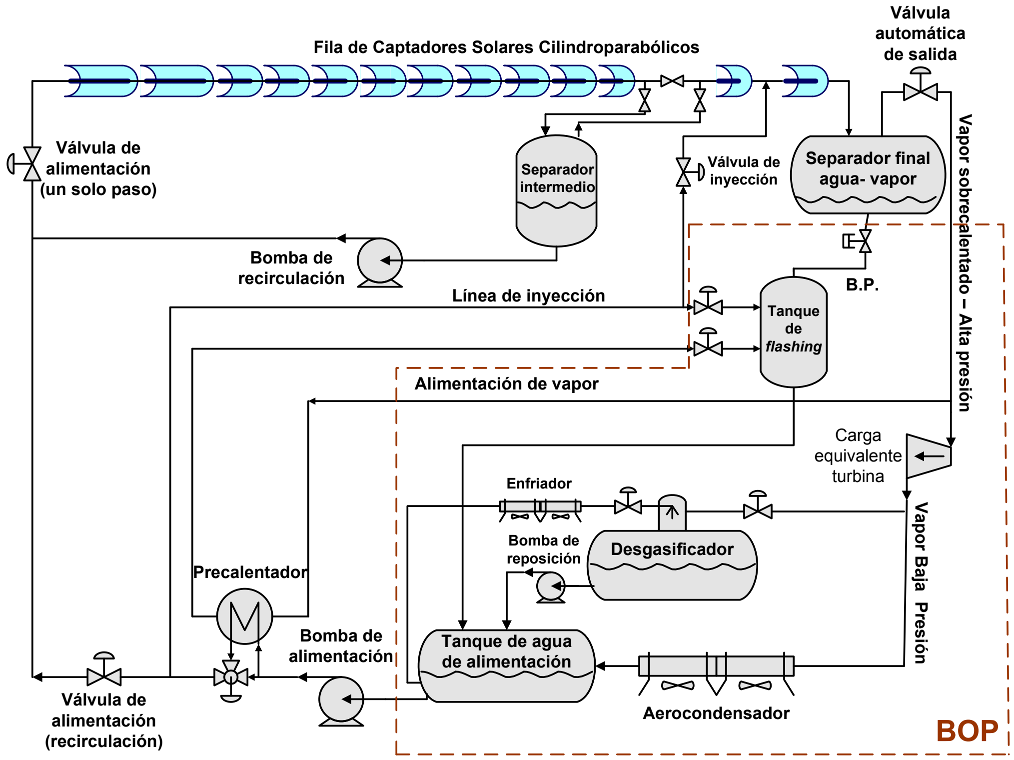


Figure 2.6. Simplified flow diagram of the PSA DISS loop

in). The facility is complete with a wide range of instrumentation for full system monitoring (flow rates and fluid temperatures in the various zones of the solar field, load loss in collectors and connectors, temperature and thermal gradients in the transverse sections of the absorber tubes, etc.) and a data acquisition and process control system which has a database where 5-s process data are recorded 24 hours a day.

Among the capacities associated with this facility are the following:

- Component testing for parabolic-trough collector solar fields with direct steam generation in their receiver tubes (receivers, joints, water-steam separators, specific instrumentation, etc.).
- Study and development of control schemes for solar fields with direct steam generation
- Study and optimization of the operating procedures that must be implemented in this type of solar field

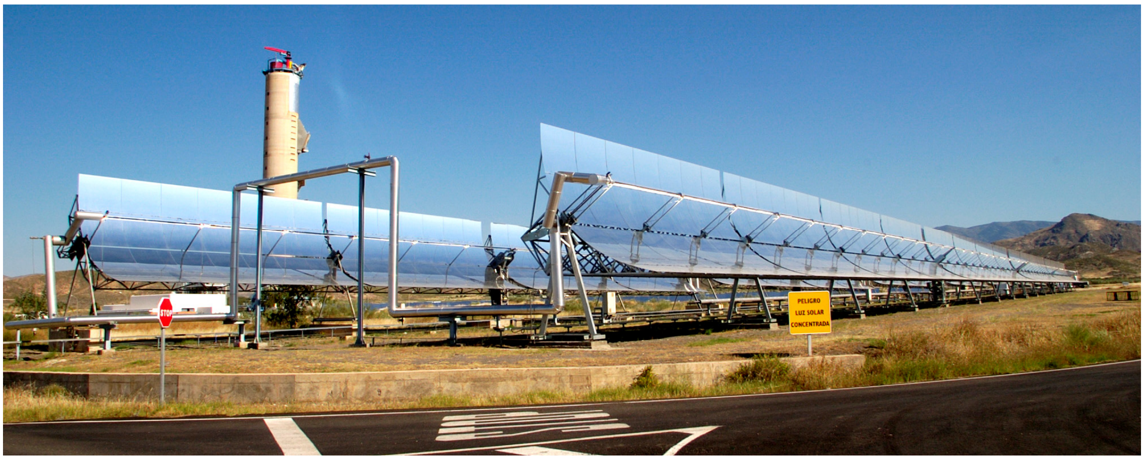


Figure 2.7. View of the DISS plant solar field in operation

- Study of heat transfer coefficients in horizontal tubes where there is two-phase flow of water/steam
- Study of the correlations for calculating load loss with two-phase flow of water/steam in horizontal tubes

2.3.3 Test Loop for pressurized gas in parabolic-trough collectors

The purpose of this experimental facility is to study pressurized gases as working fluids in parabolic-trough collectors, which has not been done to date, evaluating their behavior under a diversity of real operating conditions. The parabolic trough technology is currently the most commercially developed for solar thermal power plants with over 2.5 million sq. m of collectors in routine operation and a nominal capacity of 340 MW_e. In spite of its commercial maturity, ways must be found for this technology to reduce costs and increase performance for it to become more competitive with conventional power plants.

One of the options for lowering costs and increasing performance is the use of new collector working fluids. 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 been studied experimentally yet. The activities in this project are directed by Prof. Carlo Rubbia, holder of the Nobel Prize in Physics.

The purpose of this experimental facility is to study of innovative working fluids in parabolic-trough collectors which have not been studied until now, evaluating their behavior under a diversity of real operating conditions.

The experimental test loop is located north of the DISS loop control building, which houses the equipment necessary for its control and data acquisition.

The facility was originally designed to work at pressures and temperatures of up to 100 bar and 400ºC, and consists of the following components:

- Two east-oriented EUROtrough parabolic-trough collectors, each 50 m long with a 274.2-m^2 collector surface. The collectors can be connected in series or in parallel by means of a by-pass.
- An 400-kW air-cooler able to dissipate the thermal energy in the fluid coming from the collectors. It has two 4-kW motorized fans.
- A blower driven by a 15-kW motor which supplies the flow necessary to cool the collectors adequately.
- A data acquisition and control system that allows the temperature, flow rate, pressure, irradiation and humidity in the loop to be completely monitored.

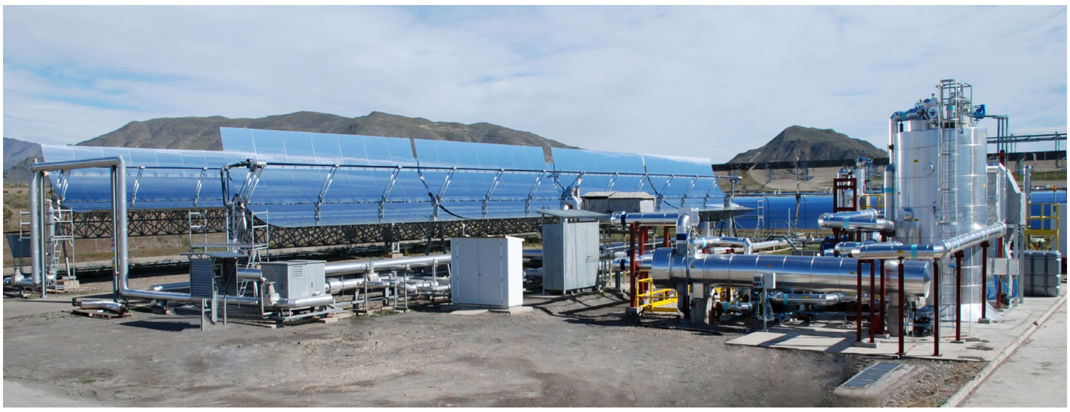


Figure 2.8. View of the pressurized gas test loop connected to a molten salt thermal storage system.

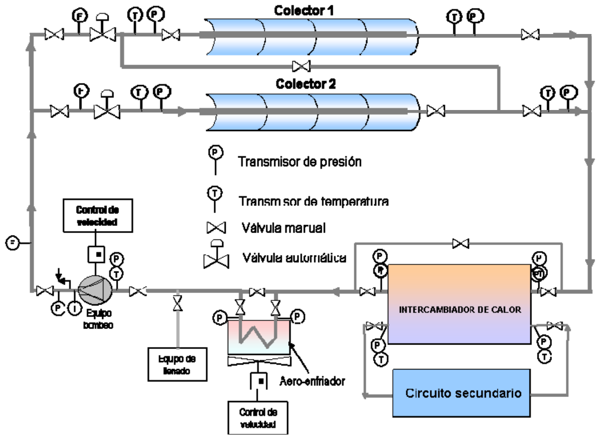


Figure 2.9. Simplified system diagram of the innovative fluids experimental facility.

- Automatic control valves that allow precise, safe variation in the collector fluid feed flow rate
- A secondary loop for filling the test loop with gas.

The collectors are provided with an innovative hydraulic solar-tracking system, which after testing at the Plataforma Solar de Almería, is already available on the market for installation in commercial solar thermal power plants currently under construction.

When testing at 400ºC were successfully completed at the end of 2009, it was decided to modify the test loop for fluids at up to 500ºC and integrate the loop in a molten salt storage system to test their joint capacity for collecting and storing solar thermal energy with a view to making use of them in dispatchable high-performance thermal cycles.

This increase in test loop design conditions to 100 bar and 500ºC has made the following modifications necessary:

- The conventional absorber tubes in Collector 2 were replaced with advanced high-temperature tubes
- The main pipe in the circuit had to be changed from Collector 2 to the air cooler outlet and the tube bundle in the cooler had to be modified.
- The test loop layout had to be modified to operate with two parabolic-trough collectors in series only, eliminating the bypass and automatic flow rate control valves.

The molten salt thermal storage system which forms part of a larger experimental salt loop, basically consists of:

- Two 39-ton salt tanks, hot and cold, able to provide about six hours of thermal storage
- An 344-kW air cooler to cool the salt with ambient air
- A 344-kW gas/salt exchanger providing the salt circuit with the solar energy collected in the innovate fluids test loop

The high-temperature test loop was commissioned at the end of 2010 and the associated salt storage system will be operating in 2011.

2.3.4 The FRESDEMO Loop

The FRESDEMO loop is a “Fresnel linear concentrator” technology pilot demonstration plant. This experimental plant currently belongs to the CIEMAT by agreement with the “Solar Power Group” Consortium and MAN Ferrostaal, which transferred ownership to the CIEMAT at the end of Stage I of the FRES-

DEMO Project. Nevertheless, the CIEMAT continues to make this plant available to the Solar Power Group and Man Ferrostaal for execution of the second stage of the FRESDEMO Project, carrying out new tests for evaluating its operation with the scientific-technical assistance of the PSA.

This 100-m-long, 21-m-wide module has a primary mirror surface of 1,433 m^2, distributed among 1,200 facets mounted in 25 parallel rows spanning the length of the loop. This collector loop is designed for direct steam generation at a maximum pressure of 100 bar and maximum temperature of 450º.

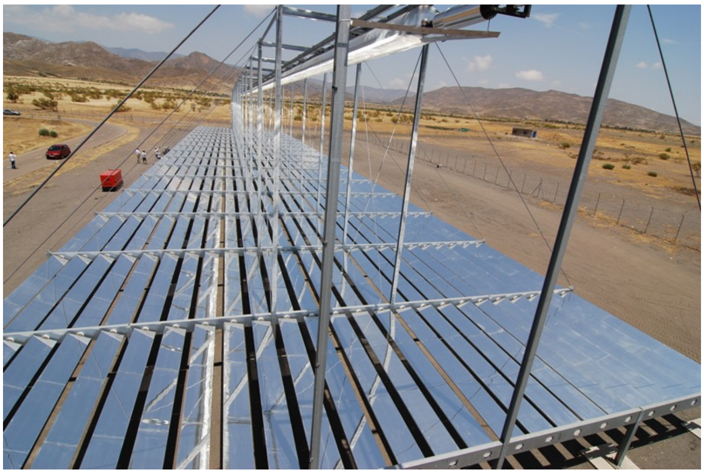


Figure 2.10. Photo of the MAN linear Fresnel demo collector erected on the Plataforma Solar de Almería (PSA).

It is presently connected by pipes to the PSA DISS (Direct Solar Steam) loop from where it is supplied with solar steam at different pressures and temperatures for testing in the three work modes: preheating, evaporation and superheating.

2.3.5 CAPSOL Facility

CAPSOL is a concentrating solar thermal energy test facility designed and built at the PSA for testing of small-sized, high-precision parabolic-trough solar collectors under real environmental conditions.

The facility is designed to operate with pressurized water under a wide range of operating conditions: fluid temperatures from ambient to 23ºC, flow rates from 0.3 to 2.0 m^3/h and pressures up to 25 bar. It also allows testing of different collector orientations and sizes (apertures up to 3 m). High-precision instrumentation has been installed for measuring all of the parameters required for adequate evaluation of parabolic-trough collectors. In particular, the facility has a flow meter (a *Yokowaga* Coriolis), with a ±0,1% measurement accuracy), a pyrheliometer (Eppley, with 8 μV/(Wm^{-2}) sensitivity) and two types of temperature sensors at the inlet and outlet of the solar field (4-wire PT-100 thermal resistors with an accuracy of ±0.3ºC in a 100 to 200ºC range). In addition to these instruments, the facility has sensors for measuring other parameters, such as fluid temperature at various points in the circuit, pressure, tank level, ambient temperature, wind speed and direction, etc.

Figure 2.11 below shows a Photo of the test facility with two CAPSOL-02 prototypes installed. These prototypes were developed under the CAPSOL Project funded by the MICINN (CIT-440000-2008-5).

Figure 2.11. CAPSOL solar thermal test facility for small-size parabolic-trough collectors.

This test facility makes it possible to find the efficiency parameters required for characterizing parabolic-trough collectors: peak optical-geometric efficiency, incident angle modifier, overall efficiency and thermal losses when collectors are out of focus. The stationary state conditions needed for performing these tests is reached thanks to the inertia of the expansion tank and auxiliary heating and cooling systems. The data acquisition and control system facilitates monitoring and recording of the parameters measured as well as system operation from the control room.

Both complete small-sized parabolic-trough collectors and their components, such as absorber tubes, reflectors or tracking systems, can be tested in this facility. Furthermore, the facility also allows analysis of technical aspects of the collectors, such as materials durability, structural resistance, component assembly, etc. under real operating conditions.

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 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.

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

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 EUROdish units.

Figure 2.12. 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.

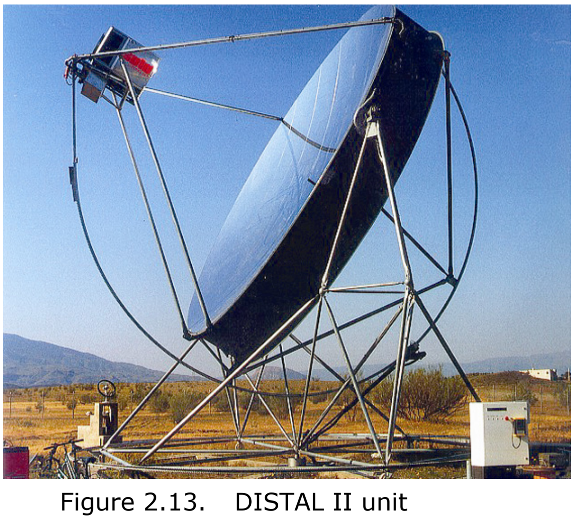


Figure 2.13. DISTAL II unit

2.4.4 EURODISH

Under the Spanish-German EUROdish project, two new dish/Stirling 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 molded composite-material system.

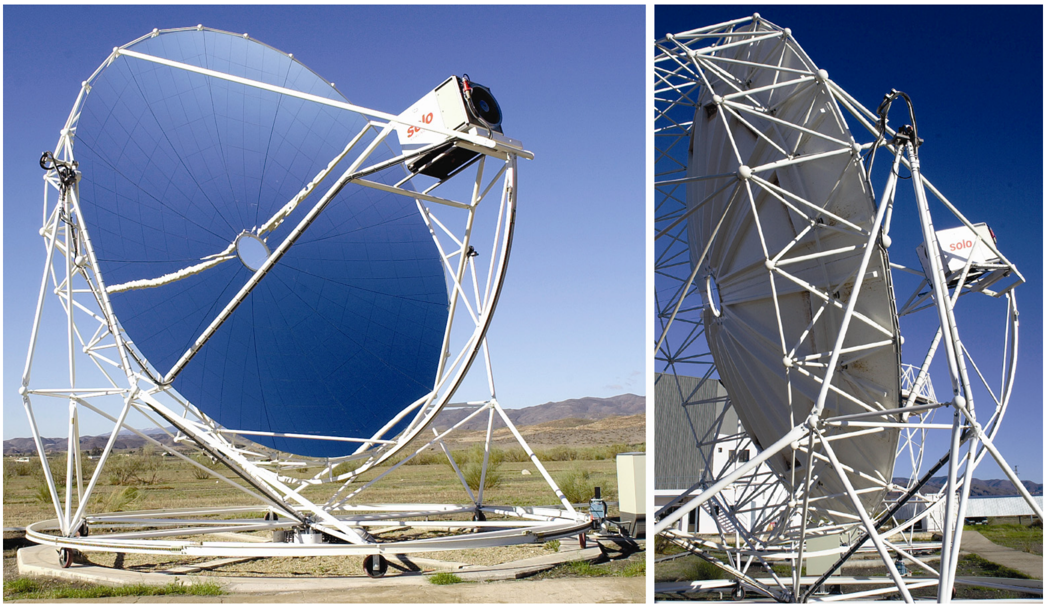


Figure 2.14. Front and back views of the EURODISH

- Improve the SOLO V161 'Stirling' motor, especially the components in the receiver cavity.
- 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.

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, a test table movable in three directions (East-West, North-South, up and down) places the test samples in the focus with great precision.

La PSA now has three solar furnaces called the SF-60, SF-5 and SF-40. The SF-60 is completely operative, while the SF-40 and SF-5 will be in 2011. These three furnaces are described below.

2.5.2 SF-60 Solar Furnace

In this furnace, the heliostat collects solar radiation and redirects it to the concentrator. The heliostat's reflective surface is made up a multitude of flat, non-concentrating facets, which reflect the sun's rays horizontally and parallel to the optical axis of the concentrator, continually track the solar disk.

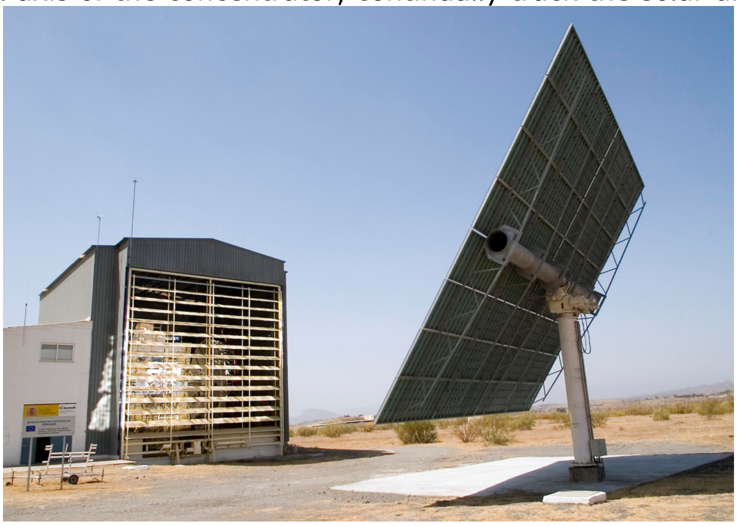


Figure 2.15. Exterior view of the SF-60 in operation.

The only heliostat associated with the SF-60 is the Solucar 120, which has 28 flat facets with a total surface of 120 m^2 and 92% reflectivity. Its focal distance is 7.45 m. The parabolic surface is achieved by spherically curved facets distributed along five radii with different curvatures depending on their distance from the focus.

The shutter (attenuator) consists of a set of horizontal louvers which turn on their axis to control the amount of sunlight incident on the concentrator. The total energy in the focus is proportional to the radiation that goes through the shutter.

The test table is a mobile support for the test pieces or prototypes to be tested that 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.

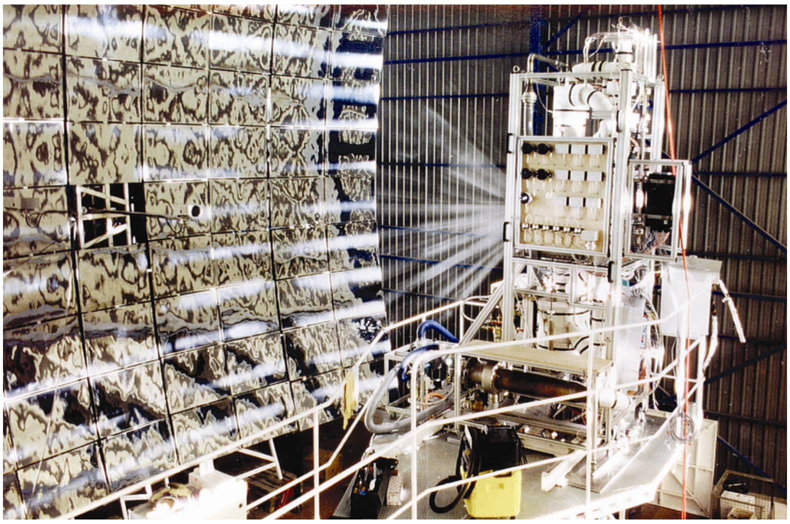


Figure 2.16. Interior view of the SF-60 Solar Furnace in operation

The combination of all of the components described lead to the flux density distribution in the focus which is what characterizes 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, 300 W/cm^2, total power, 69 kW and focal diameter, 26 cm [Monterreal, R.. Preliminar Analysis of Irradiance Distribution Shutter-100%. PSA internal document, 2005].

2.5.3 New solar furnace infrastructures, the SF-40 and SF-5 Furnaces

In 2010 construction of two new solar furnace facilities, the SF-40 and SF-5 progressed and will be operable next year. The horizontal axis Furnace, the SF-40, is now under construction lacking installation of the heliostat, and all the main components of the vertical axis furnace, the SF-5, have been installed and it is now being commissioned.

The construction of these two new solar furnaces practically triple the solar furnace capacity, although the specific characteristics of each one will make them specialize in different applications, such as surface treatment of materials with high photon concentrations or research in high-temperature industrial applications. Some further technical data are given below for these two solar furnaces.

The new SF-40 furnace, so called because of its 40-kW power, consists mainly of an 8.5-m-diameter Eurodish, with a focal distance of 4.5 m. The concentrator surface consists of 12 curved fiberglass petals or sectors covered with 0.8-mm adhesive mirrors on the front. The parabola thus formed is held at the back by a ring spatial structure to give it rigidity and keep it vertical.

The test table, in the center of the SF-40 furnace test room in front of the concentrator and in its focal zone, is moveable on three axes. It is comprised of three linear modules with operative runs of 1000 mm on the X axis, 700 mm on the Y axis and 600 mm on the Z axis, and is able to move a 150-kg load. On the north face of the test room, like a large Venetian blind, is the 11 m x 11 m louvered shutter, which controls the amount of light incident on the concentrator. Finally, the flat heliostat with a 100-m^2 reflective surface, which is still under construction, completes the installation.

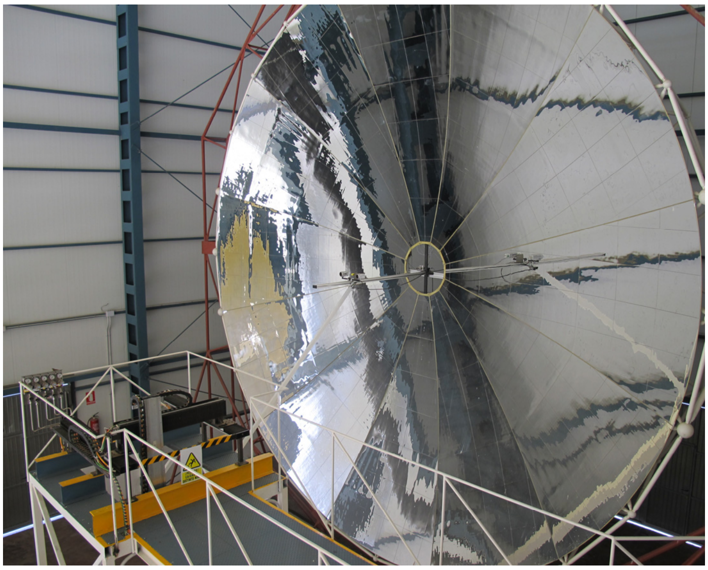


Figure 2.17. Interior of the SF40 solar furnace in its final stage of construction

The SF-5 Solar Furnace is a new vertical axis furnace designed and built at the Plataforma Solar de Almería. This new furnace was conceived for tests that require high radiant flux, strong gradients and very high test temperatures.

The new Solar Furnace is located south of the SF-60, and basically consists of a concentrator, placed upside down, with the reflective surface facing the ground, at the top of an 18-m metal tower. In the centre of the base of the tower is a flat heliostat with its center of rotation aligned with the optical axis of the concentrator.

At the top of the tower of the SF-5 furnace, in the test room and 2 m below the vertex of the concentrator, is the test table. Finally, the louvered shutter is on the “floor” of test room, in horizontal position between the heliostat and the concentrator, completing the main components of the vertical-axis solar furnace. This facility is nearly commissioned.

Figure 2.18. Vista exterior del Horno Solar SF-5, que se encuentra en su fase final de puesta en marcha.

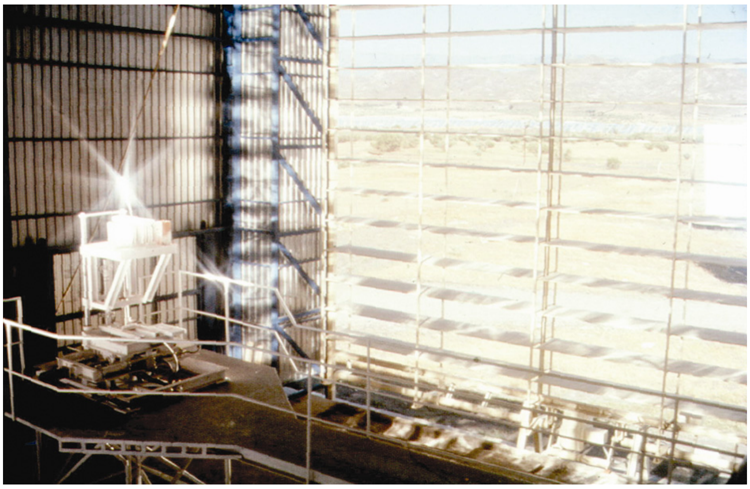


Figure 2.19. The focus and the test table, on the left. On the right, the completely open shutter allows the rays from the heliostats outside to come in.

2.6 Solar Concentrating Systems Unit Labs

2.6.1 Materials Lab

Associated with the Solar Furnaces, the PSA, among its other facilities, has a materials lab devoted mainly to the metallographic preparation and the analysis of test pieces treated with concentrated solar energy.

The lab's equipment is currently as listed below:

Figure 2.20. View of the PSA Materials laboratory

- **Leyca DMI 5000 optical microscope** with Leyca-IM50 image acquisition system and motorized table.
- **Olympus optical microscope** Union MC 85647.
- **Struers micro hardness tester** Duramin HMV-2
- **Manual hardness tester**
- **Surface Finish Measuring Unit** ZEISS Surfcom 480 with data processor.
- **Grinder** Remet SM1000
- **Automatic cutoff machine** Struers Secotom
- **Manual cutoff machine** Remet TR60
- **Mounting press** Struers Labopres-3
- **Vacuum impregnation unit** Struers Epovac
- **Polisher** Tegrapol-15 automatic with Tegradoser-5 dosing system
- **Metallographic polisher** 2 plates "LS1/LS2" (Remet)
- **Scale** Mettler E2001/MC max **60Kg**
- **Scale** Mettler Toledo classic max **320g** / min 10mg
- **Ultrasonic bath** Selecta with heater
- Olympus **digital camera** with **reproduction table**

The PSA also has an electronic microscope with the following specifications and installed in its own room, which is shared by the AMES and SCS units.

- **Scanning electronic microscope (SEM) - Hitachi**, model S-3400N II, high/low vacuum, secondary electron image, backscattered electron image, cooling stage and magnification x5 to x 300.000.
- Microanalysis by Quantax 400 Energy dispersive x-ray spectrometer (EDS)

The SEM room also has environmental secondary electron detector (**ESED**), a **critical point dryer** and **Sputterer**

2.6.2 Selective Receiver Coatings Laboratory

The selective solar receiver coatings lab has equipment for development and complete study of new selective coatings for absorbent materials used in solar concentrating systems at medium and high temperature (up to 600ºC), as well as for anti-reflective treatments for glass covers used in some receiver designs, such as receiver tubes in parabolic-trough collectors.

The laboratory has sufficient equipment to characterize and evaluate CIEMAT coating developments, and to evaluate the behavior of other treatments available on the market or developed by other public or private institutions. The equipment is also used for optical characterization of solar reflectors. A summary of the equipment available is given below:

Perkin Elmer LAMBDA 950 Spectrophotometer

The general specifications of the spectrophotometer are:

- Double beam Spectrophotometer with a 175 to 3300 nm range.
- Tungsten halogen and deuterium light sources with automatic mode switching
- Holographic grating monochromator with silica coating
- Photomultiplier detector R6872 for UV/VIS and peltier-cooled PbS for NIR
- Large-capacity sample compartment (200x300x220 mm).
- External spectrophotometer control by PC with complete software

The equipment includes the following accessories:

- Universal reflectance accessory (URA) for UV/VIS and NIR for absolute reflectance measurement with automatic angle change
- 150-mm-diameter integrating sphere, coated with Spectralon for measurement of reflectance with incident angle of 8º and transmittance at 0º
- Measurement tray for the sample compartment
- Directional reflectance and transmittance accessory

This instrument can measure:

- Hemispherical reflectance of specular or diffuse samples from 250 to 2500 nm.
- Specular reflectance as a function of incidence angle from 250 to 2500 nm
- Direct transmittance as a function of incidente angle from 250 to 2500 nm

With these measurements, the solar absorptance of selective absorbers, specular reflectance of solar reflectors, and solar transmittance of glass covers of solar collectors can be calculated.

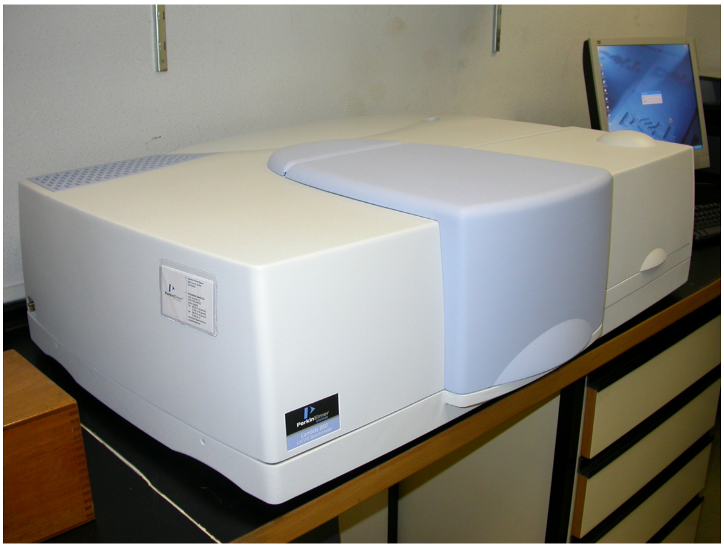


Figure 2.21. . Perkin Elmer Lambda 950 Spectrophotometer

Nicolet Magna IR Spectrophotometer

General specifications of the spectrophotometer:

- Resolution better than 0.1 cm-1.
- Pre-aligned laser source and detectors
- Measurement range 400 to 4000 cm-1
- KBr Optics.
- Large-capacity sample compartment (200x300x200 mm).
- Excellent signal to noise ratio
- External spectrophotometer control program by PC with complete software

Figure 2.22. Magna IR FTIR Spectrophotometer

This instrument has the following accessories.

- Specular reflectance accessory with 8º angle of incidence
- 100-mm-diameter integrating sphere, infragold reflectance coating for measuring hemispherical reflectance
- Direct transmittance measurement accessory

This equipment can measure hemispherical reflectance of flat samples and parabolic-trough collector receiver tubes for calculating the thermal emissivity.

Portable Optosol absorber characterization equipment

This equipment measures solar absorptance and thermal emittance of selective absorbers at 70ºC, both on flat substrates and absorber tubes.

The device for measuring absorptance has an integrating sphere with two detectors, one silica with a response up to 1.2 µm and one germanium with a 1.2 µm resolution at 1.9 µm. The illumination source is four LED diodes (blue, green, red and IR) and a halogen lamp.

For measuring emissivity, it has a semi-cylindrical tunnel which emits infrared radiation at 70ºC. The tube to be measured (maximum diameter 70 mm) is placed axially and the radiation reflected between 8 and 14 micra is collected by the detector.

It can also measure solar transmittance of the glass covers with the solar absorptance measurement accessory.

Figure 2.23. Optosol integrating sphere for measuring solar absorptance

Figure 2.24. Accessory for thermal emissivity measurement at 70ºC.

This instrument has the advantage of allowing measurement of large samples, even tubes, very quickly and simply, which is very useful for quality control. It has a 2% measurement uncertainty, but a comparative study is being carried out with measurements by the Perkin Elmer Lambda 950 spectrophotometer to try and reduce this error.

QUV weathering chamber, Q-PANEL, for accelerated ageing tests

This chamber is for accelerated durability testing of materials that work outsider, simulating UV radiation, temperature and rain. The effects of solar radiation are simulated by UV fluorescent lamps (UVB-313). These lamps increase accelerated ageing using shortwave ultraviolet light normally found on the Earth's surface. The condensation mechanism reproduces dew, which is the main cause of humidity in exposure to outdoor conditions, as well as rainfall. The exposure temperature is also automatically controlled (40ºC-80ºC), and radiation, spray and humidity can be alternated with controlled temperature. This chamber meets the specifications allowing testing following a large number of standards, such as ASTM G154, ISO 4892-10, UNE 104-281-88, and UNE-EN 1096-2. The chamber is used for coatings, solar absorbers, reflectors, paint, plastic and adhesives.

Figure 2.25. Cámara climática y detalle de los tubos de radiación UV-B

BROOKFIELD LVDV-I+ Viscometer

This equipment can measure the kinetic viscosity of liquids in a 1 to 200 cP measurement range

Viscosity is measured by determining the torque necessary to make an object submerged in the sample turn using a synchronous rotor with a calibrated Be-Cu spring.

The viscosity of liquids depends on the temperature, so the liquid to be measured has to be thermostatically controlled. The viscometer has a cylinder in which the sample liquid is placed and an outer sleeve in which a fluid can be circulated at a constant temperature maintained by a controlled temperature bath.

The instrument's resolution is 0.01 cP and the measurement error is 0.01 cP.

The instrument has a "UL Adapter" for measuring liquids with low viscosity (1-10 cP), such as the typical solutions used for the sol-gel technique.

KSV CAM200 goniometer for measuring contact angles

This instrument can measure the angle of contact and/or surface tension of liquids using an optical method. The angle of contact measures the capacity of a liquid to make a solid surface wet and is the angle formed by the plane on a tangent to the liquid-gas interface and the plane formed by the solid in three-phase solid-liquid-gas contact as shown in Figure 2.26. The form of the drop is a function of the surface tensions of the three media that make up the interface. The measuring procedure consists of allowing a drop of liquid (usually water) to fall on the surface to be measured and an image of the drop is acquired using an optical system. The contact angle is measured by software which automatically calculates Young & Laplace equations.

The applications of this instrument are surface treatments, textile coatings, and self-cleaning surfaces.

(a) (b) (c) (d) (e)

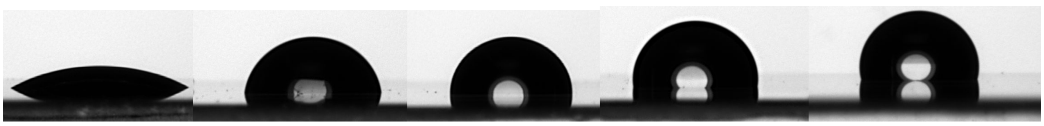


Figure 2.26. Photos showing how the angle of contact varies as a function of the hydrophobicity of the substrate.

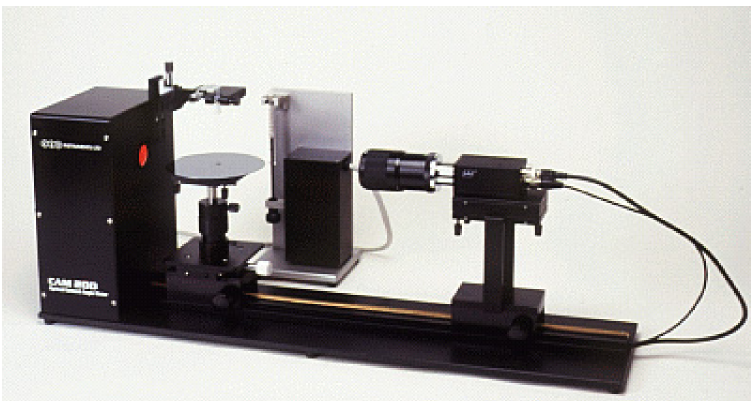


Figure 2.27. Goniometer for measuring contact angles

Kilns

There are three kilns for thermal treatment:

- 120x100x300 mm kiln with a maximal temperature of 1200ºC.
- Controlled atmosphere kiln with a maximal temperature of 800ºC
- 500x400x600 mm forced convection kiln with a maximal temperature of 550ºC.

2.6.3 Solar reflector durability analysis and optical characterization labs

The optical characterization and solar reflector durability analysis laboratories have the equipment necessary for complete study of the materials used as reflectors in solar concentrating systems.

This lab allows the characteristic optical parameters of solar reflectors and their possible deterioration to be determined. The lab has the following equipment for both quantitative and qualitative measurement of the reflectance of reflective surfaces:

- Two portable specular reflectometers, Devices and Services Model 15R, for measurement of specular reflectance at 660 nm at different aperture angles (7, 15, 25 and 46 mrad).
- Reflectometer prototype for measuring specular reflectance in a 5 cm diameter with spatial resolution of 10 pixel/mm, which measures at various wavelengths and aperture angles (model S^2R^2, designed and patented by DLR).
- Perkin Elmer Lambda 1050 spectrophotometer, with 150-mm integrating sphere and specular reflectance with 0 to 68º incidence angles (URA).
- Nikon D3 camera and 90 cm Cubalite kit for photos of specular surfaces without parasitic reflections.
- Leica 3D microscope model DCM3D (with magnifications of 5, 10, 20, 50 and 100) for finding the profiles and roughness of highly reflective surfaces.
- Optical bench with advanced features for mounting optical devices for the development of new measurement instruments.

The solar reflector durability analysis lab is designed for accelerated ageing tests of these materials for the purpose of predicting in a short time, the behavior of these materials during their useful lifetime. To do this, the environmental variables producing deterioration of solar reflectors when they are exposed to outdoor conditions are applied in a controlled manner, both separately and in combination. The following simulation equipment is installed for these accelerated ageing tests:

- ATLAS SC340 weathering chamber for temperature (from -40 to

Figure 2.28. PSA solar reflector optical characterization lab (left) and durability analysis lab (right)

+120ºC), humidity (from 10 to 90%), solar radiation (from 280 to 3000 nm) and rainfall of 340L.
- Control Técnica CSF 500A 500-L salt fog chamber with temperatures of 10 to 50ºC
- Hönle UVA Cube Ultraviolet radiation chamber
- Acid rain chamber, 300 L and temperatures up to 70ºC and humidity up to 100%, Ineltec CKEST 300
- Sandstorm chamber with speeds up to 30ºm/s and concentrations up to 2.5g/m^3, manufactured by control Técnica.
- Erichsen 494 cleaning abrasion device, with several cleaning accessories.
- Two Nabertherm LT 24/12 and LT 40/12 kilns
- Several devices for application of thermal cycles specially designed at the PSA.

Along with the lab, there are a series of outdoor test benches for exposing materials to outdoor weather conditions and comparing their degradation those found in the accelerated ageing tests.

Finally, the laboratories are equipped with accessories necessary for their proper use, such as precision scales, thermo magnetic stirrer, drier, tools for manipulating and cutting reflectors (both first and second surface), instrumentation for measuring pH, conductivity, oxygen, etc.

2.6.4 Geometric characterization of reflectors and structural frames

The concentrators used in solar thermal Systems (heliostats, parabolic-trough collectors, parabolic dishes, Fresnel lenses, etc.) require high precision concentration of the solar radiation for it to be suitable and most of it incident on the receiver component (receiver tubes in parabolic-trough collectors, receivers in tower systems, etc.).

For the geometric characterization of these concentrators, the Plataforma Solar de Almeria has a laboratory in which photogrammetry is used to quantify the optical quality of:
- Parabolic-trough collector facets
- Parabolic-trough collector modules
- Heliostat facets
- Heliostats
- Fresnel lenses and reflectors
- Parabolic dishes
- Structural frames
- Etc.

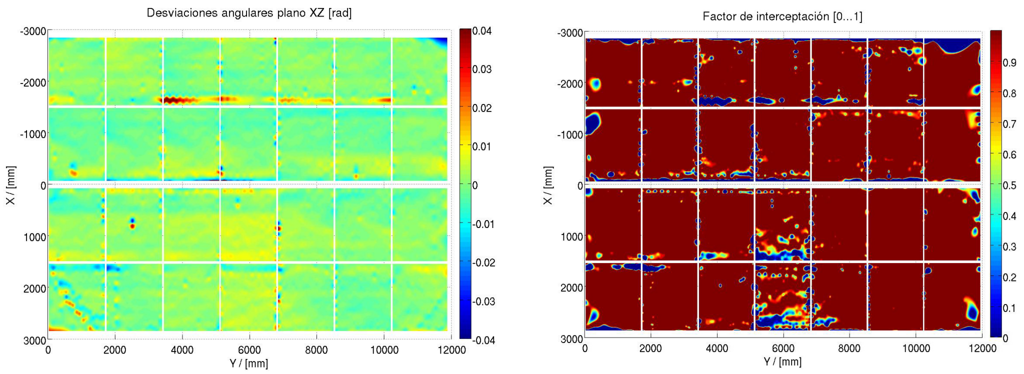


Figure 2.30. Angular deviations (left) and intercept factor of a parabolic-trough collector module analyzed by photogrammetry.

Photogrammetry consists of three-dimensional modeling of any object from photographs that capture it from different angles. Based on these photographs, the three-dimensional coordinates (x, y, z) can be calculated for the points of interest on the object being modeled. Photogrammetry modeling is precise up to 1:50000 (precisions on the order of 0.1 mm for parabolic-trough collector facets and 0.6-0.7 mm for 12-m-long parabolic-trough modules).

The equipment and resources currently available at the PSA for photogrammetric measurements are:

- CANON EOS5D MarkII Camera
- CANON EF 20mm f/2,8 USM lens
- Photomodeler Scanner V6.0 photogrammetry software.

A software package for model analysis of calculation of relevant parameters for 2D and 3D geometries in the MatLab environment has been developed in house.

Among the parameters that can be calculated from the model built by photogrammetry are:

- Deviations of real from theoretical surface on coordinates x, y, z.
- Gravity deformation between different concentrator orientations.
- Angular deviation from the normal vector to the surface compared to the theoretical normal vector.
- Deviation of reflected rays on the reflective surface of the module compared to the theoretical concentrator focus.
- Intercept factor
- (Calculation of other relevant parameters by request)

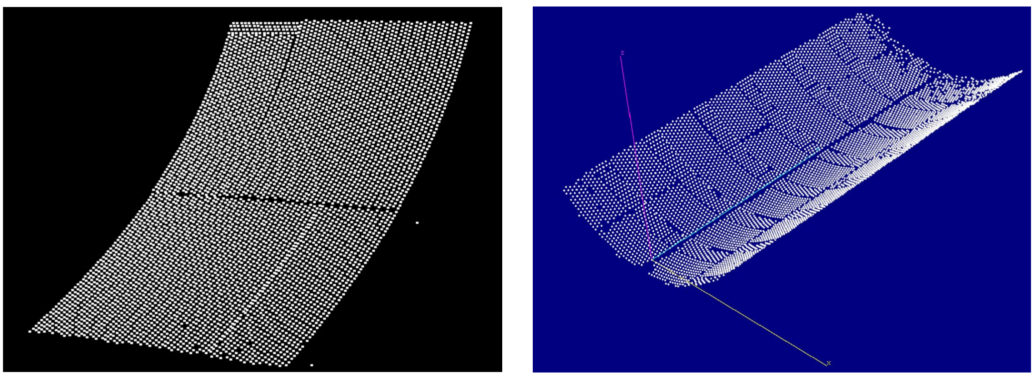


Figure 2.29. Three-dimensional models of a parabolic-trough facet (left) and a complete module found by photogrammetry.

Figure 2.31. General view of the parabolic dishes in the ageing and durability lab

2.6.5 Accelerated ageing and durability of materials lab

Solar thermal power plants are at the beginning of their mass commercial exploitation. One of the greatest challenges for the technology consists of diminishing insofar as possible, the risk associated with its main components, such as the solar receiver. These components are subjected to very high solar flux (up to 1200 kW/m^2) and high temperatures (200ºC to 1200ºC depending on the heat transfer fluid selected). The greatest technological risk of this type of plant is associated with the selection of suitable materials with which to manufacture the receiver, especially their durability under real operating conditions, recalling that the characteristic lifecycle of such plants is around 20-25 years.

From this perspective and in an international context, methodologies are beginning to be developed that approach the problem of accelerated ageing of these components and materials. This includes study of the durability of the most critical components of solar thermal power plants, not only absorbent materials, but also surface treatment and coatings that increase their absorptance. It is therefore necessary to find out and study the mechanisms of the physical degradation, fatigue and breakage of these materials at high temperatures under concentrated solar radiation.

The CIEMAT is therefore installing at the PSA, an accelerated ageing ad durability of materials laboratory to cover a demand that is becoming important in the field of solar concentrating systems.

The accelerated ageing laboratory is distributed among the CIEMAT facilities at the Plataforma Solar de Almeria and Moncloa (Madrid); and has the following capabilities:

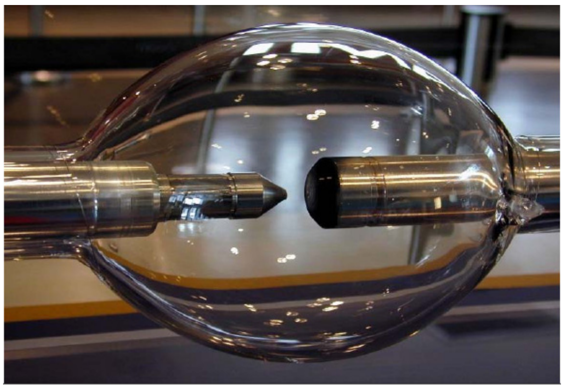
- A laboratory equipped with the instrumentation necessary for thermal cycling: two kilos, a high-temperature kilns, a weathering chamber, an air-cooled volumetric receiver test loop and associated instrumentation; and for materials analysis, optical and electronic microscopes, micro hardness tester, thermal scale, x-ray dispersion analysis, etc. Construction of this laboratory began in 2009 with funds from Plan E and began operation in the second half of 2010.
- Four parabolic dishes, three DISTAL II with a total thermal power of 50 MW and two-axis Trucking and one DISTAL-I with a total thermal power of 40 MW and one-axis polar Trucking. The Stirling engine in the four dishes has been replaced by different test platforms where materials or scaled receiver prototypes can be tested at high solar concentrations and with accelerated temperature cycling. These platforms cover a wide variety of applications, from testing with materials as such, testing of air-cooled volumetric receivers (metal or ceramic), testing of scaled receiver prototypes with or without heat transfer fluid, etc.
- A 4-kW solar simulator, installed in CIEMAT-Moncloa made up of a xenon lamp and a parabolic concentrator that can reach fluxes of up to 1400 kW/m^2.

2.6.6 PSA Radiometry Lab

The PSA Radiometry Lab came out of the need to verify measurement of highly important radiometric magnitudes associated with solar concentration. These magnitudes are solar irradiance ("flux" in the jargon of solar concentration) and surface temperature of materials (detection by IR).

At the PSA different systems are used to measure high solar irradiances on large surfaces. The basic element in these systems is the radiometer, whose measurement of the power of solar radiation incident on the solar receiver aperture depends on its proper use. The measurement of this magnitude is fundamental for determining the efficiency of receiver prototypes evaluated at the PSA and for defining the design of future central receiver solar power plants.

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



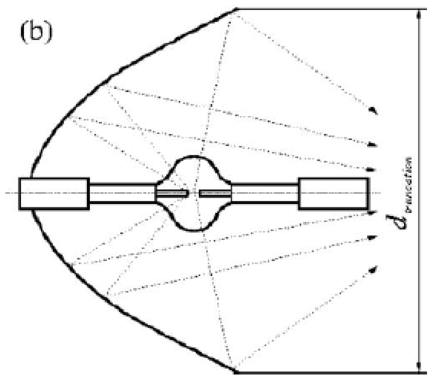


Figure 2.32. Xenon lamp used in the solar Simulator and configuration of the lamp and concentrator.

The Radiometry Laboratory has three black bodies as references for calibrating IR sensors for measuring temperature with guaranteed traceability between 0 and 1700ºC. The MIKRON 330 black body is a cylindrical cavity which can provide any temperature from 300 to 1700ºC accurate to ±0.25% and a resolution of 1ºC. Its emissivity is 0.99 in a 25-mm-diameter aperture. The MIKRON M305 black body is a spherical cavity that can supply any temperature between 100 and 1000ºC accurate to ± 0.25% and with a resolution of 1ºC. Its emissivity is 0.995 in a 25-mm-dia. aperture. The MIKRON M340 black body is a flay cavity and can provide any temperature from 0 to 150ºC accurate to ± 0.2ºC and a resolution of 0.1ºC. Its emissivity is 0.99 in a 51-mm-aperture. These black bodies have a built-in PID control system and the temperature is checked by a high-precision platinum thermocouple.

Some of the testing done at the PSA requires high-temperature measurements (>1000ºC) on the surfaces of materials. Thermocouples are commonly used, even though it is well known that contact methods are not accurate for surfaces. Therefore, the use of infrared detectors (non-contact measurement) is required.

2.7 Detoxification and Disinfection Facilities

The solar detoxification and disinfection facilities consist of a pilot CPC (compound parabolic-trough collector) plant and a PTC (Parabolic-Trough Collector) has a 32 m^2 collector surface 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.

Of the pilot plants employing CPCs, the oldest (1994) consists of three 3-m^2 modules tilted 37º from the horizontal. 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. There are also small twin prototypes (refitted in 2007) for parallel experiments. Each of these prototypes is made up of two CPC modules which together have a 3.08-m^2 illuminated surface (30-mm dia.) and a total volume of 40 L, 22 L of which are irradiated. This facility can be covered with Plexiglass transparent to solar-UV, making it possible to work at higher temperatures for photo-Fenton. The cover may be removed to compare the effect of temperature in similar experiments with and without the cover. Since 2004, another 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 50-L ozonization system (with an ozone production system of up to 1150-L

Figure 2.33. Radiometry Lab

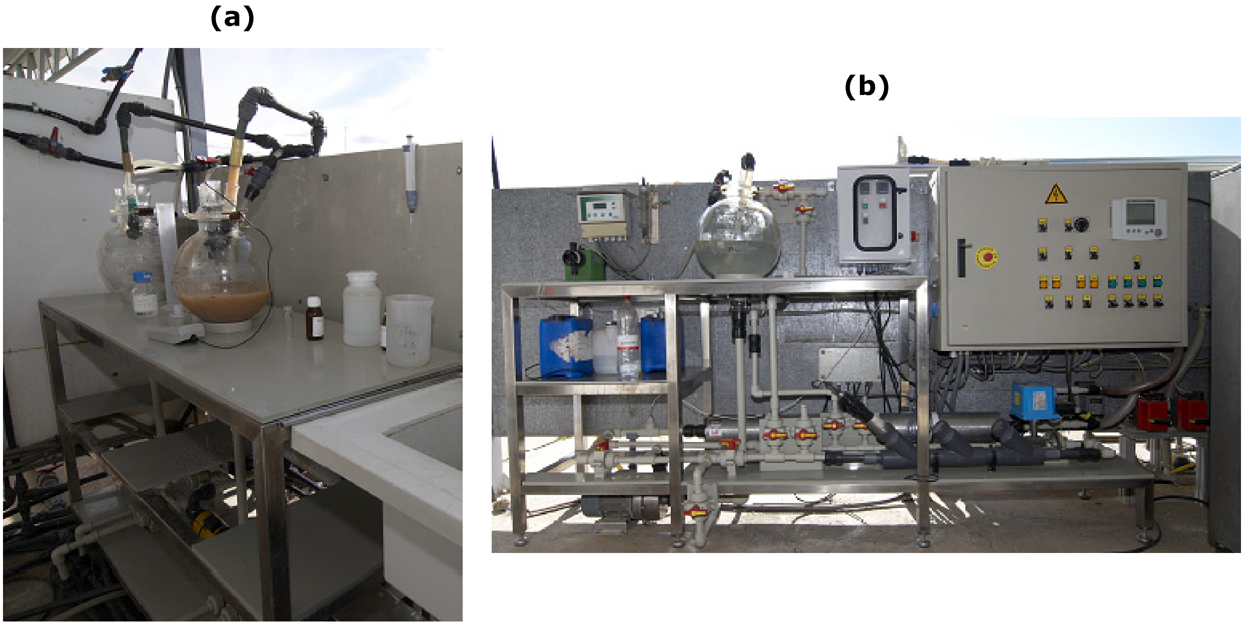


Figure 2.34. Photos of the auxiliary facilities and instrumentation remodelled in the CPC photoreactors (a) SOLEX and (b) CADOX.

fixed biomass biological reactor on an inert matrix, and 50-L ozonization system with ozone production of up to 15 g O_3/h). It is completely monitored (pH, T, ORP, O_2, flow rate, H_2O_2,0_3) and controlled (pH, T, flow rate) by computer. Also connected to this photoreactor is the biological water treatment system (Figure 2.34), consisting of three tanks: a 165-L conical tank for conditioning the wastewater to be treated, a 100-L conical recirculation tank and a 170-L flat-bottom fixed-bed aerobic biological reactor. The fixed-bed reactor is full of Pall®Ring polypropylene supports that take up 90-95-L and are colonized by active sludge from a WTP. The process is completely automatic, is instrumented with pH, REDOX potential, dissolved oxygen, and temperature sensors. Furthermore, pH and dissolved oxygen are automatically controlled by dose pumps.

There are also several prototype CPC collectors for water disinfection applications. One of these systems consists of two 50-mm outer dia. borosilicate-glass tubes installed in the reflector focus and mounted on a fixed platform tilted 37º (local latitude) and connected in series. The illuminated collector surface area is 0.42 m^2. The total volume of the system is 14 L and the illuminated volume is 4.7 L. In November 2008, another photoreactor for solar disinfection (FITOSOL) was installed, which consists of two components, a CPC solar reactor and a pilot post-treatment plant arranged on an anodized aluminum platform tilted 37º. The solar reactor consists of two CPC mirror modules, each one with ten borosilicate-glass tubes. 45 L of the 60 L total volume are irradiated in this system. The irradiated collector surface is 4.5 m^2. The reactor is completed with a pH sensor and another for dissolved oxygen, inserted in the tube and connected to a Crison MULTI44 controller for automatic data acquisition of both parameters. The water post-treatment pilot plant consists of a 100-L tank for separating the TiO_2 from the treated water.

Next to these pilot-plant facilities there is a solar simulator with xenon lamp for small-scale water detoxification and disinfection experiments in which the radiation intensity can be modified.

There are also four ultraviolet solar radiation measurement sensors, one direct with solar tracking and three global, one in horizontal position and two 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.

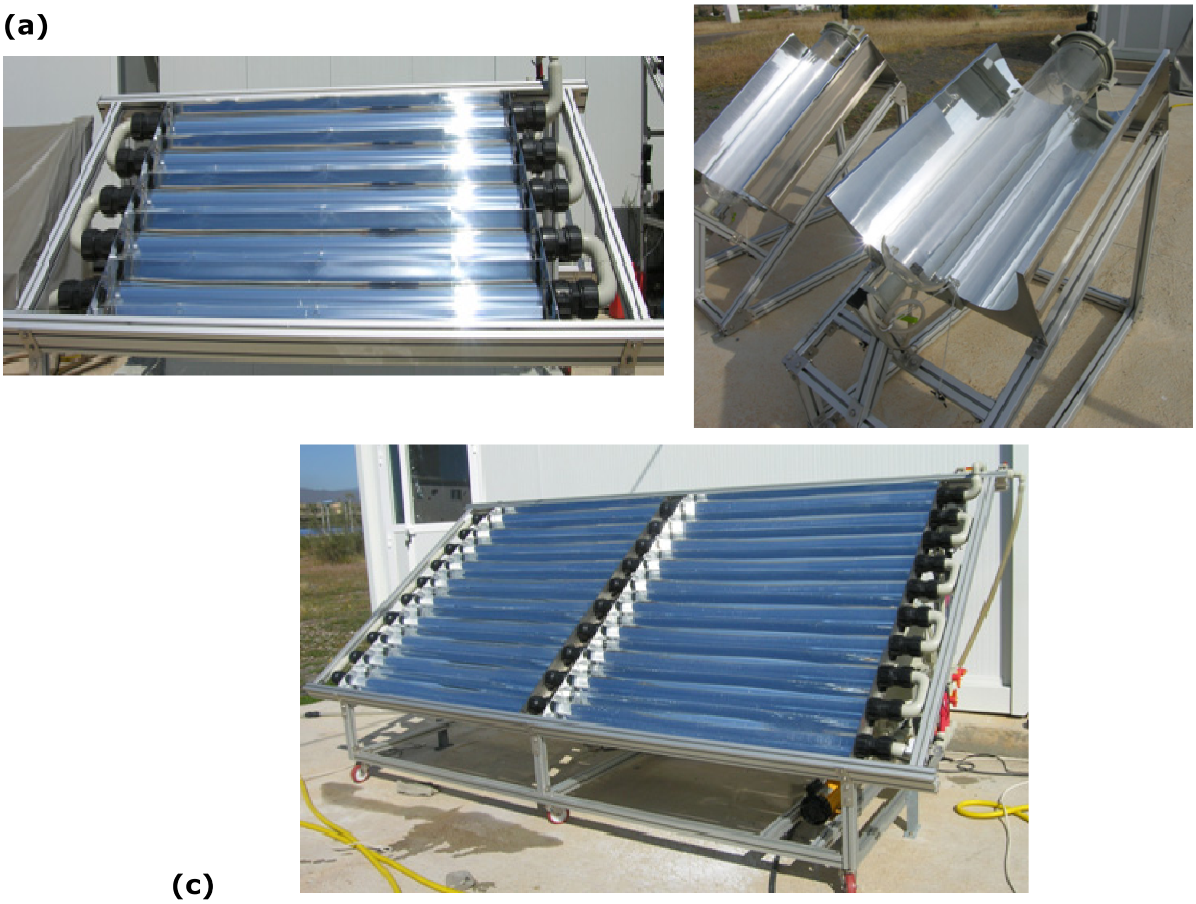
In addition, in 2010, as one of the activities funded by the Ministry of Science and Innovation under the Special State Fund for Dynamization of Economy and Employment (*Fondo Especial del Estado para la Dinamización de la Economía y el Empleo* – Plan E) the facilities were remodeled, and scientific instrumentation was acquired for solar water treatment (SolarNova Project). The solar water detoxification facility, auxiliary systems, and piping and instrumentation for the CPC photoreactors known as SOLEX and CADOX (described above) were remodeled (Figure 2.34 (a) and (b)). Furthermore, the tanks that had been used up to then for distilled water storage and supply for the pilot plants were replaced.

Finally, also with Plan E funding, new pilot plants were acquired for the solar water disinfection program:

1) Two CPC photoreactors (CPC25) for duplicate photocatalytic disinfection experiments (suspended and immobilized TiO_2) and photo-Fenton with volumes of 25 to 7 liters. Each of these solar reactors is made up of five tubes and has a total illuminated surface of 1 m^2, illuminated volume of 11.25 L and total volume of 25 L (Figure 2.35 (a)).
2) Two CPC (CPC-SODIS) photoreactors for discontinuous operation. These two 25-L stationary reactors are completely exposed to solar radiation. Each of the reactors has a large 0.58-m^2 aperture CPC mirror, in the focus of which is a 20-cm (outer diameter) borosilicate glass tube. (Figure 2.35 (b)).
3) A new CPC (FITOSOL-2) photoreactor similar to the one installed in 2008 known as FITOSOL as described above. This collector has 20 borosilicate tubes with a 60-L total treatment capacity and an illuminated area of 4.5 m^2. It is used for disinfection tests with water polluted by all kinds of microorganisms for reuse of water from treatment plants. It has a temperature control system that enables it to work at constant temperatures from 20 to 55ºC, several dissolved oxygen measurement points, and air injection to analyze the effects that oxygen injected in the line has on photocatalytic disinfection (Figure 2.35 (c)).

(b)

(a)



(c)

Figure 2.35. Photos of the new CPC photoreactors installed in 2010 for solar water disinfection applications: (a) CPC25, (b) CPC-SODIS and (c) FOTOSOL 2.

Finally, Figure 2.36 shows an up-dated panoramic view of the PSA solar water detoxification and disinfection facilities after their remodeling and installation of the new pilot plants acquired in 2010 as described above.

Figure 2.36. View of the updated the PSA solar water detoxification and disinfection facilities

2.7.1 PSA Analysis Lab

Also under the SolarNova Project funded by the Ministry of Science and Innovation under the Special State Fund for Dynamization of Economy and Employment (*Fondo Especial del Estado para la Dinamización de la Economía y el Empleo* – Plan E) the new water technology laboratory was built (Figure 2.37). The new Water Detoxification and Disinfection Group Lab is located in a new laboratory building, formerly an office building which was remodeled under this activity.

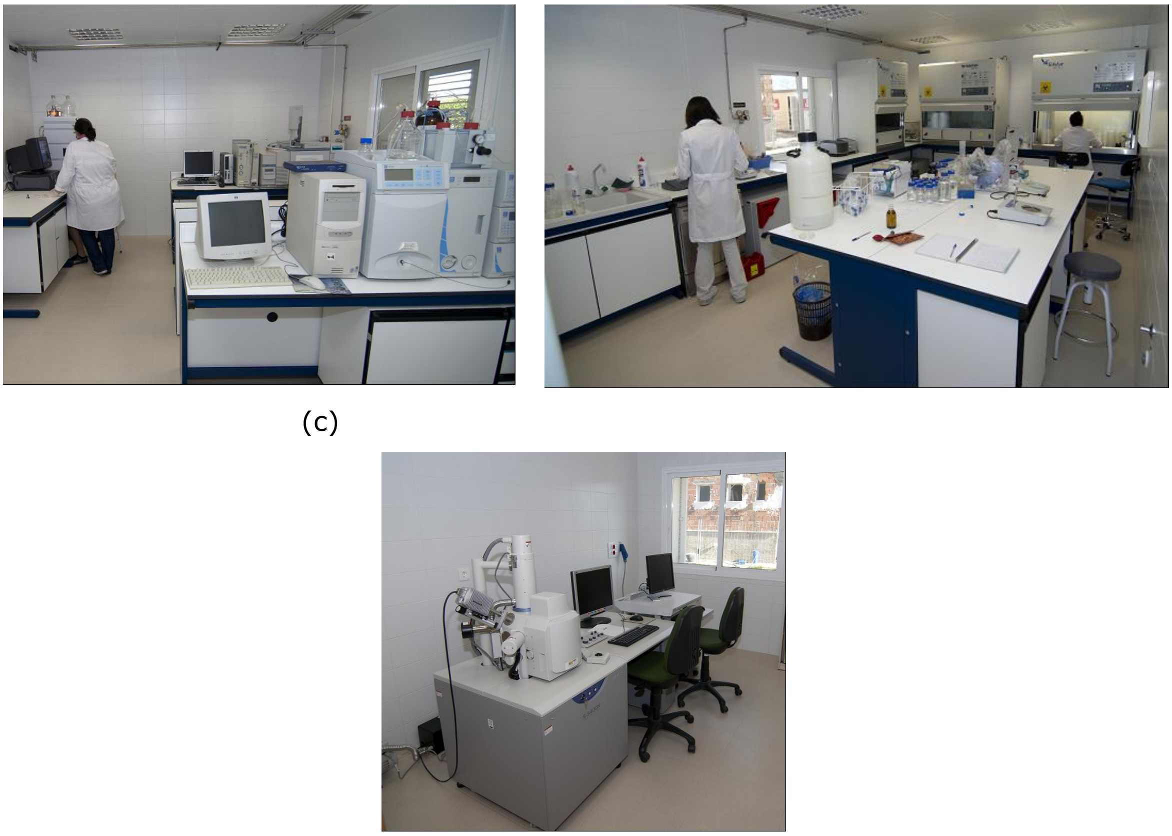
Figure 2.37. General view of the new PSA Water Technologies Lab

The new PSA water technologies lab around 200 m^2 distributed in six different rooms (Figure 2.37):

1) The main laboratory is 94 m^2 (Figure 2.37). This space contains all of the conventional laboratory equipment: three work bench islands, two gas extraction hoods, a heater, a kiln, ultrasonic bath, two centrifuges, two UV/visible spectrometers, a vacuum distillation system, ultrapure water system, pH gauge and conductivity meter, and precision-scale table. The laboratory is also equipped for *Vibrio fischeri* toxicity measurement, respirometry with active sludge, biodegradability measurement with respirometry, and measurement of biological and chemical oxygen demand. In addition it has a centralized gas distribution system, UPS, safety systems (extinguishers, shower, eyewash, etc.).

2) The chromatography lab is 23 m^2 (Figure 2.38 (a)) and contains all the analytical equipment related to environmental chemistry: two liquid chromatographs (quaternary pump and diode array detector with automatic injection, HPLC-DAD and UPLC-DAD), gas chromatograph/mass spectrometer with purge and trap system (analysis of volatile compounds dissolved in water), two ion chromatographs, one configured for isocratic analysis of cations, another configured for isocratic analysis of amines and a third for gradient analysis of anions and cations, two total organic carbon (TOC) analyzers with their corresponding samplers (total carbon analysis by catalytic combustion at 670ºC) and ultrafast real-time quantitative PCR (Polymerase Chain Reaction) equipment. All of these systems are computerized and integrated in a complete information network.

(a) (b)



(c)

Figure 2.38. Photos of the new water technology labs: (a) Chromatography lab, (b) Microbiology Lab and (c) SEM (Scanning Electron Microscope) Lab

3) The 27-m^2 microbiology lab is biosafety level 2 (Figure 2.38 (b)). All the equipment related to microbiological analysis for disinfection of water containing different kinds of microorganisms (bacteria, fungi, etc.): three microbiological safety cabinets, autoclave, two incubators, two fluorescence and phase contrast combination optical microscopes with digital camera attachment, turbidimeter and pH, dissolved oxygen and conductivity multisensor.
4) The Scanning Electron Microscope (SEM) room is 11 m^2 (Figure 2.38 (c). For the preparation of microbiological samples and catalysts to be analized in the SEM, the system is completed with a metal coater and critical point dryer.
5) 30-m^2 storeroom with direct access from outsider for storing chemicals and other consumables. It is organized on numbered and labeled stainless steel shelving with refrigerators and freezers for storing samples and standards.
6) Finally, the new water technologies lab has a small 17-m^2 office with three workstations where visiting researchers can analyze the data from the experiments carried out at the PSA.

2.7.2 Environmental Applications of Solar Radiation in Air

The Environmental Applications of Solar Radiation in Air Group laboratories are equipped for synthesis and physicochemical characterization of photocatalysts as well as the evaluation and optimization of photochemical systems for chemical and biological decontamination of air.

For synthesis of materials, the lab has a dip-coating thin-film deposition system, digestion pumps for hydrothermal synthesis, heaters, kilns, centrifuges, water distillers, etc., and for characterization it has a UV-Vis spectrophotometer equipped with an integrating sphere that can measure diffuse reflectance, and access to techniques such as XRD, XPS, N_2 adsorption and TGA-DTG DTA.

It has a multitude of different-sized lab-scale reactors and prototypes that employ solar radiation, artificial radiation sources of different types, or combinations of both, alternately or simultaneously. The solar reactors are located immediately above the laboratory on the roof of the building, enabling their connection with the analytical equipment and its continuous automatic control.

Figure 2.39. Hybrid solar/lamp photoreactor/with compound parabolic-trough collector (CPC)

Chemical analysis of gas and/or air streams is done with several different detection systems. The group has a gas microchromatograph with thermal conductivity detector (microGC), two chromatographs with FID and TCD, a chemiluminescence No_x analyzer, an IR CO_2 analyzer and two FIT-IR spectrometers, one equipped with a multiple-reflection gas cell. It also has ATR and DRIFTS cells connected to a reactor with three quartz windows for analyzing what is occurring on the photocatalyst surface during the photocatalytic reaction.

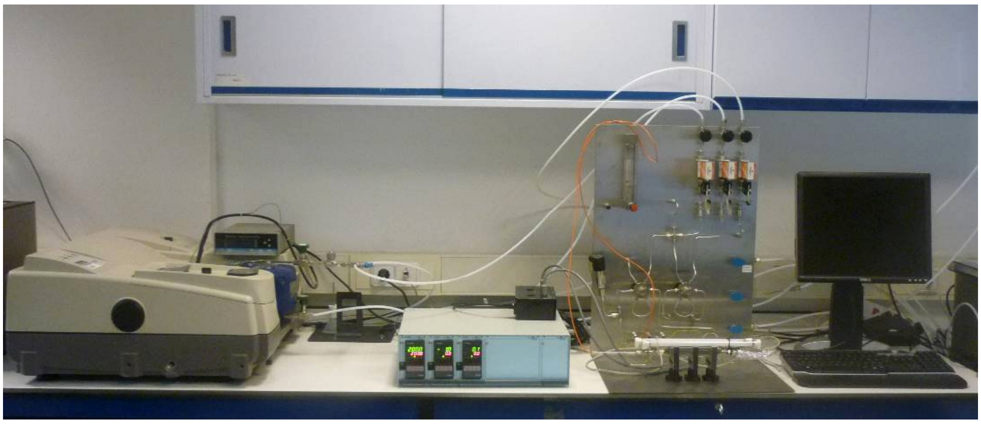


Figure 2.40. Automatic photocatalysis test bed with UV radiation connected to an FT-IR system for analysis of re

Chemical analysis of indoor air characterized by low-concentration pollution is done by automated thermal desorption gas chromatography mass spectrometry (ATD-GC-MS).

For the biological characterization of air, there is a separate laboratory equipped with a biological safety cabinet with vertical laminar flow, an autoclave for sterilization, a colony counter with

Figure 2.41. Equipo ATD-GC-MS para análisis de contaminantes en el aire interior

Figure 2.42. Biological characterization of air lab

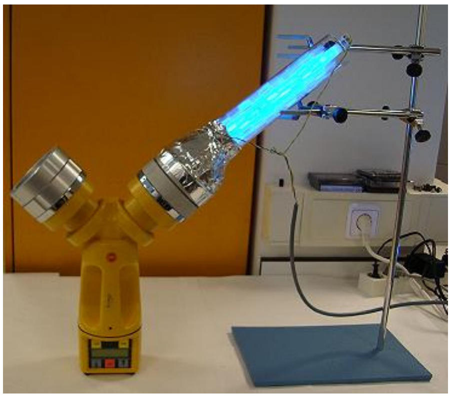


Figure 2.43. Air impacter for biological sampling connected to a photocatalytic disinfection reactor

camera connected to a computer, 63X magnifying glass with optic fiber illumination and camera, cooled centrifuge, two orbital shakers, two heaters for incubation and two refrigerators with freezer for storing samples.

Sampling and monitoring of the photocatalytic disinfection capacity of air is done by single and two-stage air impacters.

2.7.3 Solar MED-Distillation Desalination Facility

This facility is composed of the following subsystems:

- A 14-stage multi-effect distillation (MED) plant
- A field of stationary CPC (compound parabolic concentrator) solar collectors
- A water solar thermal storage system
- A double effect (LiBr-H_2O) absorption heat pump
- A fire-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 kW_t, 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 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 pres-

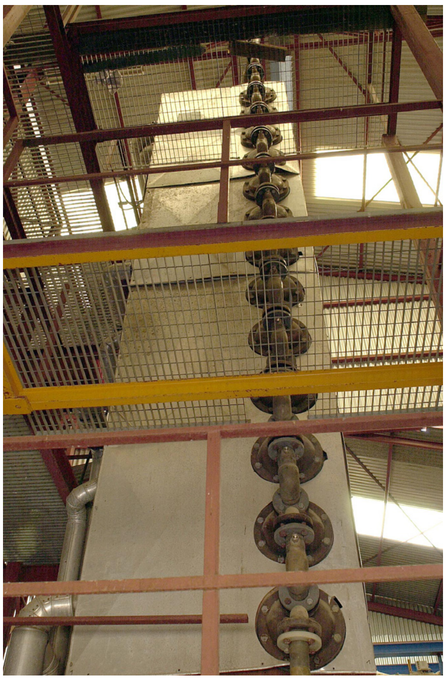


Figure 2.44. The PSA MED plant

sure 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.

Figure 2.45. Double effect BrLi-H_2O absorption pump hooked up to the MED plant

2.7.4 Membrane Distillation Module Test Platform

This relatively new facility was erected in 2007 in the framework of the European MEDESOL project, designed to analyze a multi-stage membrane distillation plant connected to a stationary collector (CPC) solar field which supplies the thermal energy for the distillation process. The pilot plant includes a series of new components developed under the project.

The main component at present is the three AGMD[1] membrane distillation modules manufactured by the Keppel Seghers Group (www.keppelseghers.com). Each of the modules has a distillation production of 5 to 15 L h^{-1} m^{-2} depending on operating conditions.

The heat exchanger is specially treated to resist the action of hot salty water. The exchanger plates have been treated with a special film, developed by one of the project partners (Univ. Stuttgart) to reduce fouling and scaling problems.

The solar collector field consists of 252 CPC (Compound Parabolic Collectors, CPC Ao Sol 1.12x[2]) and is oriented E-W to maximize the amount of energy collected throughout the year. Each collector has a surface of about 2 m^2

[1] Air Gap Membrane Distillation

[2] Collares-Pereira M., Carvalho M.J., Farinha Mendes J.,Oliveira J.,Haberle A.,Wittwer V.(1995). Optical and Thermal Testing of a new 1.12X CPC Solar Collector Solar Energy Materials, and Solar Cells, 37, 175-190.

Figure 2.46. View of DM module test plant

and a total field surface of 499 m^2. The modular and therefore very versatile collector field can be easily adjusted to the thermal requirements of the process. Because of the thermal requirements of the membrane distillation plant, it only needs to use one of the rows (125 m^2) in the field.

As auxiliary components, the facility has two 2-m^3 tanks, a heat exchanger connected to the solar thermal collector field, an air cooler connected to the cooling circuit and to the solar circuit and the instrumentation necessary for process evaluation (precise temperature, pressure, flow rate, and conductivity measurement). Data are recorded in the corresponding data acquisition system. Figure 2.47 shows a diagram of the facility.

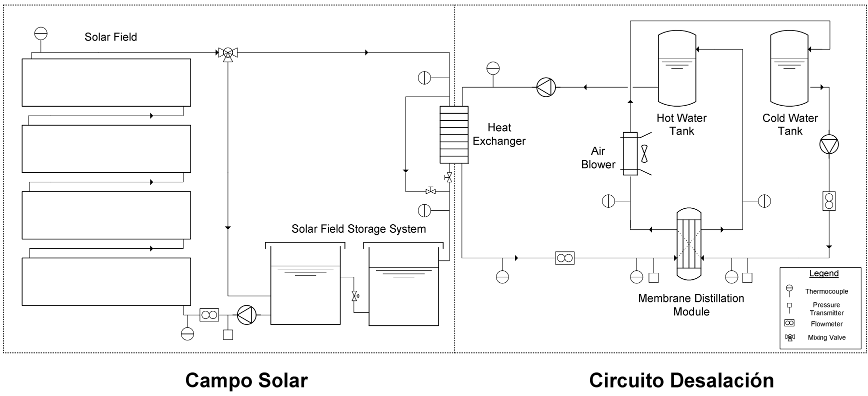


Figure 2.47. DM plant flow diagram

The versatile facility allows testing of different configurations and also of new membrane distillation modules. Modules manufactured by the Swedish firm Scarab AB (www.scarab.se) were characterized under the MEDESOL project, and later the circuit was slightly modified to adapt it for use with distillation membranes manufactured by the Keppel Seghers Company in Singapore.

Last year work was done on installing a solar field of CPC collectors specially designed to work at the DM operating temperatures. This way, the DM facility is completely independent of the AQUASOL solar field (which is currently supplying both the DM system and the MED plant) and the thermal needs will be fit to the process. The new facility will also have its own seawater-resistant air cooler.

Figure 2.48. Characterized membrane distillation modules in the plant; at the left: Scarab AB module; at the right: Keppel Seghers module.

Figure 2.49. View of the DM test plant with the Solar Spring system.

2.7.5 Solar ORC Facility

This facility, erected in 2009, was designed to evaluate the feasibility of the Solar organic Rankine cycle. The facility consists of a 5-kW prototype organic Rankine cycle generator manufactured by the Swiss company Eneftech. Its operation is based on the evaporation of a fluid which is sent to a turbine, where it expands, generating the mechanical energy which in turn is transformed into electricity. The expanded fluid is then condensed and compressed to begin the cycle again. The machine also has an internal heat regenerator and condenser cooling system which uses water from the nearby fire protection system tank. The three-phase electricity generated, once measured and the wave analyzed, is dissipated through a resistance system which is also cooled by the water circuit. The prototype proposes two innovations for improving energy transformation process efficiency:

1) The turbine is a scroll expander, specially designed for this application. Up until now, the scroll expanders used for ORC have been the reverse cycle compressors used for cooling.
2) Solkatherm SES36 working fluid is used so the cycle inlet temperature is higher than other similar facilities, thereby reaching a higher theoretical performance.

To evaporate the working fluid, the cycle requires thermal input power of 25 to 30 kW, with evaporator inlet temperature of around 200ºC. To suplí this energy, the prototype is connected to the thermal oil tank in the Acurex parabolic-trough collector solar field by a very simple circuit controlled by an automatic regulator valve. The dimensions and type of connection made enable close control over prototype inlet temperature stability and operating conditions. This facility therefore provides the infrastructure necessary for evaluating mid-temperature solar ORC schemes.

Figure 2.50. Solar ORC experimental facility

2.7.6 Stationary Solar Collector Test Platform

This facility was built in 2002 to offer additional services to the scientific research community, including energy characterization of the stationary solar collectors, with special emphasis on their application to solar desalination.

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 circulates through the tertiary circuit goes to a cooling tower where the energy from the secondary circuit is discharged into the atmosphere.

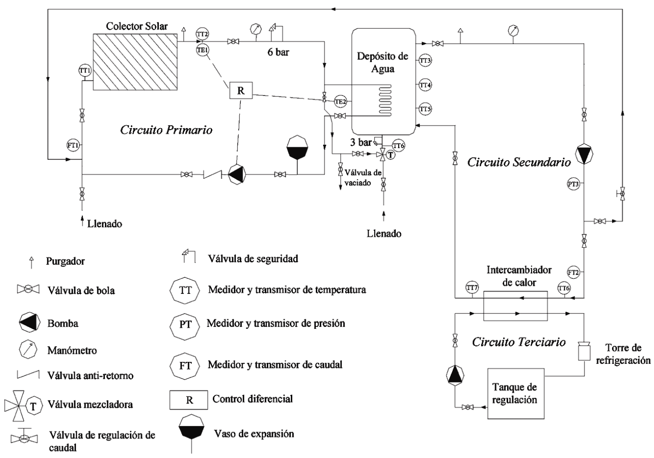


Figure 2.51. General layout of the stationary solar collector test platform

2.7.7 CSP+D TEST BED
Facility integrating MED thermal desalination in solar thermal power plants

This facility is for studying connection of a concentrating solar thermal power plant (CSP) and a water desalination plant (CSP+D) which makes use of the steam turbine outlet waste heat. The basic purpose is to simulate and analyze the various possible configurations for integrating a thermal desalination plant in a solar thermal power plant.

It is a test bench that enables different types of commercial turbines and interconnection configurations to the PSA multi-effect (MED) desalination plant to be simulated.

Figure 2.52. View of the outside of the CSP+D test bed building and the air coolers that act as the condensers in a conventional power cycle configuration.

The system power supply is thermal energy from the Acurex 3001 parabolic-trough collector field (Therminol 55 thermal oil) for temperatures up to 280-290ºC) and an auxiliary electrical power system raises the temperature when necessary. The facility makes it possible to simulate any turbine that could be used for simultaneous production of electricity and water from concentrated solar energy on a scale up to 500 kW.

Figure 2.53. Partial view of the interior of the CSP+D test bench building during the final stage of erection.

There are a series of steam ejectors for this that can produce exhaust steam with a variety of Rankine Cycle turbine outlet conditions. Other types of steam from other intermediate extractions can also be reproduced.

It is designed to study the possibility of using a part of the exhaust steam from the turbine outlet by regenerating with steam from an intermediate extraction to power an MED desalination plant. The main underlying idea is to attempt to use the first MED plant cell as the condenser in the power cycle, reducing Rankine Cycle cooling requirements and making use of that thermal energy to produce desalinated water.

The facility is also prepared to serve as a test bed for small turbines (up to 500 kW_{th}).

2.7.8 Facility for polygeneration applications

Polygeneration is an integral process for the purpose of producing two products from one or several resources. In the case of solar energy, it makes use of the thermal energy from a solar field for several simultaneous applications, such as generating electricity, desalinating water for drinking water supply and the rest for heating sanitary water (ACS).

In 2010, the Plataforma Solar de Almeria installed a solar field in the framework of the MEDIODIA Project, led by Repsol YPF. The purpose of this facility is preliminary study of the behavior of this solar field, determination of its feasibility as a heat source in polygeneration schemes, in particular in CSP+D. The collector selected was the Polytrough 1200 prototype by NEP Solar. It has a production of 15.8 kW per module (0.55 kW/m^2) under nominal conditions, with a mean collector temperature of 200ºC, and an efficiency over 55% in the range of 120-220ºC (for 1000 W/m^2 of direct normal radiation).

The field is configured in 8 collectors placed in 4 parallel rows, with two collectors in series in each row. This configuration supplies 125 kW of thermal energy. The temperature of the thermal oil can be up to 220ºC, so different schemes for making use of the thermal energy for polygeneration can be evaluated. It is a field that not only operates in a temperature range not used by the concentrating solar technology up to know, suitable for different thermal applications, but can also achieve unique operating conditions because of its modularity.

The solar field is going to be used to generate steam for supplying a double-effect absorption heat pump which in turn supplies the PSA MED

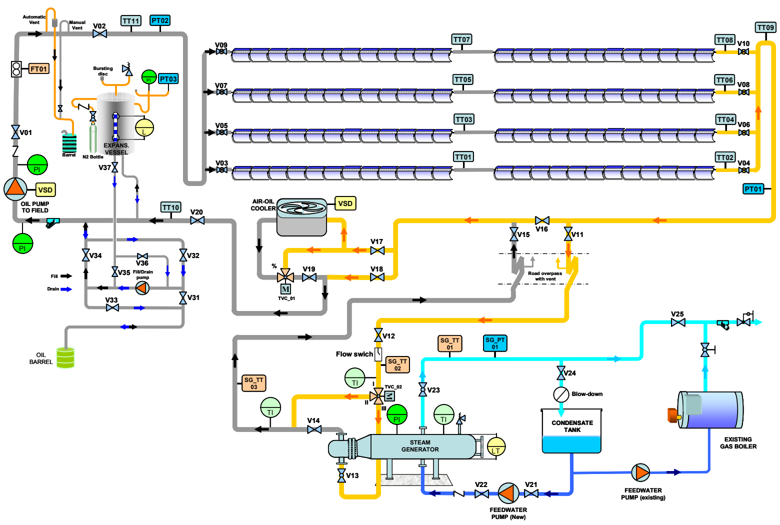


Figure 2.54. Polygeneration facility layout

Figure 2.55. NEP-Polytrough 1200 solar field

desalination plant. System operation is supplied by Santotherm-55 thermal oil by a variable-speed centrifuge pump. The hot oil can be sent or not to a steam generator. The thermal oil flow rate is controlled by a three-way valve which also communicates with an air cooler, which in turn dissipates the energy collected.

The system consists of two loops. The primary loop is the solar field, which supplies the heat necessary to generate steam. The loop for steam generated in the steam generator is the secondary circuit. Although steam generation is one of the purposes of this solar field, the facility was designed in such a way that evaluation of the collectors and their productivity is also possible through continuous monitoring of all the climate and thermodynamic parameters. Thus the design makes possible evaluation of the field and determination of its feasibility as a heat source in polygeneration schemes. It can also be combined with any other future polygeneration system.

2.8 Other facilities

2.8.1 PSA Meteorological Station

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

Figure 2.56. General view of the new PSA radiometric station

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:

3) ***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
   - Vertical temperature and humidity profile at 2 and 10 m
   - Miscellaneous weather information: rain gauge, barometer and psychrometer
4) ***The* Spectroradiometer** is so different that it must be considered an independent installation. It is a prototype developed to CIEMAT specifications by *Instrument Systems*. This equipment, based on the SP320D, which incorporates a photomultiplier and a lead sulfur detector, records the spectral distribution of the solar radiation over its whole spectral range (from 200 to 2500 nm), compared to the majority of such equipment which works only for a part of the spectrum (generally visible or ultraviolet). The basic equipment is connected to a switch in such a way that it can work with three alternating probes, which are arranged in a solar tracker to record the global, direct and diffuse solar radiation, respectively. Although it is configurable, the equipment has been programmed to record a spectrum (with an approximate resolution of 2 nm in UV and visible and 10 nm in IR) in about 7 minutes, and changes measurement probes every 10 minutes. This way, 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.
5) ***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

Figure 2.57. Spectroradiometer probes for measuring global and diffuse radiation installed in the solar tracker

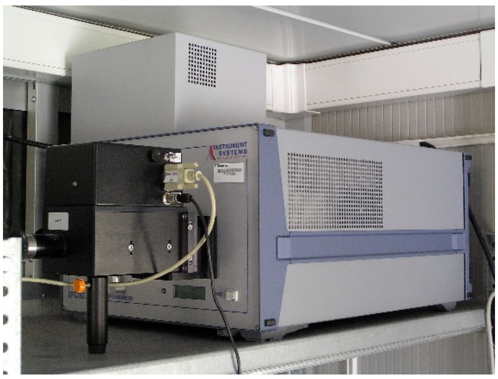


Figure 2.58. Spectroradiometer detector with three-probe connector switch

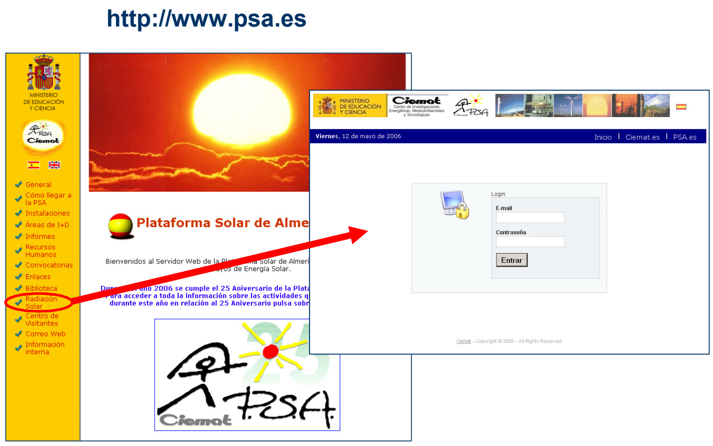


Figure 2.59. User login for access to solar radiation information.

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 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.

The meteorology station is currently under review.

2.8.2 The Spectral Calibration Lab

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.

Figure 2.60. New Spectral Calibration Laboratory adjacent to the CESA-1 building

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

2.8.3 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 Energy Efficiency in Building R&D Unit (UiE3) in CIEMAT's Renewable Energies Department.The UiE3 carries out R&D on integral energy analysis of buildings, including active and passive solar systems for reducing the HVAC energy demand. This unit is organized around three lines of research: 1- Energy Analysis of Buildings by Simulation, 2.- Passive systems in urban planning and building, 3.- Experimental energy evaluation under real conditions. The experimental facilities described here are part of the third line.

The activities in this group are heavily experimental, concentrating primarily on experimental energy evaluation of buildings and building envelopes.

These experimental activities are carried out in the LECE and in real-size buildings under real weather conditions, among them the PSE-AFRISOL Research and Demonstration Containers, one of which is described in Section 2.8.4, is also located at the PSA.

The LECE has several devices for experimentally analyzing real-size building systems under real weather conditions using data analysis applying system identification and time series analysis techniques. These experimental systems are the PASLINK test cells and other test cells, a solar chimney and a monozone building.

Furthermore, the LECE infrastructure is prepared for integrating new experimental prototypes that can be incorporated as needed in the Research Group's future projects.

Figure 2.61. Views of the LECE: Cells, reference buildings and solar chimney

LECE activities may be classified as:

- Experimental support for the CIEMAT Energy Efficiency in Building R&D Unit preparation of standards and regulations.
- Collaboration with and services for building materials and component manufacturers.
- Experimental support for drafting standards

2.8.4 The PSE-ARFRISOL R&D Container Building

The 'ARFRISOL' office Building at the PSA is part of the Unique Strategic Project on Bioclimatic Architecture and Solar Cooling (PSE-ARFRISOL) with partial funding from the Spanish Ministry of Science and Innovation.

The purpose of the PSE-ARFRISOL is to demonstrate that it is possible to save 80 to 90% of conventional energy by proper application of active and passive solar technologies, adapting the design of the building to its surroundings and to the climate. PSE-ARFRISOL includes five buildings, built in different climatic zones throughout the national territory: Almería (2), Madrid, Soria and Asturias.

Three of these five called "Research Demonstration Containers, C-DdIs" built in the ARFRISOL Project belong to the CIEMAT. Each of them is an approximately 1000-m^2 office building. These C-DdIs are designed to minimize energy consumed for HVAC, while maintaining optimum comfort. To do this, passive energy savings strategies based on architectural design and construction, and active systems that provide most of the low energy demand, and finally, they are provided with conventional auxiliary systems to supply the mall amount of energy that cannot be supplied by solar systems or others based on renewable energies such as biomass.

The C-DdIs are completely instrumented and continuously monitored by a data acquisition system recording high-quality measurements to support research activities on thermal comfort, energy evaluation of buildings and active and passive systems integrated in buildings,

- Solar field for sanitary hot water, which is also used for heating through a radiant floor and as a source of energy for an absorption pump for cooling in summer.
- Building-integrated photovoltaic panels on the façade. This is an experimental system designed to work best on a vertical plane. It supplies 7.5 kW_p for consumption in the building itself.
- Radiant panels open to night sky, for pre-cooling of offices in summer through the radiant floor.

Among the "passive" measures are the following:

- The compact building provides a larger solar collection area in winter and evacuation of energy in summer.
- The characteristics of the shell materials and concrete structure provide the building with strong thermal inertia (capacity for maintaining heat and passing it on or absorbing it from its surroundings).
- A marquee on the south side of the building provides shading in summer and is penetrated by sunlight in winter.
- A double pergola provides shading on the roof and support for the solar installations (solar collectors and radiant panels).
- Air treatment unit ducts are underground, previously tempering the air, saving energy.

The PSA ARFRISOL Building was inaugurated on December 13, 2007 and at

Figure 2.62. Research Demonstration Container (CDdI) PSE-ARFRISOL Building at the PSA

present is under surveillance by CIEMAT researchers. This stage will be extended to the end of 2010 and data acquired will lead to valuable conclusions on the mass application of the innovative technologies the building incorporates.

2.9 Plan 'E' and SolarNOVA (ERDF)

The current economic situation that Spain is going through made the Government start up a series of extraordinary measures at the beginning of 2009 to boost economic activity and employment. One of them is the Special State Fund for Dynamization of the Economy and Employment. The purpose of this fund of 3,000 million Euros is to finance action for immediate execution, chiefly in 2009, in the sphere of certain strategic production sectors.

Four hundred and ninety million Euros of these funds are allotted to RD&I actions, of which 180 million are for the Energy sector as one of the Government's goals is consolidation of leadership in Spanish technology in sectors such as renewable energies.

As a large RD&I facility in the energy sector, the PSA was included as one of the initiatives to be strengthened to increase the renewable energy contribution, granting 10 million Euros for the proposals presented for technological investment in this emerging sector.

Furthermore, the PSA received another 11.65 M€ from the ERDF for additional construction of new R&D infrastructures at the PSA.

The various actions undertaken at the PSA with this additional funding are described below.

2.9.1 Actions Related to the Experimental Facilities

The following actions, the scope of which is described in detail in other sections of this report, were concluded in 2010.

Briefly they are:

- Prototype for development of a parabolic-trough collector (PTC) without ball bearings in the connections
- New control and data acquisition system for the DISS direct steam generation test loop
- New laboratory for studying molten salt as thermal storage for CSP plants
- Scientific equipment for the new line of international collaboration in characterization and standardization of solar receivers ("certification" CIEMAT-DLR)
- New very high concentration solar furnace for high-temperature thermochemical processes
- New facility for studying the combination of a solar thermal power plant with seawater desalination by making use of the waste heat
- New experimental solar facility for polygeneration and process heat applications
- New test facilities and scientific instrumentation for studying solar water detoxification, desalination and disinfection

2.9.2 Action related to general infrastructure and civil engineering work

General infrastructure civil engineering work

The transformation o fan old office building in to a laboratory building has been included under this infrastructure improvement plan begun by Plan E in 2009.

The grounds have also been urbanized and landscaped in several different locations and this will continue until the end of the program toward the end of 2012.

New technical building for library and computation cneter

This is the only action still pending conclusion in 2011.

With the increase planned in stable CIEMAT staff as well as visitors (visiting researchers and students from many different places) it has been necessary to provide the center with a technical services building supplying the necessary educational and research resources.

This building will hold the PSA library collection which until now had been housed in the old SSPS Building. It will also be home to the new Computation center, where high-level computation services will be provided for the whole PSA scientific community.

Finally, although no less important, this building will have a classroom for 30 people where seminars and master classes can be given, continuing the trend to a higher demand for training activities by PSA scientists.

3 Solar Concentrating Systems Unit

Head of Unit: Eduardo Zarza Moya
eduardo.zarza@psa.es
Contributions from:
Félix Téllez Sufrategu
felix.tellez@ciemat.es i
Alfonso Vidal Delgado
alfonso.vidal@ciemat.es
Loreto Valenzuela Gutiérrez
loreto.valenzuela@psa.es
Javier León Alonso
javier.leon@psa.es
Angel Morales Sabio
angel.morales@ciemat.es
Aránzazu Fernandez García
arantxa.fernandez@psa.es
Mª Esther Rojas Bravo
esther.rojas@ciemat.es
Jesus Fernández Reche
jesus.fernandez@psa.es
Thorsten Denk
thorsten.denk@psa.es
Mónica Álvarez-de-Lara
monica.alvarezdelara@ciemat.es
Rafael Monterreal Espinosa
rafael.monterreal@psa.es
Jesús Ballestrín Bolea
jesús.ballestrin@psa.es
Antonio Ávila
antonio.avila@ciemat.es
Raúl Enrique Orts
raul.enrique@psa.es
Inmaculada Cañadas
inmaculada.canadas@psa.es
José Rodríguez
jose.rodriguez@psa.es

3.1 Introduction

The Solar Concentrating Systems Unit (USCS) is one of the Plataforma Solar de Almería's two R&D units and its staff is distributed between the CIEMAT facilities in Madrid and Almería. The Unit's main purpose is to promote and contribute to the development of solar radiation concentrating systems, both for power generation and for industrial processes which require solar concentration, whether for medium or high temperatures or high photon flux.

This Unit consists of three R&D Groups:

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

The activities performed in the USCS in 2010, as in previous years, were framed by the four master lines defined as partial goals:

- Develop new solar concentrating system components with an improved quality/price ratio.
- Develop new experimental capabilities and tools for simulation, characterization, analysis and diagnosis of this type of solar system.
- Encourage and promote vanguard action in solar concentrating technologies, opening the way to mid and long-term technology improvement (such as demonstration projects, prospect and feasibility analyses, etc.), and
- Facilitate development and consolidation of a national solar concentrating system industry through technical-scientific consulting and technology transfer.

The intense solar thermal power plant promotion and development activity triggered by Royal Decree 661/2007 which continued in 2008 and 2009, suffered from a period of great uncertainty during most of 2010, due mainly to rumors of possible changes in the legal framework defined by RD 661/2007, which could be applied by the Government retroactively. This situation caused many projects to go into "stand-by" that were trying to finalize their financing, since the investors resisted making a decision until these uncertainties were cleared up. In the last quarter, when these uncertainties seemed to have been cleared up and a relative calm returned to the sector, R&D activity associated with the solar thermal power plants again experienced an important boost as project promoters attempted to make up for the time lost. This meant an increase in industry's requests for collaboration with the Solar Concentrating Systems Unit.

In spite of the strong uncertainty in the sector that marked much of 2010, The USSC signed 19 collaboration agreements with entities in the thermal power sector and began to draft other agreements which are supposed to be ready in 2011. Therefore, the overload of work in our Unit that began with RD 661/2007, continued throughout 2010, in spite of the above mentioned problem about legal uncertainty in the sector. A large number of components were evaluated and characterized (reflectors, selective and antireflective coatings and so forth), as well as a diversity of solar concentrators. And at all times it was attempted to give the many companies that asked us for it, the scientific and technological support they required.

Along this line of assistance to the private sector, were two important activities, participation in several forums on standardization which have been formed under the various public and private initiatives, and the consolidation of the reflectometry laboratory begun in 2009 in collaboration with our colleagues from the German DLR.

In the field of standardization, an acute need in the thermal power sector, the USCS participated in all of the forums and working groups that were created for this purpose:

- The ASME PTC-52 standardization committee created in the USA.
- AEN/CTN Subcommittee 206/SC "Solar Thermal Power Systems", created by the joint initiative of AENOR, PROTERMOSOLAR, CENER and CIEMAT. Within this Subcommittee, the USCS participates in all three Working Groups devoted to: WG1 Plants, WG2 Components, and WG3 Thermal Storage Systems.
- The STAMP Working Group, created within the framework of SolarPACES as a German DLR and American NREL initiative for "Standardized Methodology for CSP Performance Prediction.

Continuing with the policy of spreading knowledge and according to our desire to facilitate development and consolidation of a national industry specialized in solar concentrating systems, in 2010, the course on "Solar Concentrating Systems" was given again at the central CIEMAT offices in Madrid from October 18 to 28th. Once again, this course was enthusiastically welcomed in all sectors (engineering, promoters, equipment manufacturers and research centers) involved in technological and commercial development of solar thermal power plants.

The sections below summarize the most important activities and results achieved in 2010 within the three R&D Groups that make up the Solar Concentrating Systems Unit, clearly demonstrating the intense activity carried out by all of them in their respective areas.

3.2 Medium Concentration Group

Head: Loreto Valenzuela Gutiérrez
loreto.valenzuela@psa.es

Activities carried out by the Medium Concentration Group (MCG) in 2010 are framed by a diversity of fields from component development for parabolic-trough collectors to research in innovative working fluids for parabolic-trough collectors and lending technical services to businesses in the sector.

It should be emphasized that the number of technical services given by the MCG continued to be very important in 2010, with over 15 contracts underway for activities, such as technology transfer of selective coatings for receivers developed and patented by the CIEMAT, characterizing parabolic-trough collector prototypes and their components, thermal and hydraulic studies of parabolic-trough collector systems and thermal storage systems, and studying the annual production of solar thermal power plants.

The performance of these activities has continued requiring improving our methodologies, procedures and equipment for the research, development and characterization (geometric, optical and thermal) of new linear focus solar concentrators and components for this type of system. In particular, this year many resources were devoted to improving equipment for the characterization of solar reflectors and the construction of a molten salt thermal storage facility, which were financed by Plan E·funds awarded the PSA by the Ministry of Science and Innovation at the beginning of 2009.

Among the R&D lines which the Group has been developing in previous years, one of the achievements this year was the completion of the CAPSOL project for the development and construction of a parabolic-trough collector for thermal applications up to 250ºC, as it will go on the market in 2011. During the year, research related to the use of pressurized gas in linear-focus concentrators continued, and a modular with parabolic-trough collector plant concept using pressurized gas as the working fluid with molten salt thermal storage was patented. Development of a new selective coating for absorbers with fluid temperatures above 500ºC was worked on, and the Group's capacity for design, modeling and simulation increased significantly in parabolic-trough collector systems with oil, water/steam, or pressurized gas, and thermal storage systems, with codes developed in various programming environments (MatLab, ANSYS, TRNSYS).

The activities and achievements in the various projects the Solar Concentrating Unit's Medium Concentrating Group (MCG) worked on in 2010 are summarized below.

3.2.1 Almería GDV
Puertollano GDV: Pre-commercial Solar Thermal Power Plant with Direct Steam Generation

Participants: PERSEO, IDAE, CIEMAT-PSA, AGECAM and Navarro Piquer
Contact: Eduardo Zarza, eduardo.zarza@psa.es
Funding: 20 500 000€.
Duration: January 2006 – December 2012

Background: The experimental results found at the PSA during the DISS Project (1996-2001) and INDITEP (2002-2005) demonstrated the technical feasibility of direct steam generation (DSG) in the absorber tubes of horizontal parabolic-trough collectors, the process known in Spanish by the initials GVD (*generación directa de vapor*). Nevertheless, the results found in the experimental DSG plant erected at the PSA for the DISS project are insufficient to assure the technical and commercial feasibility of large-size 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 feasible on an industrial scale.

Purpose: The purpose of this project is the construction of a 3-MW_e pre-commercial 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. Construction of this DSG plant is necessary before large commercial DSG plants can be safely undertaken.

Achievements in 2010: In 2010, after legally incorporating the consortium promoting the project at the end of 2009, permitting and licensing were begun, at the same time the detailed engineering was contracted to Iberdrola Ingeniería y Construcción. The Working Project was made and the construction license and administrative authorization were received.

The engineering team drafted the following documents, among others: General project implantation plan, preliminary BOP implantation plan, control system for the various operating strategies the plant will have, preliminary plans, ground movement, flow diagrams, Environmental Surveillance Plan, and general project coordination documents.

Among the most important changes introduced in the project is the installation of a steam turbine for both superheated and saturated steam within a certain temperature range. The installation of a turbine of such characteristics, although it is a small extra cost for the project, will without doubt be of great added value to the plant, since it will give it extremely flexible operation and make it possible to study the option of saturated steam compared to superheated steam in the future.

Participation of the PSA in the project in 2010 has mainly been concentrated on providing engineering assistance in subjects related to the DSG process, especially related to solar field operation and definition of the process regulation and control system. In the last quarter of 2010, the CIEMAT-PSA began a study of the temperature gradients expectable in the receiver tubes in the solar field superheated steam zone, which is the most critical in this respect because the heat transfer coefficients produced in it by convection are lower on the inner walls of the tubes. The FLUENT finite elements program is being used for this study in which several different wall

Figure 3.1. Location of the Puertollano GDV power plant: Puertollano (Ciudad Real), next to the 50-MW Ibersol Ciudad Real solar thermal power plant built by Iberdrola Renovables and IDAE.

thicknesses and a diversity of operating conditions are included (mainly the steam flow rate and heat flux on the receiver tube). This study is due to be completed in spring of 2011, and the results will make it possible to decide how thick the inner walls of the metal tubes in the solar field receivers should be.

Finally, considering the obviously innovative nature of the Puertollano GDV power plant, CIEMAT-PSA participated in the preparation of the application presented by the consortium in December 2010 to the public competition announced in the BOE on November 26th for an additional premium above the market price of electricity production for innovative solar thermal power plant projects.

3.2.2 Special coatings for receiver tubes

Antireflective coatings for parabolic-trough collector glass tubes

Participants: CIEMAT-PSA, Private

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

Funding: 320.000 €.

Duration: January, 2008 - December, 2011

Background: The weighted mean spectral transmissivity of glass used normally in solar applications is approximately 92%. Any increase in the solar transmissivity of such glass involves an increase to the same magnitude in the useful thermal energy supplied by the solar collector. By means of anti-reflective coatings applied on both faces of the glass, its transmissivity to solar radiation can be raised to around 97%, which means an increase of around 5% in the useful thermal energy delivered by the solar collector. Furthermore, the manufacture of antireflective coatings is not expensive so it does not penalize the commercial feasibility of the collector. These figures clearly show how beneficial the application of antireflexive coatings to solar collectors is.

Purpose: To develop antireflective sol-gel coatings, which are weather resistant, easy to manufacture and significantly increase the solar transmissivity of the glass used in solar collectors.

Achievements in 2010: Previously, the CIEMAT-PSA had developed antireflectie coatings of porous silica with very good optical properties, achieving an increase in solar transmittance of borosilicate glass from 0.92 to 0.97. However, porous silica coatings prepared by any method, have a large amount of silanols (Si-OH) on the surface, which are very reactive and induce adsorption of steam and contaminants under humid conditions. This surface adsorption results in the deterioration of the optical properties, and so forth. In 2010, we changed the formula of the coating precursor solution, so the films obtained maintain their optical properties even with 100% humidity. Figure 3.2 shows the transmittance spectra of glass coated with the antireflectant films prepared from the precursor solution and the new formula, before and after the accelerated condensation resistance test, according to the UNE-EN-1096-2 code. As may be observed, the spectra of the two samples before the test are the same, with solar transmittance of 0.971 in both cases. After the accelerated test, transmittance of the sample prepared with the previous formula had dropped to 0.945, while the film prepared from the new solution has practically the same transmittance spectrum, with a solar transmittance of 0.970. With the new precursor solution, the mechanical properties of the coating have improved.

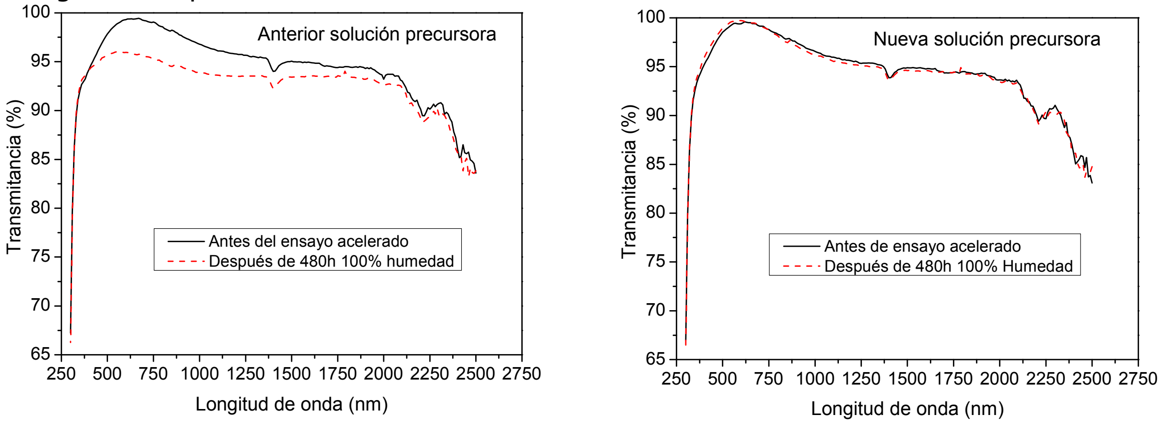


Figure 3.2. Transmittance spectra of borosilicate glass with antireflective coating prepared from the previous solution and the new solution, before and after accelerated testing according to UNE-EN-1096-2.

It is worth mentioning that contracts for licensing technology developed by CIEMAT in this field, with two foreign companies, have already begun production in one of them and are scheduled to begin in the first quarter of 2011 in the second of these companies.

Publications: [3.1]

Selective high-temperature absorbers

Participants: CIEMAT-PSA, Private
Contact: Angel Morales, angel.morales@ciemat.es
Funding: 750.000 €.
Duration: January, 2008 - December, 2011

Background: One of the most important in the solar concentrating systems, both linear-focusing (parabolic-trough collector and linear Fresnel reflector) and point-focusing concentrator (central receiver and parabolic dish) systems is the receiver, since this is where the concentrated solar radiation is converted into thermal energy. Due to the high technological load, although here has been important commercial deployment, especially of solar thermal technology with parabolic-trough collectors, in recent years, on the market there are still few manufacturers who can supply glass absorber tubes for this kind of collector. The CIEMAT has been working on the development of new selective coatings suitable for their use on absorber tubes for several years, and has related patents.

Purpose: Development of selective absorbent coatings (high absorptance and low emissivity) based on the sol gel technology for mid-to-high temperature, for application to both absorber tubes for linear-focusing concentrators either with (solar thermal power plants) or without (for moderate working temperatures) vacuum.

Achievements in 2010: In 2010, studies for increasing the durability of selective high-temperature absorbers for use above the current 500ºC, valid not only for parabolic-trough collectors, but also for central receiver systems. The thicknesses of anti-diffusion barriers and platinum infrared reflector have been increased to reduce diffusion of the infrared reflector on the substrate, which is the degradation mechanism of this absorber. The preliminary results show that selective absorbers obtained are stable at 600ºC in air on austenitic stainless steel substrates and have a solar absorptance of 0.96 and a thermal emissivity of 0.087 at 400ºC and of 0.11 at 500ºC. Figure 3.3 shows the complete high-temperature absorptance spectrum developed by CIEMAT.

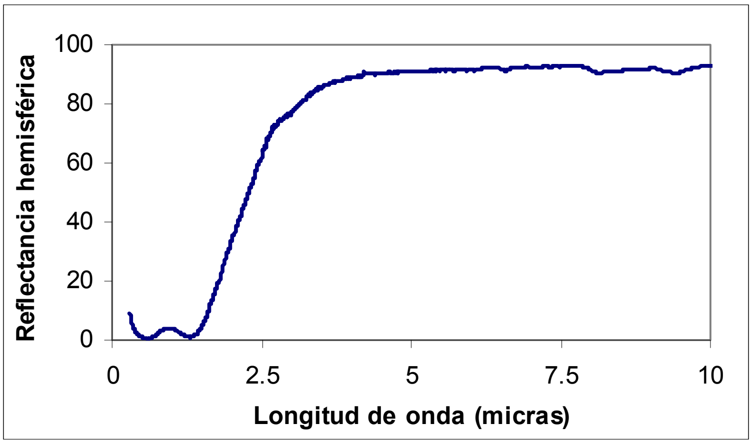


Figure 3.3. Complete spectrum of the selective absorber developed at CIEMAT

At the present time, layers are deposited by extraction from the tube of a container with the precursor solution at a constant speed. To simplify industrial layer deposition and reduce the amount of precursor solution necessary to coat the tubes, a new deposition system is being developed which enables each layer to be formed by depositing only 20 ml of precursor solution. This device is protected by Spanish patent pending P200901973.

Studies are being directed at reducing the number of layers from six to four to make it more industrial competitive. The results for the elimination of the first layer show that they maintain the optical properties of the absorber, but with a considerable reduction in thermal stability. New materials for the first layer that allow the operating temperature of the new absorber to be increased are now under study.

3.2.3 CAPSOL
Parabolic-trough solar thermal collector for thermal applications up to 250ºC

Participants: CIEMAT, Universidad de Almería, y Composites-Sol
Contact: Aránzazu Fernández, arantxa.fernandez@psa.es
Funding: 235 k€
Duration: Mayo 2008 – Mayo 2010

Background: The main motivation for this Project is to have a solar collector that can cover the demand for thermal energy at temperatures below 250ºC, with a cost/efficiency ratio that enables its competitive market penetration, and geometric and weight characteristics that facilitate its integration in industrial, commercial and residential areas. The processes susceptible to admitting solar thermal energy in the temperature range indicated are: industrial process heat, HVAC and refrigerating, thermal energy supply at temperatures below 100ºC for high-consumption facilities (sanitary hot water or heating for large buildings like industrial bays, hospitals, schools, sports installations, pools, prisons, airports, etc.) and other applications such as pumping water, desalination, detoxification or electricity generation in organic Rankine cycles.

Purpose: The purpose of this applied research project is the design, manufacture, evaluation and marketing of a parabolic-trough solar collector for producing thermal energy at temperatures up to 250ºC, which covers the demand for industrial processes or HVAC in buildings where there is currently no commercial solution with an adequate cost/efficiency ratio that makes use of solar energy. To achieve this fundamental goal, the following specific objectives have been set:

- Design of a parabolic-trough solar collector with performance, cost, size and weight characteristics that provide a technically and commercially feasible product
- Manufacture of a series of prototypes which meet the specifications
- Develop a set of tools and facilities for optical and thermal evaluation of this type of system
- Determination of design and manufacturing improvements for the solar collector based on the evaluation results

Achievements in 2010: In the two first years of the Project, the design and construction of a test installation for evaluation of small parabolic-trough collectors was undertaken at the PSA. The detailed design, fabrication and assembly of the first solar collector prototype, CAPSOL.01, was also started. In the last months of 2009, fabrication and assembly of two units of the second prototypes, CAPSOL-02, which incorporated the improvements proposed in view of the first prototype test results (See Figure 3.4).

The main improvements included in the second prototypes were the following: improvement in the position and alignment of the absorber tube, elimination of the negative effects of the angle of unmolding, improved collector air tightness, elimination of condensation on the inside and improvement of the interception factor by including an internal frame in the concentrator. These two CAPSOL-02 prototype units were installed in the CAPSOL test bed at the end of 2009 and were evaluated in the first semester of 2010.

By means of a photogrammetry study, a considerable improvement was found in the optical-geometric quality of the concentrator of the CAPSOL-02 prototypes over CAPSOL-01, due to the insertion of the inner stiffening frame. This improvement led to an increase in the interception factor from 92.3%

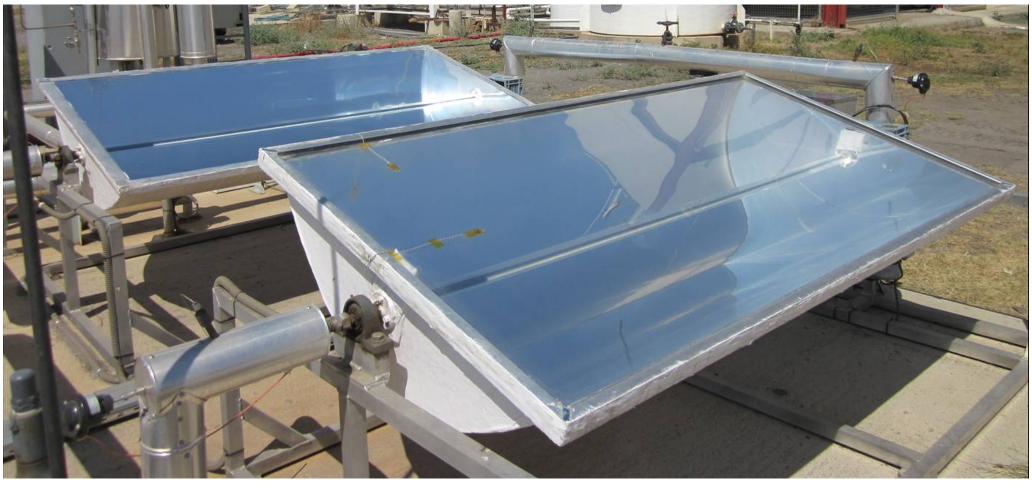


Figure 3.4. CAPSOL-02 parabolic-trough solar collector prototypes.

(CAPSOL-01) to 96.5% (CAPSOL-02). The theoretical peak optical-geometric performance calculated from the characteristic parameters of the components supplied by the manufacturers is 63.2%. The experimental results show 63±3% in CAPSOL-01 and 64±5% in CAPSOL-02. This verifies that the optical-geometric quality at a zero angle of incidence is as expected. This value will increase considerably in commercial collectors, which will have antireflective surfaces on both glass covers.

The experimental results of modifying the angle of incidence in both protoypes are similar, since no modification affecting this parameter was made. The negative effect of the angle of incidence in this type of small collector will be diminished considerably in commercial facilities, since the collectors will be installed in a north-south orientation and with the axis of rotation inclined with respect to the horizontal.

Finally, the results of overall performance testing showed a slight decrese in the second protypes over the first as the operating temperature rose. This decrease in performance is because of increased thermal losses, possibly caused by deterioration in the quality of the absorber tube. To solve this problem, the CIEMAT is going to start a line of work for fabrication of suitable absorber tubes for this type of collector.

Publications: [3.2]

3.2.4 Pressurized gas as a working fluids for parabolic trough collectors

Participants: CIEMAT, Polytechnic Univ. of Madrid; Abengoa Solar NT, Acciona, SAYCE.
Contact: Eduardo Zarza, eduardo.zarza@psa.es
Funding: 950,000 €.
Duration: December, 2005 - December, 2011

Background: The parabolic trough collector technology is current the most commercially developed for solar thermal power plants with over 4.5 million sq. meters of collectors in routine operation with a nominal power over 900 MW_e at the end of 2010. In spite of its commercial maturity, this technology must seek ways to reduce costs and increase performance to make it more 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 solar collectors used in these plants. Up to now, all commercial plants have used thermal oil as the working fluid, but this oil has clear disadvantages. Some of the drawbacks associated with thermal oil are environmental risk of pollution from leaks, risk of fire and limitation of maximal temperature in the solar field. Since to avoid these problems, the current thermal oil must be replaced, three possible substitutes have been proposed, water/steam, molten salt and pressurized gas. To find out which of these candidates is the best option, they have to be studied under real operating conditions.

Purpose: Experimental study of the use of pressurized gas as the working fluid in parabolic-trough collectors, evaluating their behavior under a Diversity of real operating conditions and analyzing their advantages and disadvantages compared to the thermal oil now in use and any other innovative working fluids. The achievement of this final goal is based on two partial targets: 1) design and construction at the PSA of a test loop for the experimental study of new working fluids in parabolic-trough collectors, and 2) experimental study under real solar conditions using different pressurized gasses as the working fluid in the test loop built at the PSA. CIEMAT activities in this project were proposed by Prof. Carlo Rubbia, winner of the Nobel Physics Prize in 1984.

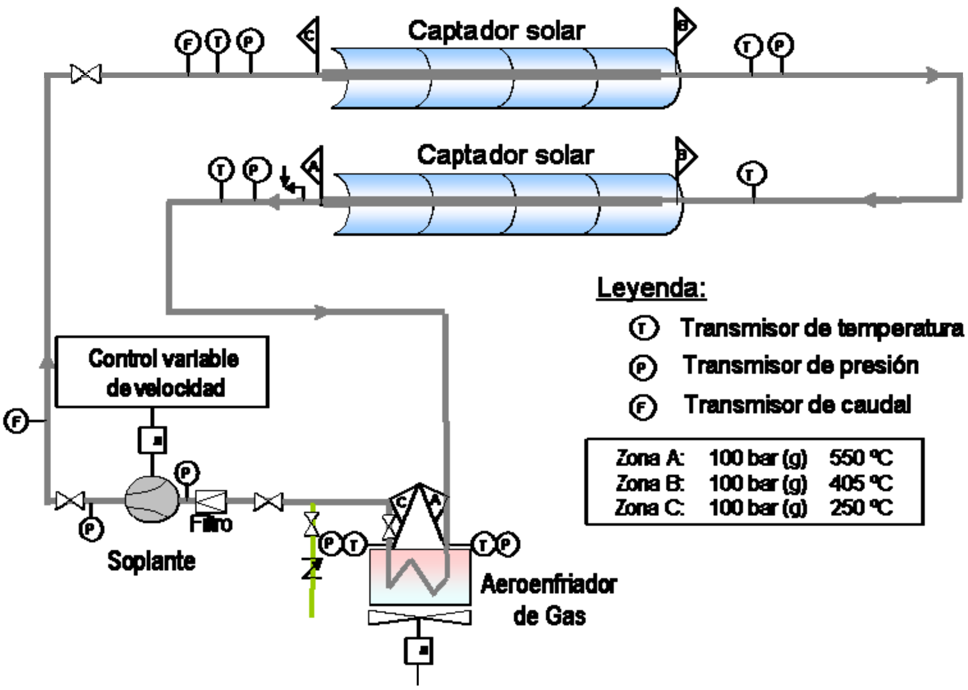


Figure 3.5. Diagram of the new configuration of the test loop installed at the PSA for the experimental study of pressurized gas as the working fluid in parabolic-trough collectors.

Achievements in 2010: Once the technical feasibility of using pressurized CO^2 (≥50bar) at a maximum temperature of 400ºC had been experimentally demonstrated by tests carried out in 2008 and 2009, PSA activity in this project in 2010 was concentrated on modifying the test loop built in 2007 to increase the working temperature up to 500ºC. The new configuration of this experimental loop is shown in Figure 3.5. As may be observed in this figure, the possibility of connecting the two solar collectors in parallel is no longer included since the parallel connection would require CO^2 flow rates that would be too low to achieve a temperature of 500ºC and the heat transfer coefficients in the receiver tubes would also be too low, which would mean high risk to their integrity.

In 2010, ANSYS simulation studies were also carried out to predict the thermal gradients that could arise in the receiver tubes when operating at temperatures over 400ºC. The results do not show any foreseeable damage to the tubes as long as an appropriate flow rate is maintained and during solar radiation transients steep increases in direct solar radiation without immediately increasing the working gas flow rate equally are avoided.

In 2010, studies were also done in collaboration with the Polytechnic University of Madrid (UPM) to compare the advantages ad disadvantages in using different pressurized gases as the working fluid in parabolic-trough collectors. Although, in spite of the advantages and disadvantages associated with CO_2 and N_2, no very significant advantages clearly showing the suitability of one over the other. The working group finally decided for N_2, especially considering the ease with which it is produced at a reasonable price at the plant itself, which would reduce operation and maintenance costs in a commercial plant.

The possibility of replacing the current ball joints with graphite packing by flexible connectors to eliminate the need for ball joints definitively was studied during 2010 and will continue in 2011.

Finally, the CIEMAT continued patent procedures for its new modular commercial plant concept with pressurized gas as the working fluid and thermal storage with molten salt. The concept developed and patented by CIEMAT would solve one of the main drawbacks of gas as the working fluid in parabolic-trough collectors, the pressure drop in the solar field and resulting parasitic consumption by pumping. The project Working Group plans to construct a small pilot plant where all the components and essential equipment that would comprise a commercial solar thermal power plant based on this modular concept can be tested.

To study heat transfer experimentally, construction of a solar field using pressurized gas as the working fluid and a thermal storage system using the sensible heat of molten salt was begun in 2010. This small experimental loop has 40 Tm of molten salt in a 290ºC cold tank a 505ºC hot tank. The salt is a mixture called Solar Salt, which is 40%-60% potassium nitrate and sodium nitrate. Although at the end of 2010, mechanical assembly was practically complete, the first operating tests done just at the end of year showed the need to carry out important work before the system is operative.

3.2.5 Characterization and durability analysis of solar reflectors

Participants: CIEMAT and DLR
Contact: Aránzazu Fernández García, arantxa.fernandez@psa.es.
Funding: 600 k€.
Duration: July 2010 – July 2014

Background: The motivation for this project is the study of materials used as reflectors, because they are one of main components of solar concentrating systems.

Purpose: The purpose of this Project is the optical characterization and durability analysis of reflector materials used in concentrating solar systems. Within this general goal, the following specific objectives are included:

- Research in the degradation of materials under environmental variables and its effect on their reflectance and performance of concentrating solar systems.

- Find experimental physics equations on the degradation of certain relevant reflective materials that allow prediction their mid-to-long term performance.
- Find any correlations between tests under accelerated conditions and exposure to real outdoor conditions.
- Establish the best process and measurement instruments for optical characterization of solar reflectors.
- Establish the standards and protocols that can standardize tests related to solar reflector durability.
- Perform testing for companies that so request when this is advisable for the development of solar concentrating systems.

Achievements in 2010: In 2010 construction work on the building housing the two solar reflector analysis laboratories, one for optical Studies and reflectance measurements and the other for accelerated durability testing, was completed. Instruments necessary to complete laboratory equipment purchased in 2009 were also acquired: several portable specular reflectometers, a 3D microscope (to be used jointly by the PSA Materials Laboratory), a spectrophotometer with integrating sphere, a weathering chamber for temperature, humidity solar radiation and rainfall, a saline mist chamber, an ultraviolet chamber, kilns with and without special atmospheres, and devices for thermal cycling. In particular, a device for accelerating abrasion by cleaning and two accelelerated testing chambers, one to simulate sand storms, specially designed for solar reflector desert applications, and an acid rain simulation chamber were purchased. For the optical reflectance measurement laboratory, a specular reflectance accessory was acquired for the spectrophotometer already there. By the end of the year all the equipment and auxiliary systems had been installed and put into service.

Among other activities in this project was the significant progress in standardizing reflectance measurement process for optical characterization of solar reflectors. A round robin test was performed for this in which two entities participating in this project and a third public institution from the United States, the National Renewable Energy Laboratory (NREL) participated. The results of this test led to a series of conclusions that enabled progress in measurement protocols and finding errors associated with the measurement instruments used both by research centers and companies in the sector.

Two cooperation agreements were also signed with solar reflector manufacturers for a study of possible surface treatments to diminish the

Figure 3.6. PSA Solar Reflector Lab Building

amount of dirt that accumulates on them. The purpose of both studies is to decrease the costs of cleaning the concentrators in solar thermal power plants, with the resulting savings in their maintenance cost.

For optical characterization of reflector degradation, a new reflectometer has been developed that enables specular reflectivity to be measured at different aperture angles (designed and patented by DLR). The system is based on a photographic method that makes it possible to measure a 5-cm-diameter area with a 10 pixel/mm resolution. By analyzing these images, the percentage of the total reflector surface deteriorated can be detected. This measurement method has helped make significant advances in characterizing corrosion in aluminum reflectors.

Publications: [3.3]

3.2.6 Thermal storage for solar thermal power plants

Participants: CIEMAT-PSA, Spanish and European businesses, foreign research centers
Contact: Esther Rojas, esther.rojas@ciemat.es
Funding: 3,200,000 €.
Duration: May 2008 - December 2012

Background: Red Eléctrica Española in its report, "Additional information necessary for evaluating grid access: evaluation of the manageability of solar thermal power plants" of July 26, 2007, found that this type of plants had to have four hours of storage to be considered manageable. The group of companies promoting this type of plants and research centers expert in solar thermal power plants, CIEMAT among them, manifested the high risk that such a demand involves because of the many technical and scientific uncertainties still associated with large thermal storage systems. This led to the demand for storage being diminished somewhat in March 2008, when it was transformed into a possibility. Knowing that this is only temporary, it is essential that the most relevant technical aspects be solved in the near future to ensure reliable competitive thermal storage.

Purpose: development and optimization of effective, economical thermal storage systems, mainly for use in solar thermal power plants, although other industrial process heat applications are not discarded.

Achievements in 2010: the activities on thermal storage systems for solar thermal power plants can be grouped into:

Design and optimization of thermal storage system components

Knowing that one of the barriers to economic storage in the form of latent heat is the low conductivity of the materials used up to now as the phase-change storage medium (different compositions and mixtures of inorganic salts) and that one approach to solving this problem is to design storage with a larger energy transfer surface, an exhaustive review of possible exchanger designs for use with phase change has been made, including research projects, patents and related scientific articles. The fruit of this research has been a proposal for a new storage design with phase change.

For sensible heat, an analysis is being done of the behavior of storage with thermocline tanks. A simulation model designed by CIEMAT in the Matlab environment is being used for this. The study analyzes the influence of different storage materials, filling characteristics, if any, their porosity, working conditions, etc.

Experimental evaluation of components, equipment and procedures

In 2010, the PSA Molten Salt Thermal Storage Experimental Plant was built and commissioned. This installation is expected to go into operation before summer 2011.

Under the 7th Framework Program SFERA project, characteristic parameters and types of thermal storage were defined. Along the same line, the CIEMAT cooperated in standardization of the methodologies for characterizing solar thermal power plant components on international (like the ASME PTC-52 and the SolarPACES STAMP) and national (AENOR) committees. There is a specific working group for thermal storage in all of them.

Cooperation with other national centers and international initiatives

In 2010, the CIEMAT actively cooperated in new European initiatives under EERA (European Energy Research Alliance, the purpose of which is to strengthen research capabilities in the European Union based on joint programs between research centers) and KIC (Knowledge and Innovation Communities, a strategic network for joint mid-to-long-term planning of innovation to meet the challenges of the European Institute of Innovation and Technology, EIT). Of the four KIC projects selected in 2010 by the Commission, one of them was on thermal storage and in 2010, this project was led and coordinated by the CIEMAT.

A national cooperation agreement was signed with the Fundación Centro de Investigación Cooperativa en Energía - CIC energiGUNE in the area of energy storage (electrochemistry, high-temperature thermal and by thermochemical cycles).

Publications: [3.4]-[3.5]

3.2.7 Drafting standards for solar concentrating systems

Participants: CIEMAT and other Spanish public entities and companies
Contact: Javier León, javier.leon@psa.es
Funding: As there is no outsider funding, the budget is released internally as needed each year, without any prior total.
Duration: January 2010 – December 2012

Background: One of the greatest deficiencies in the worldwide solar thermal power plant industry is the lack of standards to define technical characteristics of the various components and systems in this type of plant, as well as characterization, monitoring and evaluation procedures which must be applied to them. To solve this deficiency, at the end of 2009, several initiatives were started up in the United States and Europe to make such a standard. In particular, in Spain, several national solar thermal research centers, CIEMAT logically among them, encouraged the start up with the cooperation of AENOR, *Asociación Española de Normalización y Certificación*, of an activity for drafting national standards to respond to the current vacuum.

Purpose: Draft national standards for solar concentrating systems.

Achievements in 2010: After a proposal presented to AENOR by a group including representatives of related industry and solar thermal research bodies, on March 2, 2010, AENOR created Subcommittee SC1, "Solar Thermal Power Systems" under Technical Committee AEN/CTN206, "Power Production". The intention was to create one or several standards that allow limits to the movement to be set at this time of deployment of the technology in Spain within a period of two years.

The subcommittee has therefore created three working groups who will perform their tasks in parallel:

- WG-1: Solar Thermal Power Plant. Standards related to solar thermal power plants in general.
- WG-2: Solar Thermal Power Plant Components. Standards related to specific components of a power plant with these characteristics.
- WG-3: Characterization of the Thermal Storage Medium for Solar Concentrating Applications. Standards that enable the storage medium and specific components to be characterized.

The kickoff meetings were held in April 2010, with follow-up meetings every two or three months in which both the content and distribution of the work subpackages were developed as follows:

Working Group 1

The guideline for approaching standardization in this group is:

- Standardization of the procedure for solar thermal power plant feasibility studies
- Standardization of preliminary acceptance of the solar thermal power plant
- Standardization of final acceptance of a solar thermal power plant
- Standardization of energy parameters for operational monitoring of the power plant

As part of this group's work, the subgroup "Meteorological Data for Solar Thermal Power Plants" was created to define the terminology and procedures for generating meteorological series for solar power plant simulation.

Working Group 2:

This group undertakes standardization of characterization of solar thermal concentrating collectors and their components for which the following subgroups have been created:

- Solar reflectors
- Receiver tubes
- Structures
- Specific sensors
- Trackers
- Working fluids
- Joints and other components

Working Group 3:

This standard establishes the methodology for performing, in the first place, characterization of the thermal properties of the medium (sensible or latent) for accumulating energy in a thermal storage system for solar thermal power plants, and also their working limits (temperature, pressure, impurities, etc.), and in the second place, thermal cycling tests (accelerated or not) which provide information on the thermochemical stability of this material, establishing its useful lifetime under the conditions of service.

Finally, and as a task common to all groups, a specific terminology has been created to refer to the tasks undertaken based on the ISO 9488:1999 standard entitled, "Solar Energy Vocabulary". Each group has defined the words not recognized in that standard and has adapted those in it so that once the definitions have been refined they are unified for creating a single glossary.

3.2.8 Other Medium Concentration Group Activities in 2010

In addition to the R&D activities described in the paragraphs above, the Medium Concentration Group of the PSA Concentrating Systems Unit has carried out other activities in 2010, such as:

- Evaluation of new parabolic-trough collectors and components for these Systems. The characterization s performed during 2010 span from geometric characterization of parabolic-trough collector facets and structures by photogrammetry to determine the intercept factor, to the determination the characteristic parameters of a collector, e.g., peak optical performance, incident angle modifier and thermal performance. These tasks were done under confidential cooperation agreements with business and therefore, no further information on the work done or results found in 2010 related to this activity may be revealed.
- Improvement of the methodology and codes for modeling and simulation of solar thermal power plants with parabolic-trough collectors and direct steam generation, in the Matlab/Simulink® programming environment. Preliminary thermohydraulic studies of various collector loop configurations using reference collectors, including sensitivity analysis as a function of certain operating conditions and geometric collector parameters, to determine the load loss in the different cases studied.
- Diffusion of the parabolic-trough collector technology participating in numerous lectures and courses on renewable energies. In this field, the most significant contribution of the Medium Concentration Group has been our participation in the course on "Solar Concentrating Systems" given in Madrid on October 2010.
- Consulting for contractors, component manufacturers and equipment and engineering firms involved in the parabolic-trough collector technology. The number of Spanish and foreign companies interested in this technology continued to be significant in 2010. The motivation for this huge interest is the premium established by Royal Decree 2007/661 for electricity generated by solar thermal power plants. This has led not only to companies being interested in promoting commercial projects, but also in manufacturing some of the main components (absorber tubes, solar reflectors, drive units for solar tracking, etc.). Continuing the trend already begun in 2006 and 2007, in 2010, a multitude of companies have come to the PSA for information and advisory services. Although the resources we have available for this purpose are limited, it is our intention to continue giving these companies as much assistance as possible.
- Apart from the national standardization activities carried out in the framework of AENOR, in 2010, the MCG also participated in other similar international initiatives such as those promoted by the American Society of Mechanical Engineers (ASME) in the US, and by the National Renewable Energy Laboratory (NREL) and DLR under the auspices of SolarPACES. the MCG is participating in all these standardization initiatives, contributing its experience and knowledge on solar thermal concentrating systems.

Publications: [3.6]-[3.12]

3.3 High Concentration Group

Head: Félix M. Téllez Sufrategui
felix.tellez@ciemat.es

Activity I the High Solar Concentrating Group is mainly concerned with Central Receiver Systems, but also includes activities related to other point focus systems that provide high solar flux, such as the Dish/Engine and Solar Furnace. The commercial deployment of central receiver (power tower) solar thermal power plants (STP-RC) has had a shy beginning in Spain with the inauguration of PS10 (2007) and PS20 (2009) and is maintained with the construction of Gemasolar which, during 2010, was almost complete. Internationally, at the end of 2010, renewed interest in point focus plants has been observed with four plants in operation (including the two Spanish plants), 11 under construction (six of them in the US) and 22 in the project stage (19 of them in the (US and one in Spain).

Until PS10, in full commercial operation since March 2007, was commissioned, the "learning curve" of central receiver solar thermal power was based on testing at more than 10 experimental central receiver facilities in the world, as complete systems and a wide variety of components (heliostats, receivers, storage devices).

The experience accumulated has demonstrated the technical feasibility of the concept and its ability to operate at high incident radiation fluxes (typically from 200 to 1000 kW/m^2), which makes it possible to work at high temperatures (from 250ºC to 1100ºC) and integrate it in more efficient cycles, from Rankine with saturated steam to Brayton cycles with gas turbines. It has also been demonstrated that it can easily be hybridized in a wide variety of options and has the potential for generating electricity with high capacity factors by using thermal storage, so that at present systems with over 4500 equivalent hours per year are possible. System efficiency predictions solar-to-electric conversion, are 20-23% at design point and 15-17% annual.

Unlike the technological homogeneity observed in the current deployment of parabolic-trough collectors, central receiver plants provide total conversion efficiencies (associated with operating at higher solar concentrations and temperatures) on one hand, and on the other, a wider diversity of design options, with less experience accumulated in the implementation of each typology or component. Nevertheless, the high investment cost still constitutes an obstacle toward full commercial exploitation of its potential. The first commercial applications that are beginning their deployment still have installed power costs of 2,500-9,000€/kW (depending on the storage size) and estimated costs of electricity produced of around 0.16-0.20€/kWh. A reduction in cost and risk perception associated with the technology's short commercial experience is therefore essential for its extension to more commercial applications. In particular, the accumulation of experience and developments must contribute to confirming its reliability, durability and ability to lower STP-CR costs.

This goal of lowering electricity production costs is directing the R&D efforts, on one hand to improve the existing options and on the other to demonstrate the feasibility of new design options such as: 1) The choice of heat transfer fluid and the receiver operating temperature (choosing from water-steam, nitrate salt or air), 2) The optimum plant size (choosing from single tower or multi-tower fields, which add modularity in construction) associated with thermal storage solutions and/or hybridization to make them more dispatchable, 3) the efficiency/cost compromise in the concentrator field (choice between two opposite trends, large-size heliostats of around 100 m^2

or more with good optical quality and lower specific cost of tracking devices, or small heliostats of around 10 m^2 with better land use and possibility of group drives).

Aware if the diversity of competing choices, with no clear criteria for deciding on the choice, the HSCG, in addition to participating in the first commercial power tower demonstration projects, maintains a permanent line of R&D in technological components and systems in order to generate information that can assist in reducing the uncertainties and analyze the technical feasibility of the different options.

In 2010, in addition to contributing to activities in common with the rest of the SCSU, such as improving own R&D capacity and technological training of third parties, the High Concentration Solar Group (HCSG) had performed three basic types of activities:

- Collaboration in system development, which at this time of commercial deployment of these technologies could be understood as accompanying companies that are promoting the first generation of commercial solar thermal power tower plants, such as PS10, PS20 and Eureka (with Abengoa Solar) or Solar Tres/Gemasolar (with Sener/Torresol). This section includes the startup of installation and characterization of small power tower prototypes and Dish/Stirling plants.
- Participation in component development for the Central Receiver technology by initiative or collaboration in national (like SOLGEMAC, etc.) and international (like SOLHYCO) projects.
- Improvement of experimental capability and quality procedures (through SFERA project, continuing activities in the Radiometry and High Temperature Laboratory and adjusting capacity for accelerating aging with high solar flux and high temperatures).

The activities carried out by the HCSG in 2010 are summarized below.

3.3.1 Research, Innovation and Development for the Gemasolar power tower plant.

Participants: GEMASOLAR, CIEMAT-PSA, TeKniker
Contacts: Juan Ignacio Burgaleta (ignacio.burgaleta@sener.es); Jesús Fernández-Reche (jesus.fernandez@psa.es)
Funding: CDTI-TORRESOL. (GEMASOLAR/CIEMAT Agreement). 405 k€.
Duration: August 2009 a December 2011

Background: The good results during the construction, testing and evaluation of the prototype molten salt receiver for the Solar Tres project carried out in agreement between Sener and CIEMAT with support from CDTI, were determining in the final launching of GEMASOLAR, a 17-MW_e central receiver plant with molten salt as the coolant and thermal storage fluid, promoted by Torresol Energy in Fuentes de Andalucía (Seville).

Purpose: The purpose of this Project funded by the CDTI now concentrates on the following points. i) Accompany Torresol Energy in the installation, commissioning and operation of the GEMASOLAR plant; ii) Prediction and monitoring of weather data at the GEMASOLAR site (Ecija-Seville Province), iii) Testing at the PSA of new thermal insulation materials and concepts for later installation in GEMASOLAR; iv) Design, testing and validation (in collaboration with Tecniker) of a new low-cost radiometer for incident solar flux over 1000 kW/m^2; v) Testing of components for use in molten salt systems: valves, pumps, piping, sensors, etc.; vi) Accelerated aging and durability testing of materials subject to high incident solar flux and to heating and cooling thermal cycles.

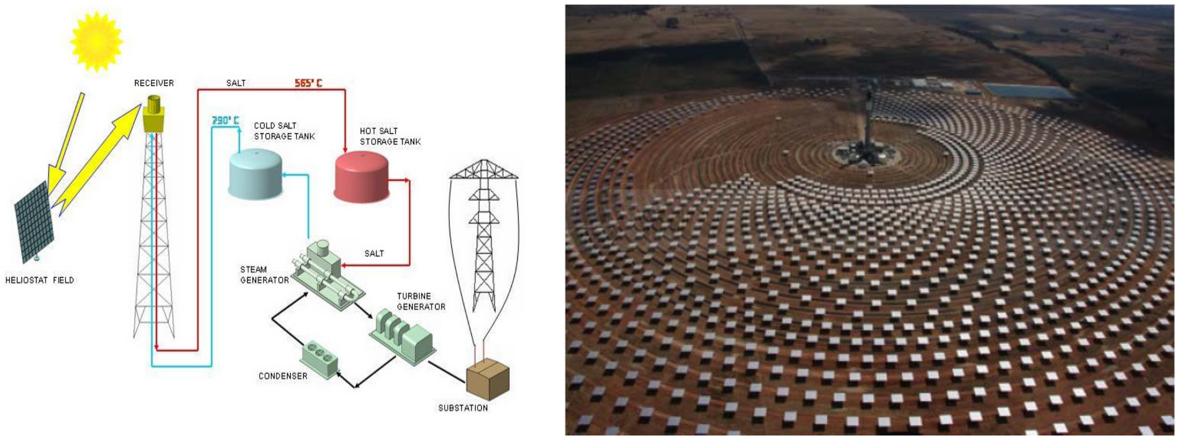


Figure 3.7. Flow diagram of the GEMASOLAR plant and construction site in 2010.

Achievements in 2010: In 2010, Consulting for Torresol Energy increased noticeably because GEMASOLAR was in the final stage of construction and especially, coinciding with commissioning which began at the end of 2010. Within the tasks performed by CIEMAT under this project are:

- Analysis of an incident flux measurement system in the receiver and its control by thermographic cameras.
- Preparation of a training course for operators at the GEMASOLAR facility concerning basic notions of power tower solar technology and operation and maintenance of central receiver solar tower plants. This course will be given in the first quarter of 2011.
- Meteorological study of the GEMASOLAR power plant site, including Typical Meteorolgoical Year and annual fluctuations in the last 20 years, as well as radiation forecasting models for the site.

Metalographic analysis of prototype salt receiver materials that were under testing at the PSA from 2006 to 2009 under the project, "Development of a Salt Panel" and analysis of their degradation. The purpose is to infer the useful lifetime of a receiver of this type subjected to daily cooling and heating cycles under highly concentrated solar radiation.

Publications: [3.13]

3.3.2 SATOHE: Salt storage in solar tower with heliostats.

Participants: GEMASOLAR, SENER, CIEMAT-PSA, Univ. Almería (UAL)
Contacts: Juan Ignacio Burgaleta (ignacio.burgaleta@sener.es); Rafael Monterreal (rafael.monterreal@psa.es)
Funding: Corporación Tecnológica Anadaluza-GEMASOLAR. (GEMASOLAR/UAL/CIEMAT Agreement). 525 k€.
Duration: May 2008 to December 2011
Purpose: The project has two specific purposes:

A) Technological development of a molten salt heat transfer and storage system for application in a solar thermal power tower plant for generation of electricity in high-efficiency Rankine cycles
B) Check and validate the new heliostat developed by the SENER Group for use in the GEMASOLAR plant.

The second purpose is the one that the HSCG has concentrated on. The most relevant secondary goals are: i) Minimize the cost of manufacture, ii) Reduce the time of assembly and installation in the solar field, iii) achieve high aiming capabilities; iv) Adequate tracking during all the hours of sunlight and all the seasons of the year.

Achievements in 2010: In 2010, testing of the SATOHE heliostat designed by SENER was carried out in the test bed at the PSA heliostat prototype test platform (Figure 3.8). The tests are for quantifying the functional characteristics of the prototype heliostat, both aiming capability at a fixed target during the day and its optical quality, that is, capacity for concentrating the solar radiation.

Six-months of testing followed an optical characterization and aiming quality protocol prepared by the PSA for this purpose (Table 3.1).

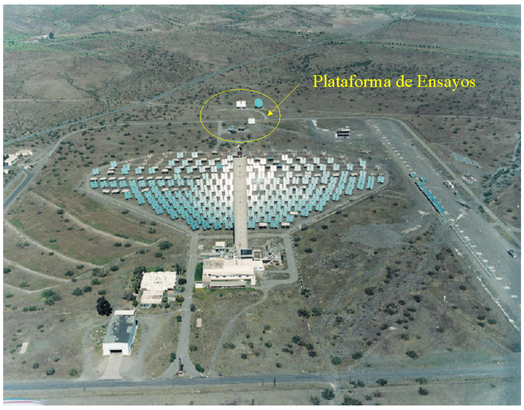


Figure 3.8. Location of the PSA heliostat test platform

Figure 3.9. Front view of the SATOHE heliostat in normal tracking

Table 3.1. Test protocol for prototype heliostat functional characteristics

PURPOSE OF CHARACTERIZATION:		TYPE OF TEST
I	Local Control	E1. Local control response to commands
II	Optical quality	E2. Tests of optical quality of facets E3. Tests of optical quality of heliostat E4. Tests of evolution of optical quality of heliostat during the day
III	Aiming quality	E5. Tests of heliostat aiming quality at midday E6. Tests of repetitiveness of heliostat aiming E7. Tests of evolution of heliostat aiming quality during the day

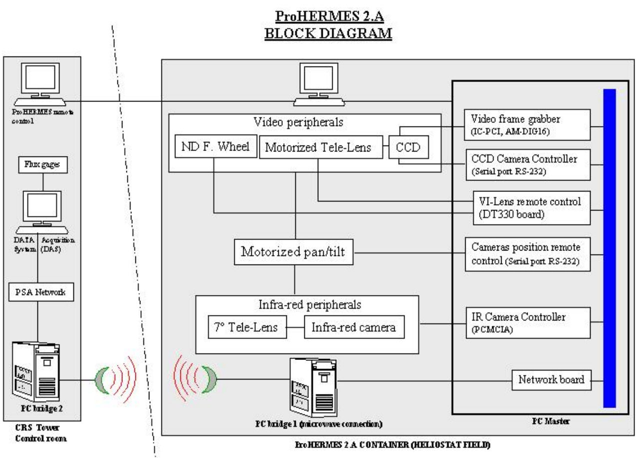


Figure 3.10. Block diagram of the ProHERMES 2.A

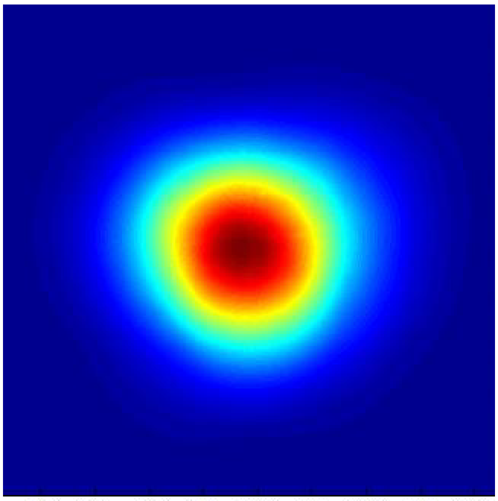


Figure 3.11. SATOHE heliostat image at solar noon on 21-07-

del heliostat characterization system 2010

The control system enables the heliostat to be remotely operated from the CESA-1 control room located 380 m from the heliostat. Figure 3.10 shows a block diagram of the PSA heliostat characterization system, called ProHERMES 2.A, which includes measuring heliostat concentration and aiming capabilities. Figure 3.10 also shows the SATOHE heliostat image projected on the test target of the CESA-1 tower at solar noon on July 21, 2010.

The synthetic heliostat image was generated by the Fiat_Lux code developed at the PSA for this purpose based on the heliostat model and the solar disk projection under test conditions.

3.3.3 SolHyCo (SOLar HYbrid power and CO-generation plants)

Participants: DLR (D, coordinator), Turbec (I), CIEMAT (E), CEA (F), Ormat (IL), Abengoa (E), FTF (D), sonatrach (DZ), GEA (POL), Vitalux (BRA), and IIE (MEX)
Contact: Peter Heller (peter.heller@dlr.de);
Thorsten Denk (thorsten.denk@psa.es)
Funding: EU 6th Framework Program (Contract nº 019830).
Project total: 3 M€; CIEMAT Participation: 0.5 M€.
Duration: January 1, 2006 to June 30, 2010

Background: This project is the successor to the successful REFOS, SOLGATE and HST projects that developed pressurized air Receiver solutions for integrating solar heat in gas or combined cycles and with a 250 kW system demonstrated its capacity for generating electricity in a hybrid scheme (with conventional fuel backup). This type of solar-hybrid system combines solar energy with fossil fuel, but would only be 100% sustainable if biofuels are used.

Purpose: The main purpose of the SolHyCo Project is to develop a very-high-efficiency solar-hybrid microturbine which operates with concentrated solar radiation and with biofuel, making it a complete renewable system. Other project goals are studies on introducing this technology on the market in sunbelt countries, especially Algeria, Brazil and Mexico.

At the Plataforma Solar, solar testing in the CESA-1 tower was scheduled in two stages. The first was carried out in 2008 and 2009 at the 60-m level with 250-kW_e turbine manufactured by the Israeli company, Ormat, which operated so successfully in the Solgate project. This turbine was fed by three pressurized air turbines (one tubular and another two volumetric) with a total thermal power of 1 MW. The difference from Solgate was the replacement of kerosene by a 100% biological diesel fuel ("biodiesel").

The second stage was executed in the same place in 2010 with an Italian/Swedish Turbec 100-kW_e turbine. For this turbine, a new type of pressurized air receiver was developed based on the tube concept and apt for use with high-technology multi-layer tubes. These tubes have three layers, the outside is very-high-temperature steel, the middle one is copper for better heat distribution around the tube circumference, and the inner layer is again steel, but very thin, to mechanically stabilize the copper layer. However, due to important problems in manufacturing these tubes, they could finally not be tested and the receiver had to operate with conventional tubes.

Achievements in 2010: The installation of the components in Work Package 5, the tube receiver and the 100-kW Turbec turbine was completed in autumn of 2009. The commissioning tests lasted all winter 2009/2010 because of various problems with hardware and control, such as slightly damaged turbine stator blade and spark plug malfunction. An important problem was the very long time required to preheat the receiver without sun in startup at the beginning of each test. That was solved with "solar preheating" the receiver before each test by focusing a few heliostats on it. Another unexpected problem was that the difference in temperature between the heat exchanger outlet to the receiver and the turbine outlet before this exchanger was around surprisingly low at 10 K. (The connection between the components may be seen in Figure 3.24). As the receiver inlet temperature was limited to 600ºC for technical reasons (materials), it was impossible to operate the turbine in solar mode a full power (100 kW) but only at around 70 kW.

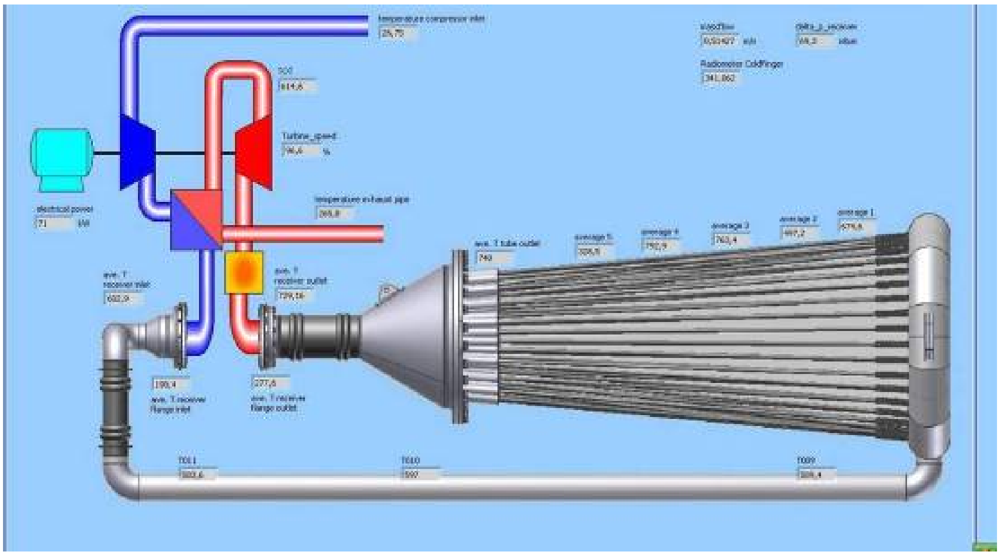


Figure 3.12. Data acquisition system screen

At the end of May 2010, a receiver outlet temperature of 700ºC was reached for the first time. In June, stable operation up to 780ºC was achieved. The previous efficiency estimation was below 50%. Three causes were identified: i) The first was operation with a low air mass flow due to solar field power limitations. ii) The second was the open design of the cavity receiver. Free convection, plus forced convection by wind carried away an important amount of system heat. These losses were substantially reduced by installing a quartz window (Figure 3.14) which impeded the exchange of air currents between inside and outside the receiver cavity through the aperture. With this window, the design temperature of 800ºC was reached easily and receiver efficiency rose 3%. However, these data continue far from predicted (the turbine was expected to operate at 100% and the receiver at 800ºC, with 68% efficiency without a window and 81% with window). iii) The third and probably the most important reason for the receiver's low performance was the outer insulating cavity wall concept. Due to thermal expansion of the insulating sheets and the somewhat weak structural design, gaps opened between the insulation sheets allowing hot air inside the cavity to escape.

However, the turbine was finally operated for more than 165 hours, with over 100 hours with concentrated solar radiation, including 30 hours with the quartz window.

At project completion, continuation of testing with redesigned insulation was considered, but in the end, DLR could not get enough funding. In 2011, the receiver and the turbine were disassembled and will probably be shipped to Brazil for a possible new system facility.

Figure 3.13. Solar test in the plant at 65 m in the CESA-1 Tower

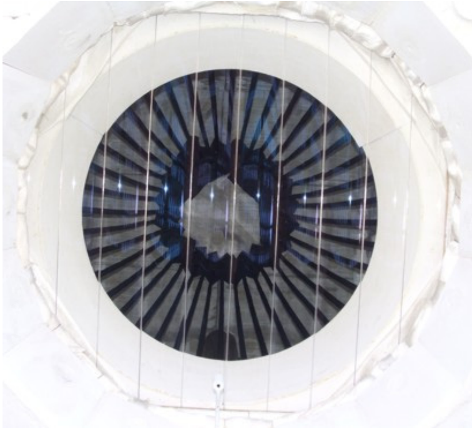


Figure 3.14. Apertura con ventana en receptor SolHyco.

Publications: [3.14]

3.3.4 R&D for improving key central receiver technology components

Participants: ABENGOA SOLAR NT, CIEMAT-PSA
Contacts: Félix Téllez (felix.tellez@ciemat.es);
Antonio Ávila (antonio.Avila@ciemat.es)
Funding: CENIT + ABENGOA-SNT: 200 k€
Duration: January 2008 - December 2011.

Background: This Project is Activity 3 within the CENIT Consolida strategic industrial research project, "Solar R&D Consortium", coordinated by Abengoa Solar NT and approved under the fourth CENIT Program Ingenio 2010 initiative.

Purpose: The purpose of CIEMAT support, partly updated in 2010, consists mainly in i) advising and selecting measuring instruments to be used in the superheated steam receiver, ii) set up a test plan and process control protocols, iii) magnitudes to be measured and other important process variables for simulation, iv) Sensitivity analysis of receiver design and solar field configuration options.

Achievements in 2010: i) Proposal for diagnostic instrumentation for prototype receiver measurement methods. Assistance in mapping incident flux maps and comparing forecasts with own codes (Fiat_Lux). ii) Advising on solar field operating and control methods to optimize performance. iii) Start sensitivity analysis of the receiver design and solar field configuration options. With the available design capabilities (WinDelSol, NREL-SAM, Macros-Excel and Matlab, etc.) undertake the optical-thermal optimization of the following components:

- Optimized heliostat field solution for a cavity central receiver with and without storage
- Optimized solution for the heliostat field for a panel central receiver with and without storage
- Proposal for optimal aperture of a cavity receiver for a plant with and without storage
- Proposal for optimal dimensions (height and diameter) of a panel-type receiver for a plant with and without storage

3.3.5 SOLGEMAC R&D PROGRAM (Using solar thermal energy manageably, efficiently and modularly in high-concentration systems)

Participants: IMDEA-Energía (Coordinator), URJC, CIEMAT-SSC, CIEMAT-DQ, INTA, UAM, TORRESOL Energy Investment y Hynergreen Technologies

Contacts: Manuel Romero (Manuel.romero@imdea.org);
José González-Aguilar (jose.gonzalez@imdea.org) ;
Mónica Álvarez de Lara (monica.alvarezdelara@ciemat.es)

Funding: Comunidad de Madrid. (Total Project: 225,000.00 €/a. Total Ciemat-PSA: 48,500.00 €/a)

Duration: January 2010 – December 2013

Purpose: The general purpose of this R&D program is to set the scientific and technological basis for developing new and more efficient concentrating solar thermochemical systems that are dispatchable and modular. Therefore, research is focused on a search for technological options that lead to development of a future generation of power plants and solar thermal systems that open the range of applications to new thermodynamic cycles and more efficient thermal machines and high-temperature endothermal chemical processes.

These general goals have been approached in four areas of activity:

Act. 1. Modular concentrating systems de (Coordinator: IMDEA Energía)

Evaluation of all solar concentrating Systems and their possible modularization: High-performance dish/Stirling systems, with no water consumption and unit powers of 3-10 kW, Modular Multitower systems for 100 kW pilot projects, for installation and testing in the Region of Madrid and solarization of a gas microturbine for use in mini solar towers.

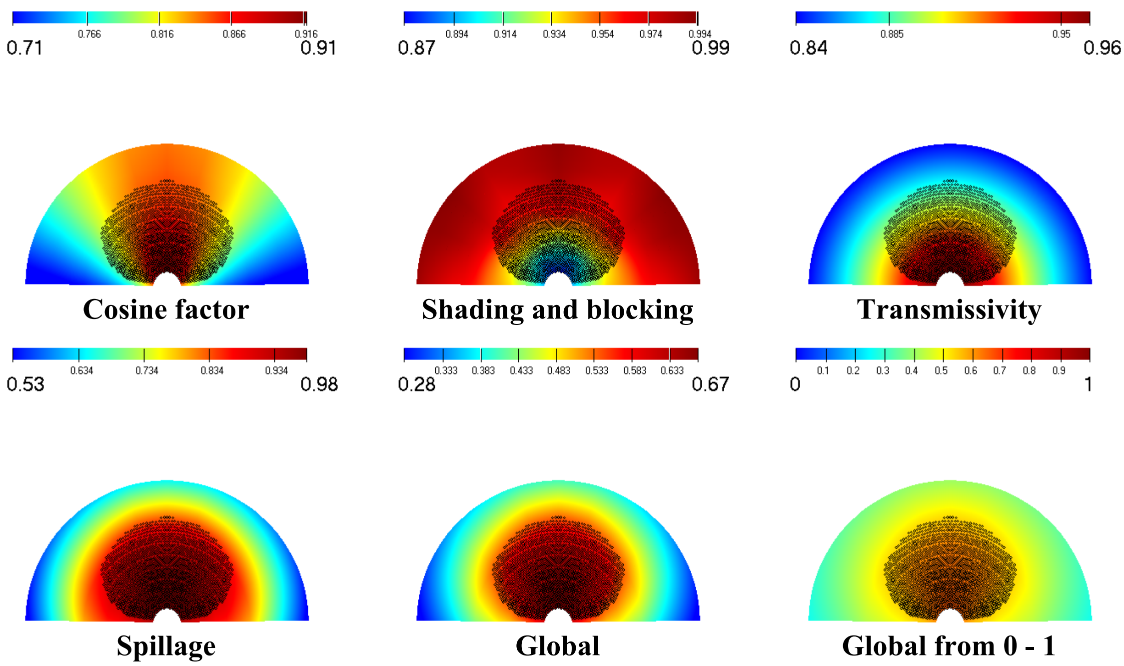


Figure 3.15. Example. Optical performance of the 50 MWe plant generated by WD along with the heliostat field proposed.

Act. 2. High-concentration/high-temperature solar receivers/reactors (Coordinator: CIEMAT-SSC).

Modularity is associated with the need to develop receivers and reactors to operate at higher concentrated solar radiation fluxes. It is intended to design and evaluated metal and ceramic volumetric receivers and particle receivers for selecting the best.

Act. 3. Energy storage systems for distributed solar thermal power plants (Coordinator: URJC)

Four wide areas of research are being studied to optimize energy dispatchability according to demand: Development of *thermochemical cycles for hydrogen production based on redox pairs using oxides* $M_xCe_{1-x}O_2$, Mn_2O_3/MnO, [$MxMe_1$-xFe_2O_4], *hydrogen storage in metal-organic framework (MOF) materials*. This activity occupies the entire project, and this first year synthesis and evaluation of the physicochemical and thermodynamic properties of mixed oxides, and synthesis, modification and study of MOF compounds in the literature have begun. Chemicals for developing electrodes by coating them with thin layers of semiconductor oxides and/or conductive organic molecules are also being synthesized and characterized.

Act. 4. Integration (Coordinator: INTA):

This activity is intended to *compare the* development and maturity of *technological options*, *integration* of different concentrating systems in densely occupied territories, and finally, a *life cycle analysis* following the ISO 14040 standard to determine the advisability of integrating distributed or central generation systems and a detailed analysis of environmental, economic and social impact. The SimaPro computer tool and the Ecoinvent database will be used. Although this activity is scheduled to begin in Month 36, a comparison of all the large scale technologies has already been done.

<u>Achievements in 2010</u>: Activities began in January 2010 and we can highlight the advances in the four sections as follows:

Activity 1: To date, the simulation tools have been perfected and are now being validated for optical design and sensitivity analysis for dish/Stirling systems, with developments in Excel-macros and "validation" with available tools such as STEC-TRNSYS and SAM.

Activity 2: One outstanding result is completion of a test bed for thermal characterization of volumetric absorbers and receivers and it is intended, at the end of the project, to have developed high-thermal-efficiency receiver prototypes for temperatures from 700-1300ºC.

In particle receivers for H_2 production with mixed metal oxides, the design and assembly of the facility for testing under solar radiation was completed. Furthermore, in the framework of development of these new receivers, it is important to find out the behavior of the materials used. Degradation in the materials under operating conditions must be understood, and appropriate aging methods have to be developed for this. In this first year, materials durability test methods for high-temperature solar receivers have been perfected.

Activity 3: We contributed to assessment of the use of *hydrogen* in turbines and *gas microturbines*, an analysis of an existing gas microturbine (power, type of cycle, operating temperature, performance, etc.) and a thermo-fluid dynamic study of the gas cycle with hydrogen as the fuel for optimizing the current microturbine modified for operating with hydrogen.

Activity 4: Participation in state-of-the-art reviews with perfection of tools and methods for comparative analysis of technologies and the potential impact of innovations on costs.

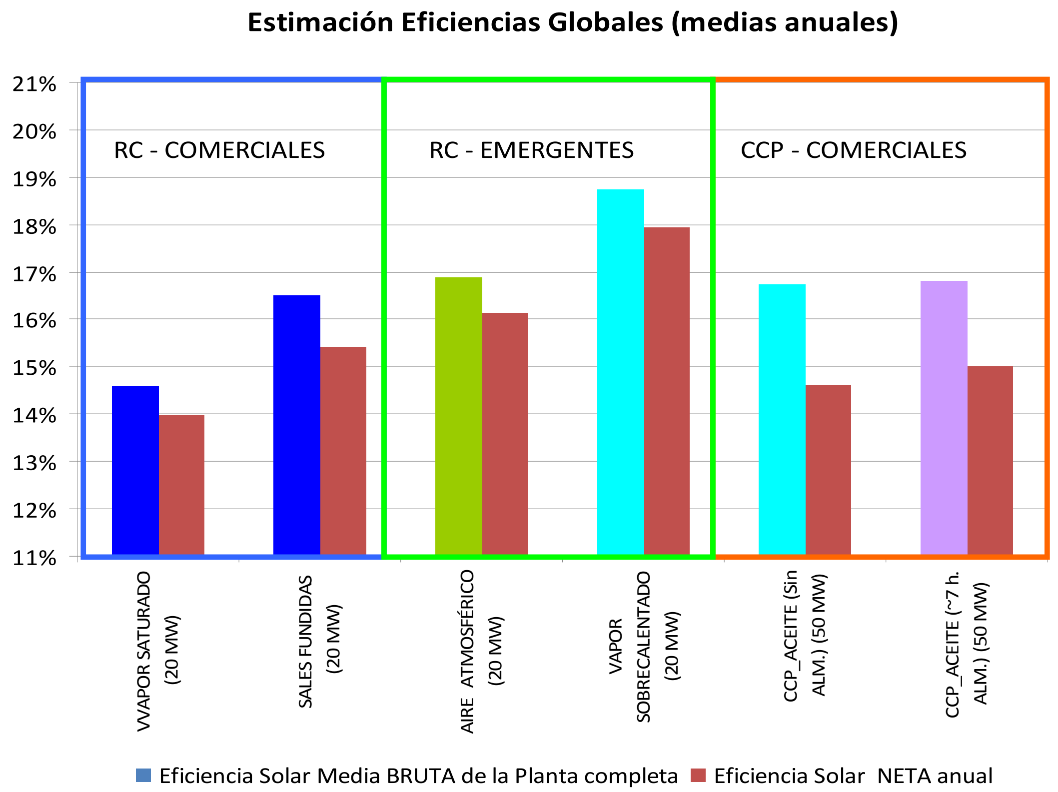


Figure 3.16. (Example) Comparative estimation of global solar-to-electric conversion efficiencies for several different technologies..

Publications: [3.15]

3.3.6 Central receiver technology feasibility study

Participants: ACCIONA, INGETEAM, CENER, CIEMAT
Contact: Félix M. Téllez (felix.tellez@ciemat.es)
Funding: CENER/Ciemat Agreement (42 k€)
Duration: January-December 2010

Background: To date, central receiver solar thermal power technologies (STP-CR) are still in a weak implementation context in which they must compete with other alternatives. This scenario, along with doubt about the regulatory perspectives supporting the technology, make it necessary to continually revise comparative feasibility analyses (with other alternative investment options) to identify opportunities for short-to-mid term commercial/technological development. Furthermore, within the STP technologies, the different design solutions for central receiver plants (CR) compete with each other leaving the challenge of finding the solution that has the best short-to-mid term path to profitability or business strategy to engineering firms. Even though in Spain there will only be 50 MW_e of these CR technologies connected to the grid at the end of 2011, interest is reactivating with new projects of up to 50-MW_e per unit. This is incorporated in an international panorama in which its deployment is catching up to the parabolic-trough technology and also leaving its space in the market to the dish/Stirling technology.

Figure 3.17. Calibration of IR detector in laboratory.

Purpose: Update feasibility analyses of the different central receiver technology options and define the technical-economic impact of accessible innovations.

Achievements in 2010: In 2010, in collaboration with CENER, an exhaustive review of the state-of-the-art from elements and components to demonstration and commercial central receiver STP systems. The feasibility analysis tools have also been updated.
Publications**:** [3.16]-[3.19]

3.3.7 Radiometry Laboratory

Participants: CIEMAT
Contact: Jesús Ballestrín (jesus.ballestrin@psa.es)
Funding: National R&D Plan (2002) CIEMAT funds
Duration: December 2003 (Ongoing activity)

Background: The Plataforma Solar de Almeria (PSA) Radiometry Laboratory arose out of the need to verify measurements of important radiometric magnitudes associated with solar concentration. These magnitudes are the solar irradiance ("flux" in the solar concentration jargon) and surface temperature of the materials (IR detection). In this sense, we are participating in the European SFERA Project within the "Flux and Temperature" activity to define flux and temperature measurement standards. We are also undertaking other matters related to radiometry such as atmospheric attenuation of solar radiation, measurement of the solar spectrum, etc.

During execution of the MEPSOCON Project (**ME**dida de **P**otencia **SO**lar **CON**centrada – Measurement of Concentrated Solar Power in solar power plants, Reference DPI2003-03788) a procedure for calibrating high-solar irradiance radiometers was drafted. Up to now, there had been no established procedures for calibrating these sensors. A systematic error was detected and corrected in measurement of high solar irradiance. The calibration of high solar irradiance radiometers is done habitually in this radiometry laboratory; in this sense, services are provided to national and foreign companies and institutions, such as Solucar, CENIM, DLR, CIEMAT, etc.

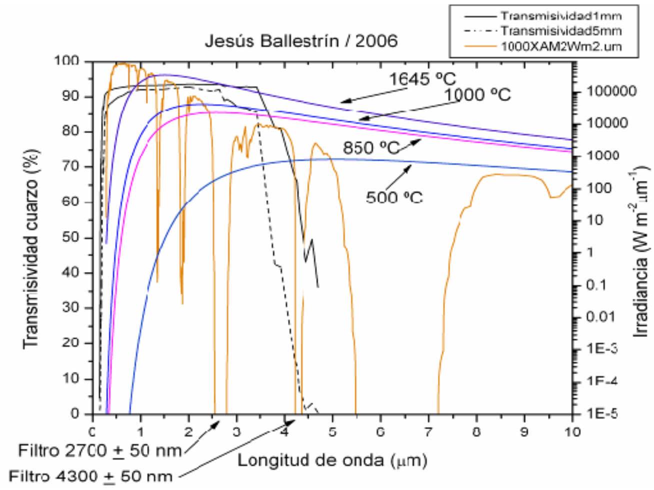


Figure 3.18. Problem of measuring surface temperatures in the solar context

Testing at the PSA requires measurement of high temperatures (>1000ºC) on the surface of materials. In some cases, quartz windows are even necessary to be able to work in an inert atmosphere to prevent rapid oxidation of the materials. The quartz window allows most of the solar radiation to go through, but keeps most of the infrared spectrum emitted by the hot surfaces from getting out in the opposite direction. The use of thermocouples is the method most commonly used even though it is well known that contact methods are not suitable for measuring surface temperatures. Therefore, infrared detectors are required (non-contact measurement) that allow the radiation emitted by the hot surface to be distinguished from the solar radiation reflected by the same surface.

The most promising lines of research propose use of infrared sensors that work in shortwave spectral ranges with H_2O and CO_2 atmospheric absorption bands so band-pass filters can detect the hot surface radiation even through quartz [3.20] without any distortion by the reflected solar radiation (Figure 3.18). It has been shown that although pass-band filters in the atmospheric solar absorption zones of 1900, 2700 and 4300 nm are "solar-blind", any variation in the distance and humidity that differs from the calibration conditions affects measurement. An IR camera with pass-band filters in two narrow "solar-blind" spectral regions outside of the atmospheric absorption bands, and therefore, insensitive to changes in distance and humidity, has been defined, designed and validated. The filter is changed automatically by filter wheel control software.

In collaboration with the meteorology station group at the PSA, spectral solar irradiance characterization studies continue. Studies of atmospheric attenuation of the solar radiation with the MODTRAN code have been begun.

Publications:[3.20]-[3.23]

3.3.8 Materials Durability and Accelerated Aging Laboratory activities

Participants: CIEMAT-PSA (E).
Contacts: Jesús Fernández-Reche (jesus.fernandez@psa.es),
Mónica Álvarez de Lara (monica.alvarezdelara@ciemat.es)
Funding: ERDF funds, SOLARNOVA Project (Plan-E), SFERA Project(CE) and own funding. (~200 k€)
Duration: 2009-… (Ongoing activity)

Background: One of the uncertainties in power tower systems is the long-term behavior of operation and durability of materials and components that are subjected to high incident solar radiation fluxes and temperatures of up to 1000ºC in daily heating/cooling cycles. One of the main components are the solar receivers. The AVANSOL Project had already begun to undertake the subject of absorber material durability and as a result of this project, the Plataforma Solar de Almeria started up a line of strategic research in durability of materials subjected to high solar flux and high temperatures. Fruit of this line is the laboratory described below.

Purpose: i) Develop test methods for accelerated aging and inference of the durability of materials subjected to high solar flux and high temperature, ii) reduction of the uncertainty associated with the durabilitiy of components for central receiver solar plants, iii) analysis and choice of suitable materials for each power tower receiver technology, tube receivers, volumetric receivers, and for different coolants, water/steam, molten salt, air, etc.

Achievements in 2010: In 2010, some facilities have been improved and adapted for testing thermal cycling and accelerated aging of materials under real concentrated solar radiation conditions. Along this line, in the PSA parabolic dish facility a DISTAL-I dish and three DISTAL-II dishes have been adapted for this type of testing.

- The dish control system was replaced by new equipment with PLC which allows control of movement to track the Sun all day long and also control cycling tests, focusing or defocusing the dish to test requirements.
- A new azimuth/elevation engine has been installed in the dishes.
- All the dishes have been entered in an internal optical fiber network that allows remote control of experiments.

For testing materials in the DISTAL I dish, a special support has been installed for automatic cycling. Furthermore, to be able to adjust the solar flux to the specific requirements of each test, this support may be moved all along the radial focus distance. For this, the radiation map was characterized at different focal distances depending on the direct normal irradiance (DNI). For control of test temperatures, an air-cooling system with blinds for fast cycles simulating thermal shock has been completed and installed.

Figure 3.19. View of DISTAL-II with new equipment and retail of the control box

Figure 3.20. View of DISTAL-I with new automatic thermal cycling system

The metals characterization lab has also been updated, so metal samples can be prepared with metallographic finishing and make different metallographic attacks for post-test examination to identify and compare materials behavior after receiver testing under real or simulated conditions (Preparation of samples for optical and scanning electron microscopy, etc.).
Publications: [3.24]-[3.25]

3.3.9 Improvements and activities in the CESA-1 tower

Participants: CIEMAT-PSA (E).
Contacts: Raul Enrique Orts (raul.enrique@psa.es)
Funding: ERDF, SOLARNOVA Project (Plan-E) y Own funding.
Duration: 2009-… (Ongoing activity)

Achievements in 2010: The CESA-1 facility already described in this report has benefited from several funding allotments for infrastructure improvement directed and managed by the HSCG. Among the improvements made in 2010 were:

- Work on the electrical equipment room, which was reconditioned, out-of-use tubes were cleaned, and new electrical boxes and condenser batteries were installed.
- New control boxes were installed in the CESA-1 field and 150 heliostats were canted after drafting a canting procedure and designing the equipment.
- The HERMES project target was dismounted and a new support frame for the SOLSYN project was installed.
- The molten salt receiver was dismounted and the salt tank was emptied.
- Existing equipment, such as the anemometer and pyrheliometer, field manholes were repaired and two new cloud transient surveillance cameras were installed in the heliostat field.

3.3.10 Characterization of small point systems

Contacts: Jesús Fernández-Reche (jesus.fernandez@psa.es)
Funding: Collaboration agreements and/or contracts with companies and/or public institutions.
Duration: January 2010-

Background: Over the years, the Plataforma Solar de Almería has developed a series of solar thermal point system modeling, testing and characterization methods: Heliostat field simulation, measurement of solar flux and total power in the focal plane of tower systems, parabolic dishes, geometric characterization of reflective surfaces, etc.

With the boom in the solar thermal market, many contractors and component manufacturers have come to the PSA to simulate and evaluate small power tower plant or parabolic dish prototypes for consulting on the development of new components, etc.

In all cases, the procedures and methods developed by the CIEMAT at the PSA over the years are directly applicable. So a series of collaboration agreements or research contracts have been signed with many national and foreign companies for consulting, characterization or assistance in product development.

Achievements in 2010: Cooperation with AORA SOLAR SL: This company contracts a prototype modular low-power solar power tower plant (100 kW_e). These plants are comprised of a small heliostat field that concentrates the solar radiation on a pressurized-air volumetric solar receiver feeding a gas turbine in a Brayton cycle. This plant concept employing natural gas when there is no solar radiation permits easy hybridization.

During 2010, the CIEMAT signed a research contract with AORA SOLAR where we cooperate in the design, characterization, testing and evaluation of a prototype solar power tower plant which is going to be installed at the PSA.

Specifically, work in 2010 focused on the design of the heliostat field and modeling the heliostats, so with the use of our own algorithms, we were able to simulate the energy behavior of the heliostat field at any time of the year. Based on these results, erection of the final heliostat arrangement selected will begin in the first quarter of 2011 and later, along with AORA SOLAR,

Figure 3.21. Examples of activity in the CESA-1 Facility in 2010

commissioning and operation during the characterization and evaluation of the system.

Cooperation with DLR in revaluing dish/Stirling prototypes existing at the PSA and for characterization of new prototypes: Since the early nineties, several parabolic dish prototypes have been installed at the PSA for testing and evaluation. When the respective projects were completed, these prototypes were disassembled, or maintained at the PSA for minimal use. To revalue these prototypes, the CIEMAT and the DLR signed a cooperation agreement which involves replacing the hardware (motors, control panels, sensors, etc.), and sharing use of the dishes for own research activities or in cooperation with companies which involves, among other things, accelerated aging tests and thermal cycling of materials and components, testing and evaluation of new Stirling engine prototypes, etc.

One of the tasks done in 2010 was optical-energy characterization of two of the three PSA DISTAL-II parabolic dishes.

3.3.11 Other activities of the High Solar Concentration Group in 2010

In addition to the R&D activities described in the paragraphs above, the High Solar Concentration Group of the Solar Concentrating Systems Unit carried out other activities, very similar to the Medium Concentration Group, which are:

- Improvement of capacities (modeling and instrumentation) for optical characterization of heliostats by acquisition and analysis of images projected on a white target on the tower.
- Testing/verification of auxiliary components for STP plants (such as valves, nitrate salt filters, auxiliary heating systems, etc.). The confidential nature of this type of work prevents us from giving more specific information on what was done by the PSA in 2010 in regard to these subjects.
- Dissemination of central receiver technology: giving many lectures and courses on renewable energies. In this area, the most significant contribution of the High Solar Concentration Group was our participation in the course on "Solar Concentrating Systems" given three times in Madrid in 2010.
- Consulting for contractors and engineering teams and firms involved in central receiver technology in those areas where the HSCG has accumulated significant experience, such as measuring high solar flux, diagnosis of heliostat incidents, selection of materials for solar receivers and storage systems, design tools, simulation and estimation of annual electricity production, etc.
- Make feasibility studies for central receiver STP technology in which the state of the art is reviewed, the potential of innovations already available or implementable in the short term or that analyze cost production scenarios for regional systems (e.g., case study for Costa Rica).
- Ongoing technology progress review (commercial projects, precommercial, component development, applications, etc.) and strategies for directing HSCG activities, attempting to boost some concepts which we are convinced have high potential for being competitive in the short-to-mid term (such as leveraging CR technology with ambient air as the heat transfer fluid).
- To the extent of the material and human resources available, we have maintained cooperative activities and initiatives in project proposals for partial funding with regional, national and/or European funds.

3.4 Solar Hydrogen and Solarization of Industrial Processes Group

Head: Alfonso Vidal Delgado
Alfonso.vidal@ciemat.es

In view of the low level of energy self-sufficiency in our country and its high energy consumption, initiatives directed at making use of renewable resources for energy diversification based hydrogen production or integration of solar technology in very intensive energy sectors could improve the well-being and wealth of our country. Production of fuels such as hydrogen, and integration of solar concentrating technologies in industrial processes are the main objectives of the Solar H_2 and Solarization of Industrial Processes Group.

The use of fossil fuels is the main source of greenhouse gas emissions. This situation is not sustainable in the mid-term and government insistently notes the need to prepare a controlled transition to a new form of clean energy production and consumption that is safe and reliable. One of the answers to this upcoming crisis is the use of hydrogen as an energy resource and its transformation into electricity using fuel cells. Thus, the term hydrogen economy responds to a vision of the future where hydrogen, generated cleanly and economically, would supply the greatest part of society's energy needs. This proposal would reduce today's dependency on fossil fuels, since hydrogen could be generated from other primary sources, such as renewable or nuclear energies. Air pollution would also decrease and the emission of greenhouse gases, since the only waste generated by a fuel cell is water. Hydrogen is called on to be the perfect replacement (clean, inexhaustible, etc.) of fossil fuels, which in Spain make up 84% of the total primary energy consumed and which is 99.5% dependent on foreign sources.

The interest awakened by hydrogen as an energy vector in the transportation industry and the doubtless fact that it is very attractive because of its clean production from solar energy, make the PSA give adapation of high-temperature solar concentrating technologies for application to mass production of hydrogen special attention. This activity is undertaken within the following projects underway: the SYNPET Project, "Solar thermochemical application for production of syngas from heavy crude oil", a private initiative the purpose of which is to demonstrate the technical feasibility of solar gasification with the participation of Eidgenössische Technische Hochschule ETH (Switzerland) and PDVSA (Venezuela), the HYDROSOL-3D Project, "Scale Up of Thermochemical HYDROgen Production in a SOLar Monolithic Reactor: a 3rd Generation Design Study" the main purpose of which is detailed study of a 1-MW solar thermochemical plant producing H_2 by water splitting.

Some national initiatives recently completed could also be mentioned, such as the SOLTER-H, "*Generación de hidrógeno a partir de energía solar térmica de alta temperatura*" (Generation of hydrogen from high-temperature solar thermal energy) in cooperation with the Hynergreen company, funded by the National R&D Plan under the Ministry of Education and Science PROFIT Initiatives in 2004 (FIT-120000-2004-66), 2005 (FIT-120000-2005-56) and 2007 (FIT-120000-2007-23) which have made it possible to make an exhaustive study of solar H_2 production. Or the PHYSICO2 Project, which was funded by the Region of Madrid to coordinate the research capacities of research groups located in Madrid (URJC, CSIC, CIEMAT, and INTA) related to the study and development of hydrogen production processes.

These national and international initiatives show the clear decision of CIEMAT for these technologies. Since 2007, the CIEMAT has been a member of the European initiative called European Joint Technology Initiative (JTI), which will invest about 430 million Euros over six years in research, technology development and demonstration in H_2 production and fuel cell technologies.

CIEMAT has wide experience and working groups for scientific and technological development in sectors such as H_2 production and development of fuel cells. In the first case, the main CIEMAT objective is research and development in sustainable, efficient and competitive hydrogen production technologies that lead to implantation of the hydrogen economy in Spain in the transportation and stationary consumption sectors based on native energy sources.

The PSA is a fundamental instrument for development of renewable hydrogen production processes making use of the abundant solar resource available in our country and the excellent knowledge of solar concentrating technologies applicable to reactors operating at temperatures above 1000ºC.

The lines of activity related to hydrogen are concentrated in two fields:

- Development of fossil fuel decarbonization processes and technologies and revaluing them by solar gasification, with special attention to low quality carbonaceous materials.
- Pre-commercial scale demonstration of the technical and economic feasibility of water splitting for hydrogen production through the use of thermochemical cycles with concentrated solar energy.

Application of solar concentrating technologies to high-temperature industrial or thermal processes of interest is another field of enormous importance in which the PSA has been working. The purpose of this area of work is to show the technological feasibility of the use of solar thermal energy as the energy supply in different industrial processes which have high temperature as their common denominator. The work being carried out at the PSA in this field has awakened the interest of a large number of research groups, which have been given access to our facilities through the Access Program funded by the Ministry of Science and Innovation. .

This report summarizes some of the still current objectives of the SOLARPRO Project (2003-2007) which was the start of research in this field, but which the PSA continues to undertake and add to.

3.4.1 SYNPET
Solar gasification of petcoke project

Participants: The solar gasification of petcoke project is in cooperation with the company Petróleos de Venezuela (PVDSA), the Technology Institute of Zurich (ETH) and the CIEMAT.
Contact: Luís Zacarias, luis.zacarias@pdvsa.com
PSA Contact: Thorten Denk, thorsten.denk@psa.es
Funding: Project funded by the partners, with PDVSA majority share Total budget: $6,950 k. CIEMAT budget: $1.940 k.
Duration: September 1, 2002 –February 28, 2011

Background: Solar gasification has some important advantages of its solarization, such as being a strongly endothermal process, which makes it possible to make maximal use of the heat supplied by the solar radiation. Another undeniable advantage is that gasification is a known process, normally used in industry and with completely proven and developed technologies. Solarization in the short-term of H_2 production has technical problems inherent in the use of solar radiation, that is, adaptation of these processes to variations typical of solar energy flux, especially in developing receivers/reactors.

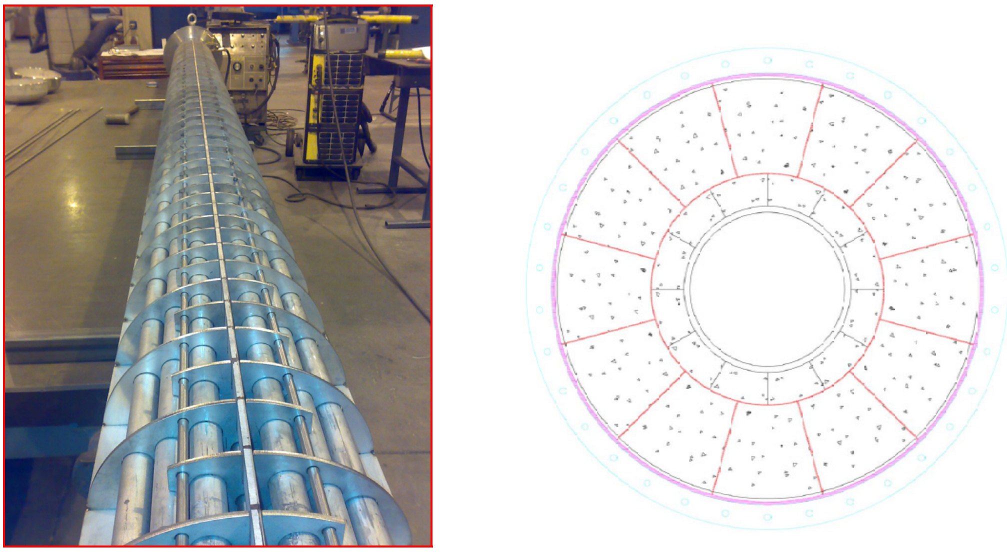


Figure 3.22. View of the exchanger located at the output of the SYNPET reactor and configuration in the brick-shaped receiver aperture.

Purpose: The main purpose of the SYNPET Project is to demonstrate the technical feasibility of solar gasification of waste from extra-heavy oil in the *Faja del Orinoco*. The development concentrates on finding the thermodynamic and kinetic parameters of the associated reactions, in the design of a solar reactor with quartz window and scaleup to and evaluation of a 500 kW installation located on the highest level of the PSA CRS tower.

Achievements 2010: Testing continued in 2010. In general terms, the current situation of the SYNPET plant is good, as few defects/malfunctions have been found in the equipment installed during commissioning. It is important to highlight the data from the last test where a temperature inside the reactor of 1050ºC was reached. The response of inner insulation was excellent, although some defects (cracks, breaks, etc.) were also found in the front cone, and so it had to be replaced. These first tests were made with the quartz window, at irradiance flux of up to 1.5 MW/m^2.

Several different alternatives for a new configuration of the center cone were studied with the Fleischmann company technicians (manufacturer of the refractory material) and a modular configuration based on two rows of bricks was chosen (Figure 3.22), which buffers the stress from high incident flux in the front cone. The same materials were used as in the first stage of the project: FISA-CAST 190 and 170 alumina ceramics.

Results of the tests that were started this year with this new configuration were very promising for its durability.

On the other hand, it should be mentioned that this project on a whole has meant the complete revision of some concepts: the design of a new support frame for large-aperture quartz windows and design of new systems for heat waste recovery from the gas, keeping in mind the special characteristics of these processes (high temperatures and high concentration of solids in the gas stream at the receiver outlet).

To date, two patents have been acquired in the United States corresponding to the gasification process and the solar reactor [3.28]. In June 2009, the documentation was also sent to patent the quartz window used in this application. A detailed design study of the window will be published in later editions of the Annual Report.

Publications:[3.26]-[3.30]

3.4.2 PHISICO2
Clean Hydrogen production: CO_2-emission-free alternatives

Participants: Universidad Rey Juan Carlos, CSIC, INTA, REPSOL, HYNERGREEN y CIEMAT.
Contact: David Serrano; david.serrano@urjc.es
CIEMAT Contact: Rocio.Fernandez; rocio.fernandez@ciemat.es
Funding: Cooperative Project funded by the 4th PRICIT-Madrid Regional Plan for Science and Technology. Total budget: 1000 k€. CIEMAT Budget, not including personnel: 240 k€.
Duration: January 1, 2006 – December 31, 2011

Background: The motivation for this project was basically to coordinate the research efforts and capabilities of research groups in Madrid (URJC, CSIC, CIEMAT and INTA) in clean hydrogen production, that is, Co_2 emission free and using renewable energies ad the primary energy source for its generation. Two companies in the power industry (REPSOL YPF and HYNERGREEN) are also involved in the project and have shown their interest in actively participating in the project and following up on the results.

Purpose: The general purpose of this project is to study the various clean hydrogen production processes in order to progress in the solution of technological and economic limitations it currently presents and that are essential to a future transition to the hydrogen economy. The alternatives under consideration In this project are characterized by avoiding the formation of CO_2 as a coproduct of hydrogen and use of renewable resources to provide the energy consumed in the formation and release of hydrogen.

The hydrogen production processes under study in this project are the following: photoelectrolysis of water, thermochemical cycles and decarbonization of natural gas. This project intends to evaluate the mid-to-long term technological and economic feasibility as well as their ability to reduce CO_2 emissions over more conventional hydrogen production systems, such as gasification and steam reforming.

Achievements in 2010: Even though the project officially concluded in 2009, in 2010, the solar facility was mounted to conclude the commercial ferrite evaluation task.

In 2010, along with the GIQA-URJC Group, the solar fluidized bed reactor design was completed. For this, the GIQA-URJC Group carried out fluidization experiments in the lab with the ferrite selected for the first solar tests ($NiFe2O_4$ Sigma-Aldrich), and were able to fluidize particles of 125 to 250 μm, as the smallest size possible, at 900ºC. Based on the laboratory fluidization conditions, reactor dimensions were scaled up to connect it to the solar concentrating system installed in the CIEMAT-Madrid.

The concentrating device has a 6-m^2 reflective surface and can reach a solar concentration of 500X, having measured 2 kW in a diameter of 20 cm. The reaction system is complete with gas (N_2) supply mass flow control, a water injection pump for the hydrolysis stage, a ceramic heating element for preheating gas, a water condensation system and a gas chromatograph (μ-GC) (see Figure 3.23).

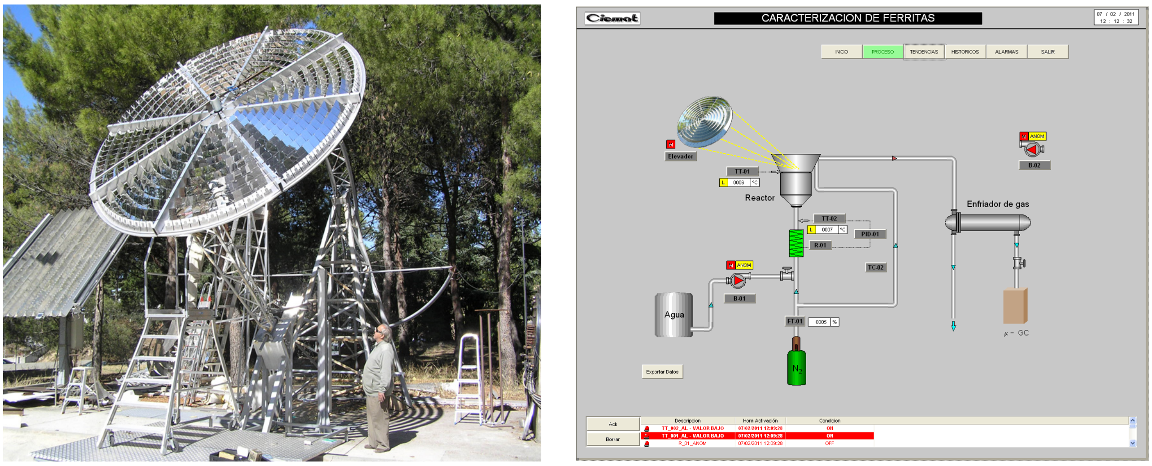


Figure 3.23. Photo of the facility and control schematic

The facility consists of a SCADA panel which does all the control and data acquisition tasks. The main characteristics of the SCADA are summarized below:

- A control box which includes a programmable logic controller (PLC) Phoenix Contact model ILC150ETH, with Ethernet port, switch for connecting the PLC and computer, data acquisition modules for incoming and outgoing digital and analogical signals, and the electrical elements (protection and maneuvering, switches, relays, transformers and direct current supply, wiring, etc.) necessary for supply, protection and maneuvering. PLC programming was done by Phoenix Contact PcWorx software.
- Process instrumentation: 2 Type K thermocouples, one for measuring the gas temperature in the heating element outlet and another for the reactor, with a 6-mm-diameter and 150-mm long sheath, head DIN IP67, with 4-20 mA convertor; 4-20 mA gas flow meter sensor with integrated controller that can regulate and measure inlet and outlet flow rates.
- Control computer with Windows XP operating system and licensed SCADA VISU+ Software programmed specifically for the process, which monitors field signals and manages process operating in manual and automatic modes, with visualization of historic data, trends and alarms. Communication of signal value and commands with PLC is by OPC protocol over an AX OPC Server installed in the computer itself.
- Electrical and signal wiring for the various system elements and channeling suitable for the wiring.

Fluidization tests began early in 2011 and their evaluation for finding out whether the system is adapted to process requirements have been scheduled.

Publication: [3.31]

3.4.3 Hydrosol-3D

Solar Hydrogen via Water Splitting in Advanced Monolithic Reactors for Future Solar Power Plants.

Participants: APTL (GR), DLR (D), CIEMAT (E), Total (F), HYGEAR (ND).
Contact: Christos Agrafiotis; chrisagr@cperi.certh.gr
Contact PSA: Alfonso Vidal; alfonso.vidal@ciemat.es

Funding: Cooperative project funded by the Joint Technological Initiative. 2008 Call. Total budget: 2100 k€. CIEMAT Budget: 175 k€.
Duration: January 1, 2010 – December 30, 2012

Background: Solar thermochemical hydrogen production faces the enormous Challenger of achieving scale up of solar concentrating Technologies and reactor sable to operate at Powers of several MW. At the present time there are developments, many of them tested by the DLR and CIEMAT at the PSA facilities, which make it possible to operate with volumetric receivers at temperatures above 1000ºC. The reason for the Hydrosol project is making use of the accumulated experience in materials development and systems with catalytic matrices using SiC with monolithic channels that were validated successfully during the SOLAIR Project. Impregnation of these ceramic matrices with mixed ferrites makes it possible to use the volumetric receiver/reactor concept in hydrogen production. The possibility of using this monolithic reactor with the ferrite fixed to a substrate greatly facilitates the separation of oxygen and hydrogen in alternating charge and discharge stages.

Purpose: The main purpose of the HYDROSOL-3D project is the detailed study of a 1-MW solar thermochemical plant producing H_2 by water splitting. The main idea comes from the technology developed and achievements in the preceding HYDROSOL I and HYDROSOL 2 projects which introduced the concept of solar monolithic multi-channel reactors in the form of a beehive panel for generating hydrogen by splitting the water molecule. The HYDROSOL 3D Project will make use of all the previous experience, concentrating on the design of a commercial plant and will include all the activities necessary for the construction of a 1-MW demonstration plant based on this technology.

Achievements in 2010:The second stage of the Hydrosol-3D's predecessor (Hydrosol-II) ended in September 2009 and its purpose was the evaluation of a 100-kW receiver in a power tower plant at the Plataforma Solar de Almeria using mixed ferrites impregnated on ceramic SiC matrices.

In 2010, testing scheduled was concluded. Figure 3.24 shows cyclical production of H_2 during the tests. The best results were during the tests corresponding to conversions of 30% water vapor.

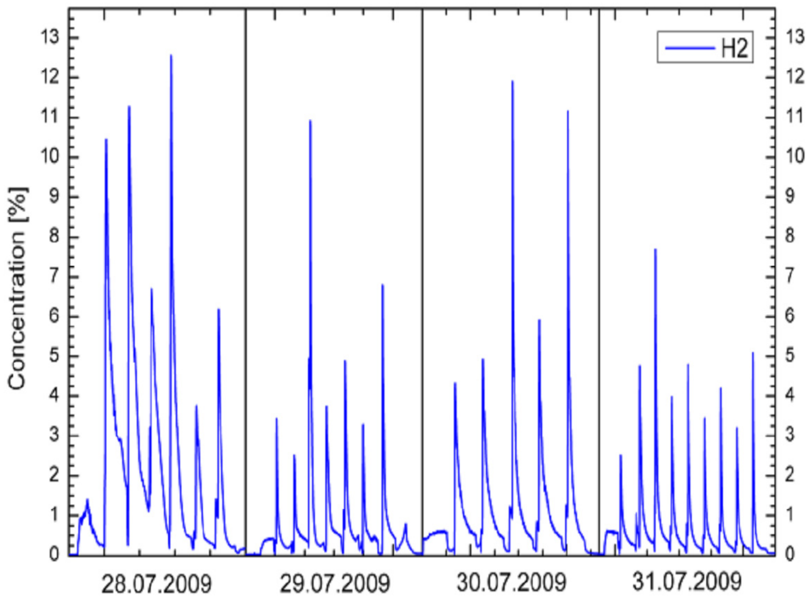


Figure 3.24. Concentration profiles in several consecutive tests

The results led to the first basic recommendations on operating strategies, especially on operation of the solar field. These tests demonstrated the operating capacity of the HYDROSOL II reactor in a field of heliostats with power tower for of semi-continuous production of hydrogen.

Taking advantage of the above, HYDROSOL-3D concentrates on the future commercialization and involvement of all the activities necessary to prepare the construction of a 1-MW demonstration solar plant based on the HYDROSOL technology. In this respect, HYDROSOL-3D includes predesign of the entire plant, including the solar hydrogen reactor and all the upstream and downstream units necessary to introduce the reagents and separate the products, as well as plant construction and maintenance costs.

This design will start by adjusting the composition of materials and configurations of advanced reactors made in the HYDROSOL and HYDROSOL-II Projects, to ensure the durability necessary and performance acceptable for marketing.

The reactors designed and control strategies will be validated by experiments going from laboratory to small-scale and pilot reactors integrated in solar power towers to make sure that they are upscalable. At the same time, the design of a control software with its algorithms and controllers necessary for automatic operation of this plant will be developed and integrated in a process simulation software.

Two alternative scenarios will be analyzed: Adapting the hydrogen production plant to an existing solar power tower field or developing a new one "from scratch", completely optimizing hydrogen production to the solar plant. The most promising option will be selected and in continuation will be analyzed in detail, developing the distribution of the plant, its definition and detailed dimensioning of all its components as well as the control system and simulation of complete plant operation.

Finally, a technical-economic study will be made and a market analysis to find out the feasibility of process scale up to MW scale, by calculating the costs necessary to build a 1-MW demonstration plan and the costs of supply and producing hydrogen. Realistic market penetration scenarios will also be calculated for the technology and the possible synergies with other technologies that complement the project, in order to demonstrate that combination of the power tower technology is a feasible way to produce large amounts of hydrogen by water splitting at a reasonable cost, without any type of greenhouse gas emissions, facilitating the path to the sustainable future of a purely renewable hydrogen economy.

<u>Publications</u>: [3.32]-[3.34]

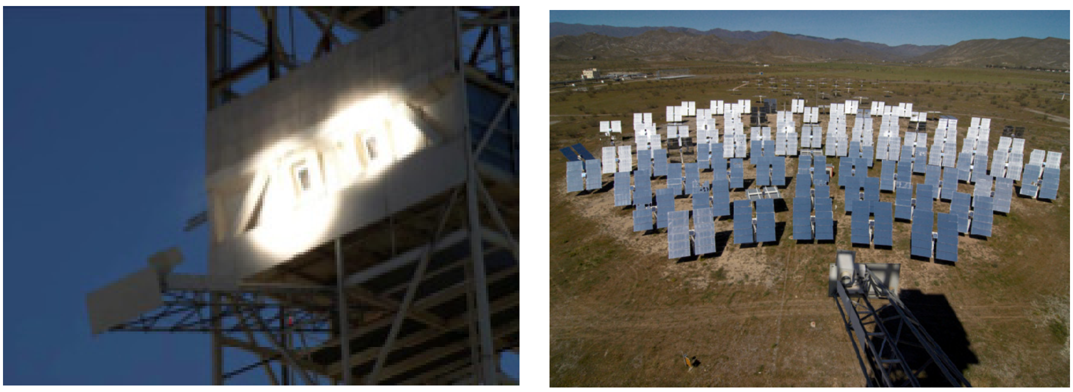


Figure 3.25. <u>Left:</u> Detail of the two HYDROSOL-II reactor apertures in operation. <u>Right</u>: View of the SSPS heliostat field as seen from one of the HYDROSOL-II reactor apertures

3.4.4 ORESOL
Oxygen from lunar regolite using concentrated solar energy

Participants: CIEMAT-PSA
PSA Contact: Thorsten Denk; thorsten.denk.psa.es
Funding: European Commission 6th Framework Programme ERA-STAR Regions (ERA – Space Technologies Applications & Research for the Regions and Medium-Sized Countries - CA-515793-ERA-STAR REGIONS) Network DeMoLOP. Total budget: 100 k€.
Duration: January 1, 2008-December 31, 2011

Background: To enable human beings to establish permanent sustainable settlements beyond the low earth orbit, economic access to essential resources is indispensable. One very important resource necessary there is oxygen, both for human consumption and for rocket fuel. If it were possible to get oxygen on the moon, a very substantial part of the cost of the transport load from earth could be saved.

Lunar regolite (dust) is rich in oxygen (up to 45% mass), but the chemical bonds are very strong, which means that to get it, very high temperatures, above 1000ºC are necessary. As a result of previous studies, the most favorable chemical reaction selected is reduction of lunar regolite, called ilmenite, with hydrogen to water (Eq. (1)), followed by electrolysis to get oxygen and recover the hydrogen (Eq. (2)).

$$\mathbf{FeTiO_3 + H_2 \rightarrow TiO_2 + H_2O + Fe} \quad (1)$$

$$\mathbf{2\,H_2O \rightarrow 2\,H_2 + O_2} \quad (2)$$

One attractive possibility for supplying the energy necessary is using concentrating solar radiation systems that would supply the high energy flux densities needed to reach the processing temperatures.

Purpose: In the DeMoLOP Project, it is intended to study how to get oxygen from lunar regolite using concentrated solar energy, in order to develop a complete demonstration system consisting of:

1) A regolite extraction system
2) A reaction system for acquiring oxygen
3) An oxygen post-processing system

The contribution to the ORESOL Project to DeMolOP is under Point 2), development, construction, testing and characterization of a device able to perform the chemicals reaction with concentrated solar radiation to acquire oxygen from a "lunar soil stimulant" manufactured by NASA.

Achievements in 2010: The main achievements of the ORESOL Project in 2010 are the assembly of most of the solar reactor and detailed design and acquisition of subordinate components, such as support, gas supply line and part of the instrumentation.

The ORESOL reactor concept is a continuous-operation fluidized bed with low-expansion, vertically concentrated solar radiation and direct absorption through a quartz window. The following Figure 3.26 shows the different stages of reactor assembly.

The inside of the reactor is dominated by the microporous insulation which minimizes heat loss. In the center is the particle container with a sophisticated fluidization bottom for uniform fluidization of the particles. An annular aperture at the top directs concentrated solar radiation to the fluidized bed. Particles loading and unloading of the reactor is continuous through fluidized auxiliary tubes.

A very important achievement should be mentioned, which was the very satisfactory evaluation of the ORESOL project by the Ministry of Science and Innovation in answer to the follow-up report.

The project was funded by the PSA with its own means, however, as practically all the hardware has already been acquired, and since the expected results may be of great value to any future solar chemistry project, work was accelerated and installation and the first tests are scheduled for 2011.

3.4.5 SOLARPRO II

Development of preindustrial prototypes for generating solar high-temperature process heat: Testing and characterization of its application to production processes and waste disposal.

Participants: CIEMAT, Univ. of Seville, Institutor de Technologic Ceramic, Polytechnic Univ. of Catalonia, Centro National de Investigations Metalúrgicas (CENIM-CSIC)

Contact: Inmaculada Cañadas, i.canadas@psa.es

Funding: SOLARPRO I and SOLARPRO II. Projects funded by the National RD&I Program (2003-2007). Total Budget: 405.6 k€. CIEMAT budget: 213.6 k€.

Duration: SOLARPRO I and SOLARPRO II: November 2003 - December 2011

Background: Because of its characteristics, solar thermal energy is the renewable energy which is called upon to play a relevant role in industry, as it can acquire directly or through a transfer fluid or absorptive material, the thermal energy necessary for many industrial processes, and can supply process heat at different temperatures.

The industrial processes that usually require the largest energy supply are those that are produced at high temperatures. A strong boost by research is necessary for the future implantation of the solar concentrating high-

Figure 3.26. ORESOL reactor assembly

temperature thermal technology in industrial processes and the technological feasibility of each particular process must be demonstrated, adjusting its design and production parameters accordingly.

Purpose: The purpose of "SOLARPRO" is to demonstrate the technological feasibility of the use of solar thermal energy as the energy supply system in different industrial processes the common denominator of which is their high temperature. So in this project, the processes studied are basically classified into two groups, industrial production processes and waste treatment processes.

- *Industrial production processes*: Since it is intended to make use of the capacity of solar concentrating systems to generate high temperatures, feasibility studies were undertaken of solar thermal energy application to different industrial processes in which high energy supply is necessary, and which are associated, if fossil fuels are used, with high acidifying emissions, such as powder metallurgy, ceramics industry, and various materials treatments.
- *Waste treatment*: Applying the same principia, it is intended to combine two effects that are beneficial to the environment: use of a renewable energy source and destruction of hard-to-eliminate waste.

Achievements in 2010: Although the original SOLARPRO-I and II officially ended in 2007, their good results merited their continuation, and the PSA has continued working in this line of R&D with its own resources In 200, not only have the three chamber or reactor prototypes designed and constructed during the previous years been in use, but work to improve viable prototypes has continued. They have had excellent results, not only the processes they were conceived for, but for new lines of research and even for other projects and new applications. The SolarPRO prototypes have thus been modified on numberless occasions and new prototypes designed (as for LF II or direct fluidized bed) which has allowed us to achieve new goals and undertake new processes.

Figure 3.27. SolarPRO Project solar reactor prototype in operation in the PSA Solar Furnace.

Work on developing second generations of these prototypes has continued with successful results in the priority lines set out in the original project and in new applications with new improved prototypes.

Cooperation agreements have also been signed with various institutions for the development of new processes and prototypes for processes and materials treatment with concentrated solar energy related to this project. Furthermore, new lines of research and cooperation have been established, some of them funded by the Plataforma Solar de Almeria access programs.

Publications: [3.35]-[3.39] [3.28]

3.4.6 Singular Scientific and Technical Facilities Access Subprogram
Access to the Plataforma Solar de Almería Solar Furnace

Participants: Instituto de Carboquímica de Zaragoza, el Centro Nacional de Investigaciones Metalúrgicas (CENIM), la Univ. Castilla La Mancha (UCLM), Instituto Madrileño de Energías Alternativas (IMDEA), CIEMAT Soil Desorption Unit

Contact: Inmaculada Cañadas, i.canadas@psa.es
José Rodríguez, jose.rodriguez@psa.es

Funding: Funded by the Ministry of Science and Innovation through the Singular Scientific and Technical Facilities (ICTS) Subprogram on design, feasibility, access and improvement of Singular Scientific and Technical Facilities. Total Budget 90 k€

Duration: 2010

Purpose: The purpose of this PSA activity is framed by the general ICTS Access Subprogram and strengthens access to the PSA Solar Furnace facilities, offering access to the facility by outside users, as well as technical support, including remote IT access.

Results achieved in 2010: Testing concentrated on the following:

- The Instituto de Carboquímica de Zaragoza tested H_2 production by CH_4 reforming in the rotary kiln. Eight tests were performed at temperatures from 500 to 900ºC and exposure times of one and two hours. Three different catalysts were employed: Ni/Al_2O_3; Fe/Al_2O_3 and BP2000.
- CENIM tested nitrided A_30_4L steel test pieces and $TiAl_4V$ titanium alloys in an LFII fluidized bed. Two test campaigns were carried out. The first consisted of five tests at 850, 1200, 1300 and 1400ºC, and fluidization flow rates from 10 to 40 L/min. The second also consisted of five tests in the LFII bed, fluidizing in N_2 with fluidization flow rates of 8 and 18 L/min, at 850ºC. The beds used were cast iron sand, Al_2O_3, corindon alumina and AL_2O_3+5%B_4C.
- The UCLM tested sintering of several M2 tools steel alloy test pieces and nitriding of Ti_6Al_4V samples in the MiniVac chamber. HYD45 gas (N_2+5%H_2) was used in the sintering tests at temperatures from 100 to 1225ºC, while the four nitriding tests were done at 900 to 1200ºC.
- The IMDEA Institute of Madrid performed two test campaigns for H2 production by manganese oxide reduction in the MiniVac chamber, in controlled Ar atmosphere at temperatures in the 900ºC to 1600ºC range.
- Thermal desorption of mercury in polluted soils was the subject of testing by the CIEMAT Soil Degradation Unit. Ten tests were carried out in the rotary kiln at temperatures of 60, 160, 220, 260, 360, 560, 650 and 750ºC and exposure times of 1 hour.

In addition to these tests, others were done in the PSA's own lines of research, such as acquisition, calibration and commissioning of the new solar-blind IR camera, and collaboration with mixed groups, such as Automatics and control from the University of Almería in collaboration with the PSA-CIEMAT. Along these lines, the following tests should be mentioned:

- The University of Almería tested automatic control of the Solar Furnace shutter, with different controllers and upward curves, at temperatures of 200 to 800ºC.
- Finally the PSA Materials Group did experiments in the processing chamber to acquire data for design of a new processing chamber that optimizes current features. Six tests were done at maximal air temperatures of 1000ºC to 1150ºC.

It should also be mentioned that during 2010, the infrastructure was improved with Plan E funds and the new SF40 Solar Furnace was built.

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4 Environmental Applications of Solar Energy Unit

Head: Julián Blanco Gálvez
Contributions: Sixto Malato Rodríguez
Pilar Fernández Ibáñez
Manuel Ignacio Maldonado Rubio
Isabel Oller Alberola
Ana Zapata Sierra
Inmaculada Polo López
Noelia Miranda García
Benigno Sánchez Cabrero
Raquel Portela Rodríguez
María Dolores Hernández
Silvia Suarez Gil
Marta Sánchez Muñoz
María Muñoz Vicente
Diego Alarcón Padilla
Guillermo Zaragoza del Aguila
Elena Guillén Burrieza

4.1 Introduction

The Environmental Applications of Solar Energy Unit has formally defined its mission as, "Generation of new knowledge associated with technological development that enables solar radiation to be used effectively in environmental processes, including seawater and brine desalination and air and water treatment and purification as the main cores of activity. This encompasses the following lines of research, each of which is structured in a different Work Group:

A) Solar wastewater detoxification and solar water disinfection (Head Researcher: Dr. Sixto Malato). The activities in this line of research include, among others:
   - Solar photocatalytic decontamination of persistent organic pollutants dissolved in water.
   - Disinfection of water by processes based on solar radiation.

- Other advanced water decontamination and disinfection processes, as well as other photochemical processes for making use of solar radiation.
- Design, construction and testing of pilot facilities for these developments to collect basic feasibility data.
- Publicize all of the above in Ph.D. theses, scientific articles in impact journals, etc.

B) Solar detoxification and disinfection of air (Head Researcher: Dr. Benigno Sánchez), with the following associated lines of research:
- Solar and artificial photocatalytic treatment of emissions and odors
- Chemical and biological characterization of indoor air, and its photochemical and photobiological decontamination
- Synthesis, physicochemical characterization and testing of new photocatalyst activity
- Design, construction and testing of photoreactors with various configurations and radiation sources.

C) Desalination of seawater (Head Researcher: Dr. Julián Blanco), with the following lines of research defined:
- Solar multi-effect distillation (MED) and/or hybrid solar-gas systems
- Incorporation of a double-effect absorption heat pump and advanced control strategies in solar MED plants
- Integration of reverse osmosis in solar thermal power systems using ORC cycles
- Solar polygeneration systems (electricity/cooling/water/heat) based on parabolic-trough collectors
- Integration of desalination technologies in solar power plants (CSP+D)

Activity along these three lines has been as intense as in similar years. Interest of business and other institutions in the processes and technologies and the traditional fields of work in the unit, which is reflected by the list above, has been maintained as demonstrated by the products and collaboration which are briefly summarized below.

Perhaps the most outstanding confirmation of this is the fact that the area of activity of collaboration and projects underway is taking place around the world on almost all of its continents, as projects and initiatives in North and South America, North and South Africa, the Middle East, Asia and Australia are added to the already intense activity in Spain and Europe

In each case the specific subject of interest is different, but all of the activities together make the unit's work highly internationalized at the same time it makes it possible for us to increase the network of contacts and collaboration as well as specific RD&I to be undertaken. In this Unit, we are convinced that this interest can only increase in the coming years.

There were 24 persons in the Unit's staff as of December 31, 2010, broken down as follows: 5 government researchers, 6 contracted researchers, 1 Ramón y Cajal fellow, 1 Juan de la Cierva fellow, 8 Ph.D. students and 3 laboratory technicians. The core of the "Air Decontamination and Disinfection" Group researchers are at CIEMAT's Madrid facilities, and another two are at the PSA. The Unit's 2010 budget, including outside income was over 650,000€.

The main activities carried out in 2010 in each of the RD&I Groups mentioned above are described below.

4.2 Water Detoxification and Disinfection Group

In 2010, work on 4 European projects (EC 6th Framework Programme) was concluded and activities on a new national project (EDARSOL) and another European one began, in addition to the activities on other projects already underway in 2009. Details of each of these projects are given on the following pages. This year, our group hosted 20 guest researchers from other research centers and universities in Spain, Portugal, Argentina, Ireland, Greece, italy, U.K., France and Cyprus. Furthermore, one Ph.D. thesis was defended (Dr. Carla Sirtori) supervised by the Ph.D.s in the Group and included in this section's list of references.

In keeping with the importance the Group gives evaluation of project results through publications in journals in impact indices, it should be remarked that 18 have been published, in addition to other articles in less specialized professional magazines. Furthermore, scientific activity has also been recognized by the following other work: 6 Ph.D. theses underway, 1 Ph.D. thesis defended in 2010, 1 book, 1 chapter in a book and 16 communications (6 of them oral or invited, also cited in this introduction) at international congresses. It should also be mentioned that two special issues in Catalysis Today and Photochemical and Photobiological Sciences were edited in association with the 6th European Meeting on Solar Chemistry and Photocatalysis: Environmental Applications, held in Prague (Czech Republic), June 13-16, 2010 (http://www.spea6.com/).

Publications: [4.1]-[4.6]

4.2.1 EDARSOL

Integration of solar photocatalytic processes in biological wastewater treatment for the elimination of emerging contaminants (EDARSOL).

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

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

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

Funding: National Plan for RD&I, MEC. CIEMAT Budget: 120 K€.

Duration: January 2010 – December 2010

Background: Although there is information on the possibility of treating contaminants by different technologies, it is also well known that non-biodegradable substances such as pesticides, pharmaceuticals, hormones and synthetic fragrances, and so on, are not eliminated in conventional wastewater treatments. Therefore, new technologies including more exhaustive processes and combining different chemical and biological techniques must be applied in water treatment.

Purpose: This project is intended to develop an integrated elimination process for emerging contaminants in waste water by combining biological treatment with solar photocatalytic (TiO_2, photo-Fenton) advanced oxidation processes (AOPs) and ionization. The general purpose of the project is to design (based on kinetic models of the biological and chemical stages), construct and evaluate treatment systems (pilot plant) that integrate a biological reactor (based on the most suitable biological treatment of those evaluated in each subproject) combined with a solar photocatalytic treatment. The specific project goals of the coordinated project, which derive from the synergies of the various subprojects, are:

1) Make an overall method for determining precisely the right detoxification and best biocompatibility of wastewater treated by advanced processes (advanced oxidation and aerobic), by comparing different methods of toxicity and biodegradability measurement.
2) Optimize the biological treatment of waste water by comparing membrane reactors (MBR), immobilized biomass reactors (IBR) and active sludge in agitated tanks (AT).
3) Select the best option from the various advanced oxidation wastewater treatments
4) Integration of processes, including their economic evaluation.

Achievements in 2010: In 2010 advanced oxidation processes (AOPs) were compared and evaluated: (i) optimization of photo-Fenton by automatic dosing of H_2O_2 as a function of dissolved O_2 concentration, (ii) solar photo-Fenton tertiary treatment of WWTP effluents, (iii) TiO_2 solar photocatalytic tertiary treatment of WWTP effluents, (iv) evaluation of toxicity during AOPs, (v) construction and startup of a new photo-electro-Fenton reactor.

Figure 4.1 shows part of the results of the study of the ratio of H_2O_2 concentration to dissolved O_2 (DO) concentration so DO can be used to control automatic dosing of H_2O_2. Excess peroxide competes for OH radicals and must therefore be controlled, but if the concentration is too low, lack of peroxide slows down the reaction. The ratio of H_2O_2 to DO concentration during photo-Fenton has been confirmed and it is therefore possible to use it to monitor treatment and for dosing H_2O_2. It is therefore necessary to optimize dosing in such a way that there is enough H_20_2 accumulated so as not to slow down the process and at the same time self-decomposition does not begin.

Results of tertiary treatment of WWTP effluents by solar photo-Fenton and TiO_2 photocatalysis are shown in Figure 4.2. Of 85 compounds studied, 55

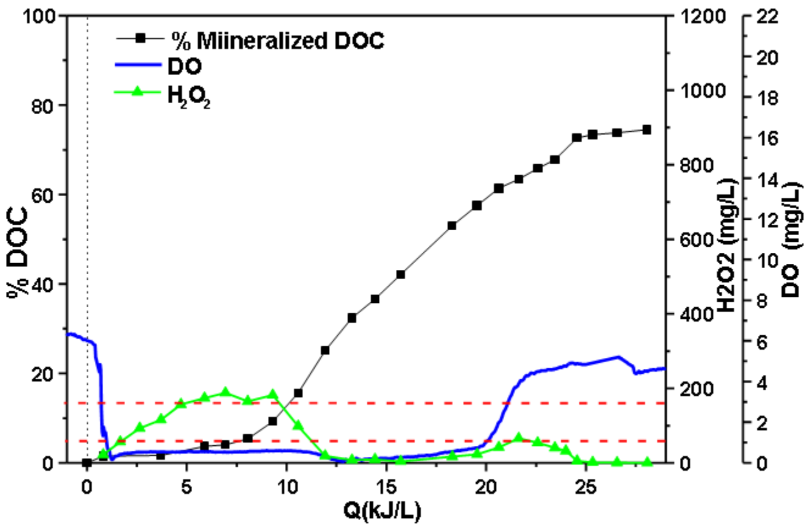


Figure 4.1. Mineralization of a mixture of contaminants (COD= mg/L) by photo-Fenton using automatic H_2O_2 dosing showing dissolved oxygen and hydrogen peroxide during the process.

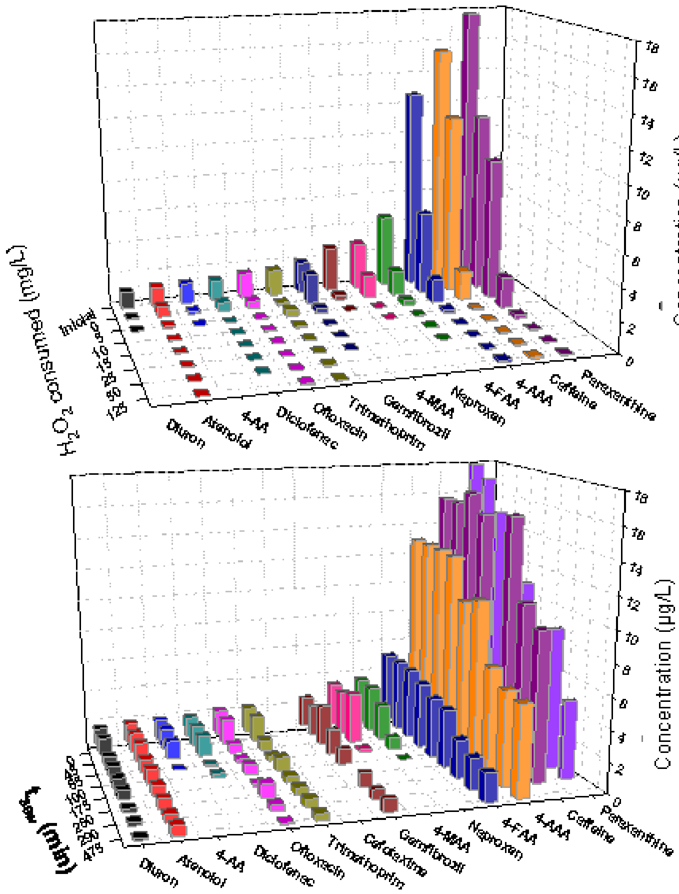


Figure 4.2. Elimination of contaminants in WWTP effluents by photo-Fenton (top) and TiO_2 (bottom). Shown are compounds detected in concentrations over 1000 ng/L.

were detected, 40% in a concentration of less than 100 ppt, most of which were pharmaceuticals, although some pesticides were also found, especially atrazine, which is now prohibited. Metabolites appear in the largest concentrations, especially caffeine and its metabolite paraxanthine, in concentrations over 15 µg/L. In the toxicity studies done with *vibro fischeri* (bioluminescent bacteria with high sensitivity to inhibiting effects of toxic agents) and respirometry using active sludge from a treatment plant, no toxicity was found at the beginning of treatment, nor did it increase during it.

In 2010, the PSA Detoxification/Disinfection Group acquired a commercial "Electrocell" electrochemical reactor (Figure 4.3) consisting of an RuO_2-coated dimensional stable anode (DSA-O_2) and a "Black Pearls 2000" oxygen diffusion cathode. The anode can generate oxidizing hydroxyl radicals from the oxidation of H_2O, while H_2O_2 is continuously electrogenerated in situ in the cathode throughout the degradation experiments due to the bielectronic reduction of O_2 contained in the compressed air blown into the reactor's air chamber. The reactor is connected to a compound parabolic collector (CPC) pilot plant in a 35-L electrochemical-photochemical treatment system. First it was operated in a configuration in which the solution was pumped from the tank to the electrochemical reactor and then through the CPC and returned to the tank. Leaks were observed under different liquid and air flow conditions. When the problematic points were identified, the modifications were made in the system configuration and to verify the proper operation of the modified system, several experiments were carried out. These demonstrated that the electrochemical reactor has a high capacity for continuous electrogeneration of enough H_2O_2 for the Fenton reaction. A stationary value is reached at around 150-250 mg/L, once the generating speeds in the cathode and destruction in the anode are equaled. Finally, it was observed that in presence of 0.15 mM Fe^{2+} in the solar photoelectric-Fenton method, the amount accumulated in the system is very small because of its participation in the Fenton reaction in the production of hydroxyl radicals. This production of highly oxidizing species must therefore serve as an argument for studying the feasibility of the solar photoelectric-Fenton for the degradation of pollutants.

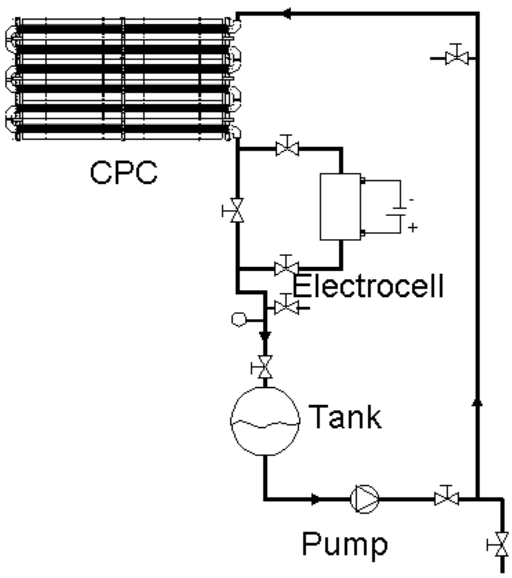


Figure 4.3. Drawing of the new photo-electrochemical reactor installed at the PSA.

Publications: [4.7]-[4.15]

4.2.2 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. (E), AnoxKaldnes (S), Water Innovate Ltd (UK), DHV (NL), Adv. Wastewater Manag. Centre (AUS).

Contact: Dr. Sixto Malato Sixto.malato@psa.es
Dr. Antonio López, antonio.lopez@ba.irsa.cnr.it

Funding: 6^{th} FP. Global Change and Ecosystems.; 2.750 k€. CIEMAT Budget: 350 K€.

Duration: November 2006 – April 2010

Background: Develop treatment processes for from industrial waste water: 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 were applied to industrial effluents (lixiviates, pharmaceuticals, pesticides, paper industry, etc.).

Purposes: (i) Study and increase the performance of promising options for industrial wastewater treatment, such as aerobic granulation, membrane contactors and chemical membrane reactors, (ii) Make progress in 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.

Achievements in 2010: Operation of the industrial system combining photo-Fenton and biological treatment for water containing pesticides was tested at the Albaida Company (CESPA Group) for several months with successful results. The composition of the industrial waste water and its treatment have been evaluated using an LC-MS-TOF chromatographic method developed by the Univ. of Almería and which allowed up to 300 different pesticides to be analyzed in 20 minutes. Furthermore, the project also studied the effect of the water matrix composition (that is, the inorganic salt content) on reaction rate efficiency and any halogenated intermediates formed during the solar photo-Fenton treatment when the water has a high concentration of chloride. This is very common in industrial waste water such as effluents from the pharmaceutical industry or lixiviates from garbage dumps.

It is interesting to note (Figure 4.4) that the reaction rates in the three matrices studied (DIW, DIW_{NaCl} and SIE) were not substantially different. The degradation rates in DIW_{NaCl} and SIE were very similar, as the effect of the high COD in SIE compared to the original COD in DIW_{NaCl} was compensated by the higher Fe^{2+} dose used in the SIE experiment. However, the main result is related to H_2O_2 consumption needed for complete degradation of NXA, which was very similar in all three cases (around 6-7 mM). This is explained by the action of the $Cl^{\bullet}$ and $Cl_2^{\bullet -}$radicals which are also strong oxidants (E^o_{SHE}, $Cl^{\bullet}/Cl^-$= 2.41 V; E^o_{SHE}, $Cl_2^{\bullet -}/2Cl^-$= 2.09 V), and as they could be present at high concentrations, could also easily oxidize NXA, reducing the consumption of H_2O_2. Therefore, in situations where a high concentration of chloride ions is observed, the $Cl^{\bullet}$ radicals and radicals formed by the reaction between the $Cl^{\bullet}$and hydrogen peroxide radicals could partly compensate capture of $^{\bullet}OH$ by Cl-. Observe that H_2O_2 consumption could be a parameter of interest for photo-Fenton if it is intended to find out when NXA has been completely degraded and would compensate to a certain extent the uncertainties that arise when only treatment times are taken into account. That is, when around 8 mM of H_2O_2 have been consumed, it may be assured that NXA has been completely degraded.

Intermediates were identified during these experiments in DIW_{NaCl}. However, the mass spectra showed the formation of only one chlorinated subproduct, when the degradation of NXA took place in a saline medium. The elementary composition and abundances of isotopes of the $[M+H]^+$ a m/z 283.0419 ($C_{12}H_{12}ClN_2O_4$; DBE: 8) ion confirmed the presence of a chlorine atom in the molecule. In the presence of chloride some Fe and Cl complexes may be generated which may in turn be photolyzed at 270.400 nm wavelengths, which would lead to the formation of $[Fe(OH_2)_6]^{2+}$ and $Cl^{\bullet}$. The $Cl^{\bullet}$ radicals formed from the Photo-dissociation reactions are quickly captured by the chlorides which generate less reactive species, such as $Cl_2^{\bullet -}$ y $ClOH^{\bullet -}$. This impedes the formation of chlorinated subproducts and would explain the scant abundance of this compound, which is also quickly degraded in later steps. Therefore, the persistence of chlorinated intermediates that could increase toxicity during treatment is discarded.

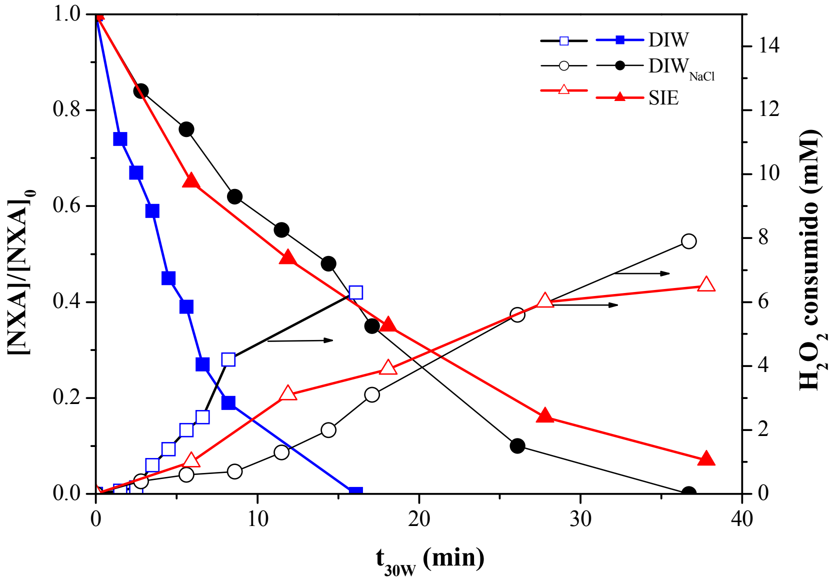


Figure 4.4. Degradation of nalidixic acid (NXA) and hydrogen peroxide consumption during photo-Fenton treatment in waste water with different salt contetnt: deionized water (DIW), natural water (SIE) and water with 5 g/L of NaCl (DIW_{NaCl})

It is possible to set the waste water DOC approximately by controlling the ratio between the number of containers washed and the volume of water used for it considering the operating mode of the container-washing plant. In the case of $DOC_0$0 480 mg/L and COD=1360 mg/L, the photo-Fenton process is continued until the original DOC is reduced 37.5%, using 15 mM of H_2O_2 and 216 minutes of illumination for it. The neutralized effluent (DOC: 300 mg/L, COD: 590 mg/L) was treated in the bioreactor for five days, resulting in a final DOC of 75 mg/L. However, after 1.5 days of biotreatment, the DOC had already been reduced to 75 mg/L. Therefore, further biotreatment for longer than two days provides no noticeable benefit to the combined process efficiency. Combined process efficiency was 84%m 37% from the photocatalytic process and 46.5% from the biological stage.

Several samples were taken during the combined treatment to evaluate the evolution of active ingredients in the pesticides as well as toxicity expressed as the percentage of inhibition of the marine bacteria *Vibrio fischeri*. Toxicity was reduced as the photo-Fenton treatment advanced and reached the minimum at the end of the photo-treatment, remaining at that minimum during the biological treatment. The identification and quantification of the active ingredients in the container wash water was done by liquid chromatography with mass spectrometry and time-of-flight analyzer (LC-TOF-MS). The main characteristic of this analytical technique is that the exact determination of the mass provides specific information on a molecule since it can be confirmed by the presence of other fragments present in its mass spectrum. In this study, we used an automated method with a library of known mass spectra from a wide variety of pesticides. This method, developed by the "pesticide waste" Group at the University of Almería Analytical Chemistry Department, is able to identify 300 pesticides in less than 20 minutes analysis time. In the container wash water, twelve main ingredients from pesticides were identified in differing concentrations. Figure 4.5 shows the evolution of the concentration of each of the twelve main ingredients during the photo-Fenton stage. At the end of the biological treatment, all of the substances were completely eliminated except for two (Pyrimethanil and thiacloprid) which were detected in tens of µg/L.

The general conclusions of this Project, which ended in 2010 were:

- When waste water is complex, integration of advanced oxidation and biological treatments is much more versatile than either of these treatments alone, and often synergic.
- The use of solar radiation in properly designed photoreactors for these processes provides significant energy savings
- All of it must be accompanied by a detailed study of the environmental impact using lifecycle analysis (LCA) and costing techniques which allow comparison of different technologies.

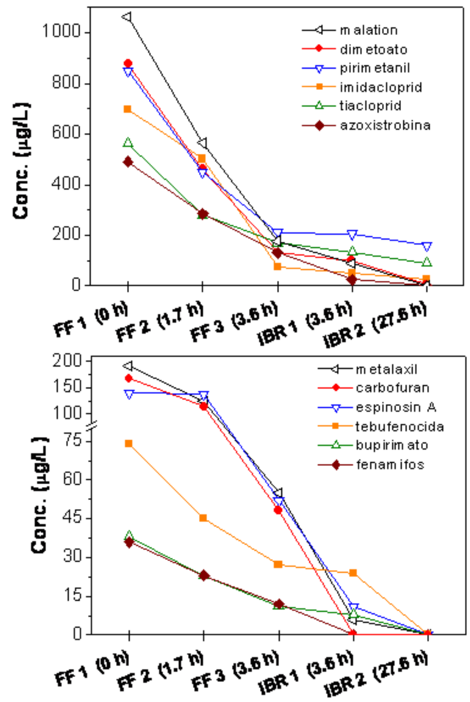


Figure 4.5. Evolution of the concentration of pesticides contained in real water Turing the combined Photo-Fenton/biological treatment (COD_0: 480 mg/L). Treatment times of each sample are included.

Publications: [4.16]-[4.25]

4.2.3 SODISWATER
Solar disinfection of drinking water for developing countries or emergencies
http://www.rcsi.ie/sodis/

Participants: RCSI (Coord., IR), UU (UK), CSIR (ZA), EAWAG (CH), IWSD (ZW), CIEMAT-PSA (E), UI (UK), ICROSS (KEN), USC (E).
Contact: Dr. Kevin McGuigan, kmcguigan@rcsi.ie
Dr. Pilar Fernández-Ibáñez, pilar.fernandez@psa.es
Budget: EC, 6th-FP. Specific International Cooperation Activities "INCO". 1.900 k€. CIEMAT Budget: 350 K€.
Duration: September 2006 – January 2010

Background: This project is mainly to demonstrate that the SODIS ("Solar Disinfection") technology for disinfecting drinking water using only solar radiation is an effective household intervention tool against waterborne diseases (in developing countries) and as help in situations derived from natural disasters. Solar Disinfection (SODIS) is a water decontamination technique that uses transparent plastic bottles full of water which are exposed to direct solar radiation for 6-8 hours.

This process lowers fecal contamination levels from 1 million bacteria per ml to zero in less than 1.5 hours and is completely effective for the treatment of the pathogens responsible for such diseases as cholera, dysentery, typhus, giardiasis, salmonelosis, gastroenteritis and polio. The only clinical test to date on this technology, made in a community in Kenya, has demonstrated that children under 5 years of age that drank water treated with SODIS were 7 times less prone to contract cholera than those who did not. There are no limits on applying the SODIS technology in areas with high solar radiation levels (e.g. Africa), as it is practically without cost and only requires transparent plastic bottles.

Purpose: The project basically focuses on the Sub Sahara. Its strategic goals are the following:

- Demonstrate that the SODIS technique is suitable and effective to decontaminate water for human consumption in small communities in developing countries that do not have easy access to "safe water". Its application will be equally effective in catastrophes or natural accidents when access to drinking water becomes difficult.
- Testing and evaluation of different strategies for spreading information and changes in behavior adopting SODIS as the drinking water treatment technique in zones with different sociocultural profiles.
- Spread information on the results of research through International aid agencies (in developing countries and areas with catastrophic damage) so SODIS is recommended as a quality intervention within water treatment standards (e.g., filtration, chlorination, desalination, etc.).
- Development of a set of technological improvements in the SODIS process to be used depending on the socioeconomic conditions, based on the use of ultraviolet dose indicators for disinfection, active photocatalysts under solar radiation and solar collector modules (CPCs).

The scientific objectives of the project are: (i) Study the effect that consumption of water treated with SODIS has on health in four African countries, (ii) analyze the relationship between water disinfected with SODIS and certain health indicators (morbidity from diarrhea and dysentery, weight loss, mortality, growth rates, productivity, etc.), (iii) demonstrate the effectiveness of the SODIS technique on a household scale and how well accepted it is as a method of disinfection, (iv) evaluate the effectiveness of SODIS for certain viruses, protozoa, helminthes and bacteria. CIEMAT-PSA is working mainly on the design and construction of a prototype low-cost solar reactor based on the use of CPC solar collectors, design and construction of a batch photocatalytic reactor, evaluation of all of the technological improvements related to the reactors and radiation sensors under real radiation conditions with suitable model microorganisms.

Achievements in 2010: Several different solar photocatalytic processes have been studied to improve the disinfection behavior of the SODIS process. These processes are TiO_2/ solar UVA, Fe^{2+}/ solar UVA, Fe^{2+}/H_2O_2/ solar UVA, H_2O_2/ solar UVA. They generate hydroxyl radicals in water which are responsible for oxidizing the molecules that make up the external membrane of the microorganisms in turn causing their death or inactivation.

Part of the experimental studies were done with *F. solani* spores as a model highly resistant pathogen in crops, and the results were compared with those found with *Escherichia coli (E.coli)* K-12 bacteria, which is a widely studied model fecal pollutant used as a reference in almost all water disinfection studies. In this case, the photocatalytic techniques used were H_2O_2 with solar radiation and H_2O_2 with Fe^{3+} salts and solar radiation.

The main result found in this study was the improved disinfection of hydroxyl radicals ($^{\bullet}OH$). Figure….. shows complete bacterial inactivation in the experiments with 1, 5 and 10 mg/L of Fe^{3+} under solar UV radiation, while in the 50 mg/L Fe^{3+} concentration inactivation was not complete. Solar disinfection alone was also to the detection limit. According to these results, 1, 5 and 10 mg/L of Fe^{3+} in the presence of natural sunlight improve bacterial inactivation compared to sunlight without additives. The best results were found with 1 and 10 mg/L of Fe^{3+} followed by 5 mg/L of Fe^{3+}. This is due mainly to the dissolved iron. Due to this increase in the iron concentration, the solution becomes reddish, causing a shading effect and diminishing process efficiency, as demonstrated with 50 mg/L, where the total inactivation could not be achieved during treatment. With *F. solani,* complete inactivation was achieved with the lowest concentrations (1, 2.5 and 5 mg/L). Solar disinfection alone (SODIS) did not achieve complete inactivation either. With 50 mg/L of Fe^{3+}, the *F. solani* concentration remained without change as did *E. coli*.

Figure 4.6 shows inactivation of *E. coli* with hydrogen peroxide and sunlight. The best result was with 10 mg/L of H_2O_2, at which concentration inactivation reached 0.97 kJ/L (4.9-log decrease). Total inactivation was also reached with 5 mg/L and 3.15 kJ/L, which was a 5.4-log decrease. Inactivation of bacteria by 5.3 log was obtained with a lower concentration of 2.5 mg/L of H_2O_2. In this case, 5.5 kJ/L of UVA solar radiation were necessary. Inactivation of *F. solani* spores by H_2O_2 and sunlight was also determined experimentally. This time all the H_2O_2 concentrations efficiently reached the detection limit. With all three concentrations tested (2.5, 5 and 10 mg/L), 14.5 kJ/L of solar UV-A were necessary to destroy the *F. solani* microconidia and 3-log decrease, a large amount of energy if compared to what is necessary to disinfect *E.coli*, since the fungus has a strong defense against oxidative stress. Total inactivation could not be achieved with SODIS, and decrease in the total concentration of *F. solani* microconidia was only 1-log.

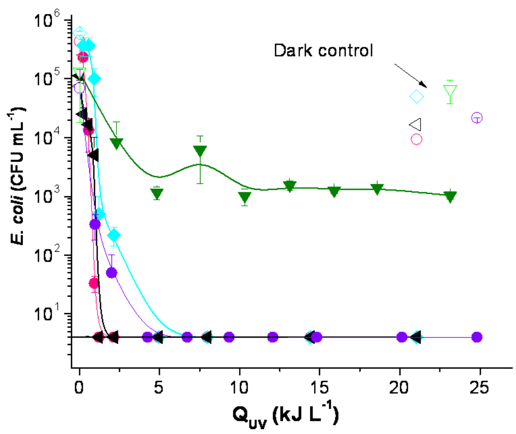


Figure 4.6. *E. coli* over time of exposure to sunlight in the presence of 1 mg/L (●), 5 mg/L (●), 10 mg/L (◄) and 50 mg/L (▼) Fe^{3+} concentrations compared to SODIS treatment (♦) (solar-only control).

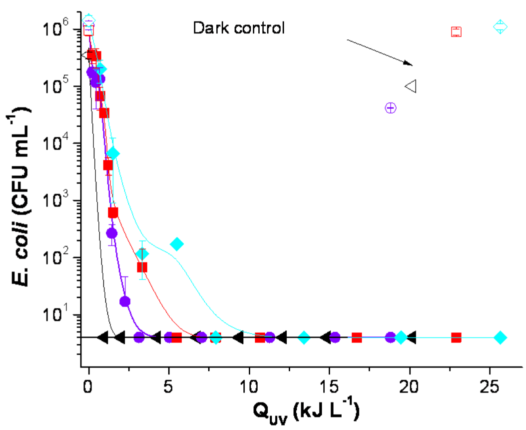


Figure 4.7. Disinfection of E. coli over QUV under natural sunlight in the presence of 2.5 mg/L (■), 5 mg/L (●) and 10 mg/L (◄)H_2O_2 concentrations compared to SODIS (♦) (solar-only control).

In inactivation of *E.coli* with solar photo-Fenton (Fe^{3+}/H_2O_2/sunlight), several concentrations of iron and hydrogen peroxide were used, and in all of them, disinfection was achieved. The optimal concentration used was 5 mg/L Fe^{3+}-10 mg/L H_2O_2, which achieved total inactiviation (4.9-log decrease) with 2.31 kJ/L. With the SODIS treatment, 5.2-log inactivation was also achieved with 4.83 kJ/L. This series of experiments was performed at a pH near neutral (5.5-6). The reason for working at this pH is that the viability of *E.coli* is compromised at pH below 4.5. Figure 4.8 (*F.solanis*) shows that the detection limit is reached at lower concentrations (1 mg/L Fe^{3+}-2.5 mg/L H_2O_2; 2.5 mg/L Fe^{3+}-5 mg/L H_2O_2, and 5 mg/L Fe^{3+}-10 mg/L H_2O_2). The optimal concentration was 2.5 mg/L Fe^{3+}-5 mg/L H_2O_2, which caused a 3.4-log decrease, completely disinfecting microconidia with 14.47 kJ/L. However, the microconidia were not disinfected at the higher concentrations (10, 35 and 50 mg/L Fe^{3+}- 10 mg/L H_2O_2) or in the SODIS tests.

Figure 4.9 shows a comparison of the best *Fusarium solani* microconidia disinfection results found with each method. Of all the tests done, the detection limit was reached by photo-Fenton (2.5 mg/L iron and 5 mg/L H_2O_2) with the least energy (14.5 kJ/L), followed by H_2O_2, which required 15.4 kJ/L. In last place, the efficiency of the method in which only iron was used (2.5 mg/L). In this test, 20.8 kJ/L were required for complete disinfection. Finally, with sola-only disinfection, inactivation of the fungus could not be achieved.

In the experiments with *E.coli* using the proper concentrations, disinfection improved over solar-only by Fe^{3+}, H_2O_2 and photo-Fenton. The best result for bacteria was found with photo-Fenton (5 mg/L Fe^{3+}-10 mg/L H_2O_2), in which complete inactivation was achieved with 0.96 kJ/L (15 minutes exposure to sunlight). While in *F. solani* tests, due to their highly resistant spores, solar disinfection did not achieve complete inactivation. The best results were found in photo-Fenton tests with 2.5 mg./L Fe^{3+}-5 mg/L H_2O_2, which achieved complete activation with 14.47 kJ/L (3 hours of exposure to sunlight). Even though H_2O_2 and Fe^{3+} are very good catalysts separately, their combined use

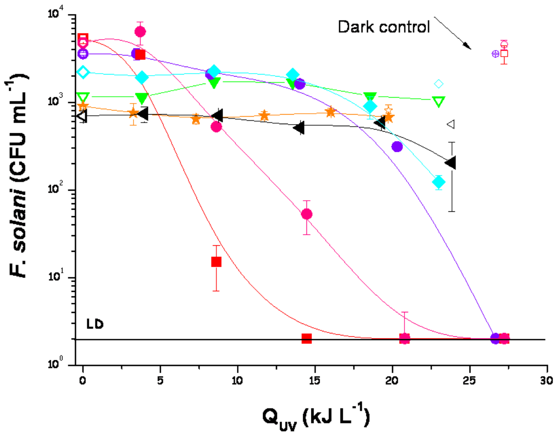


Figure 4.8. Disinfection of *solani* over Q_{UV} under natural sunlight in the presence of Fe^{3+} and H_2O_2 concentrations (photo-Fenton system) of 1 mg/L and 2.5 mg/L (●); 2.5 mg/L and 5 mg/L (■); 5 mg/L and 10 mg/L (●); 10 mg/L and 10 mg/L (◄); and 50 mg/L and 10 mg/L, respectively (▼), compared to SODIS treatment (♦) (solar-only control).

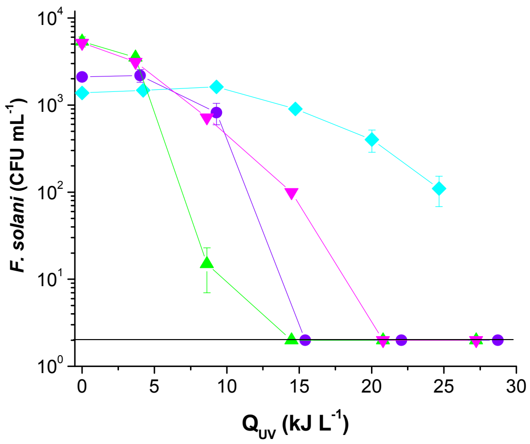


Figure 4.9. Viable *F. solani* spores over Q_{UV} under natural sunlight in the presence of 5 mg/L H_2O_2 (●), 2.5 mg/L iron (▼), and photo-Fenton: 2.5 mg/L iron and 5 mg/L peroxide (▲) concentrations compared to SODIS treatment (♦) (solar-only control).

improves performance even more, achieving complete disinfection of the microorganism.

The use of additives, such as H_2O_2, Fe^{3+} and the photo-Fenton system along with solar radiation to disinfect water polluted by highly resistant pathogens seems to be a good alternative to the use of conventional chemical disinfectants, such as pesticides, which in addition, are harmful to the environment. These new solar photochemical methods have demonstrated that they are highly effective disinfectants using very mall amounts of reagents, so they are inexpensive, sustainable environmental methods. This research will lead to future water disinfection applications. For drinking water, the solar disinfection treatment inactivates enterobacteriaceae causing diarrhea and gastrointestinal disorders in many areas of developing countries. For disinfecting irrigation water, it is possible to use different catalysts, and the photo-Fenton system is a good alternative to the use of traditional disinfectants.

Publications: [4.26]-[4.31]

4.2.4 SFERA (Solar facilities for the European Research Area) Access to the PSA

http://sfera.sollab.eu/

Participants: CIEMAT (Coord., E), DLR (Alemania), CNRS (Francia), PSI (CH), ETH (CH), WEIZMANN (IL), ENEA (I), DIN (DE), UPS (F), AUNERGY (E), CEA (F), INESC-ID (P).

Contact: Diego Martínez Plaza, diego.martinez@psa.es
Dr. Isabel Oller Alberola (Head of Access Program), isabel.oller@psa.es

Funding: EC, FP7. Capacities Programme – Research Infrastructures; 7.4 M€. CIEMAT budget: 2.2 M€.

Duration: January 2009 – May 2013

Background: Concentrated solar power is a very promising renewable energy resource, the most widely known application of which is electricity generation in thermodynamic cycles. However, it has been demonstrated that there are other applications which are also of interest, such as hydrogen production and solar fuels, wastewater treatment and advanced materials research. Europe is the leader in research and development of these technologies. Five of the largest facilities in Europe, CIEMAT-PSA, DLR, PROMES-CNRS, ETH and PSI form part of a virtual laboratory called SolLab. With the SFERA project, it intends to include the ENEA and Weizmann institutions to consolidate this association as the European Solar Research Laboratory of reference.

This project includes three activities:

1) Creation of a network to set up a framework for cooperation in which resources are shared, common standards are developed, duplication of effort is avoided and interaction with European research, education and industry is encouraged.
2) Transnational access to the most relevant research and development facilities, optimizing the use of their infrastructures and creating a critical mass for new research initiatives.
3) Joint research through development of common standards and procedures to achieve a better consortium and develop advanced instrumentation to improve services offered to the user community.

Purposes: Within the work packages that make up the SFERA Project, seven are for coordinated management of transnational access activities at the Plataforma Solar de Almeria. The PSA-CIEMAT is the coordinator of this work package as well as of six related to management of transnational access to all of the facilities offered within the consortium formed under the SFERA project. The main purpose of transnational access includes a commitment by the facilities to provide total access of 484 weeks to 174 research groups and 345 researchers.

The research activities undertaken at the PSA participating and providing services with the plan for access to the PSA are organized in three research units: Solar Concentrating Systems, Environmental Applications of Solar Energy and PSA Management. 18 scientists and five engineers in these R&D units will support users during their periods of access, so they can make the best use possible of their visit.

The Water Detoxification and Disinfection Group in particular has committed 38 weeks of access to the SFERA project, which means a minimum of 48 users and about 24 projects.

Achievements in 2010: In 2010, the PSA Detoxification and Disinfection Group covered 20 weeks of access with 14 users in five R&D projects. These projects and the most relevant results achieved during their visits are summarized below:

1) *SOL-TROF: Pilot-scale treatment of a mixture of two antibiotics present in WWTP effluents by homogeneous solar photocatalysis.* Civil Engineering and Environment Dept., Univ. Cyprus.

Researchers Evroula Hapeshi (Supervisor) and Irene Michael came for a total of four weeks. The purpose of this project was to study the oxidation capacity, elimination potential and main degradation intermediates of two selected antibiotics, trimetroprin and ofloxacin. Both antibiotics have been detected in secondary and tertiary WWTP treatment effluents. In this project, solar photo-Fenton in pilot CPC plants (CADOX reactor) for the elimination of these antibiotics was studied in four different matrices: distilled water (DW), simulated water (SW) (moderately-hard standard fresh water, simulated waste water (SWW) and real WWPT wastewater effluent (RWW). Elimination of dissolved organic carbon, chemical oxygen demand (in simulated waste water and WWTP waste water) degradation of each individual antibiotic by chromatographic analysis, generation of carboxylic acid by ionic chromatography and toxicity throughout the photo-Fenton treatment by *Vibrio* fischeri and respirometry with active sludge from a WWTP were analyzed in all of them. Finally, determination of the degradation pathways of both compounds during photo-Fenton treatment was done by UPLC-MS/MS and UPLC-ToF-MS in collaboration with Dr. Mira Petrovic at the *Instituto de Evaluación medioambiental e Investigación del Agua* (CSIC) in Barcelona.

Figure 4.10 shows the percentage of mineralization (COD/COD_o) reached during the degradation of each antibiotic in the various matrices studied as a function of H_2O_2 required in each case. It is important to mention that elimination of COD was somewhat slower in simulated water than in distilled water in the treatment of both antibiotics due to the presence of various anions (Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-, etc.) that compete for hydroxyl radicals and other reactive species. Furthermore, the use of SWW and RWW causes an increase in the amount of organic carbon present in solution (25 and 10 mg/L, respectively) which leads to a decrease in the mineralization rate compared to DW and SW.

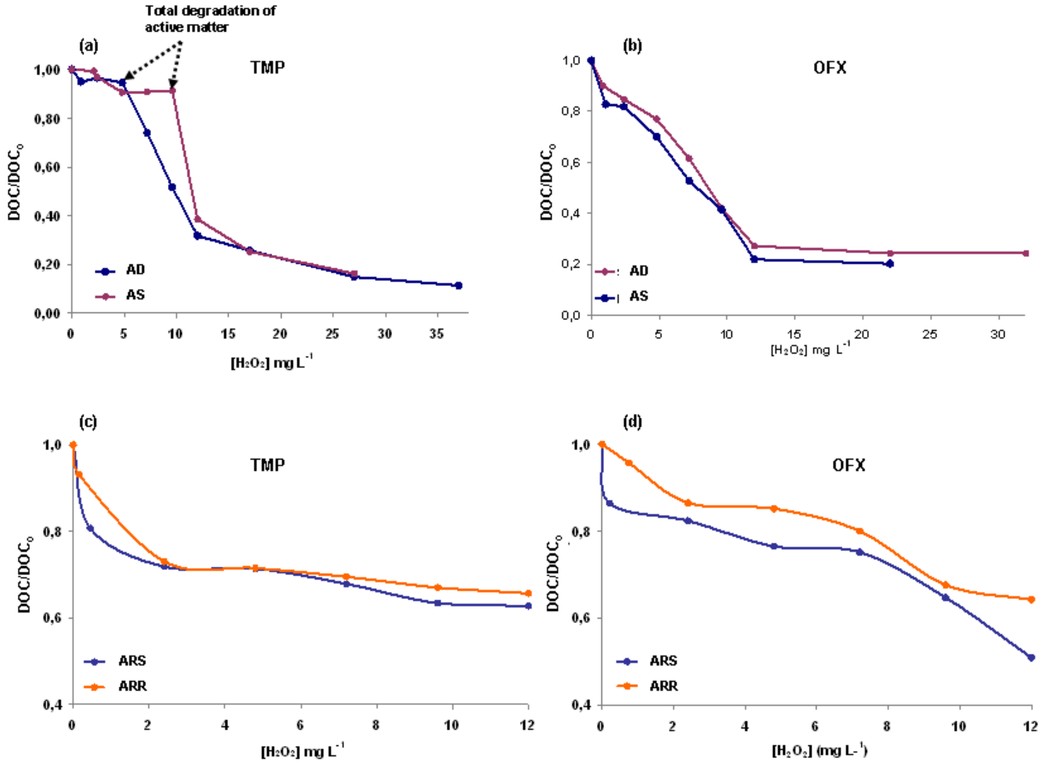


Figure 4.10. Degradation trimetroprin (TMP) and ofloxacin (OFX) by photo-Fenton for each type of matrix used: (a) TMP: DW and SW; (b) OXF: DW and SW; (c) TMP: SWW and RWW; (d) OFX: SWW and RWW.

2) *RecaSolar: Elimination of organic recalcitrant pollutants present in lixiviates from municipal dump by combination of solar advanced oxidation processes and biological treatments.* Water Research Institute, Italian National Research Council (CNR-IRSA).

Dr. Giuseppe Mascolo (Supervisor) and Daniela Cassano, researcher, stayed for a total of four weeks. The purpose of this project is to apply solar Advanced oxidation Processes (AOPs) to the treatment of a lixiviate from a municipal garbage dump partly treated by aerobic granulation in a sequencing batch biofilter granular reactor (SBBGR). It is intended to compare the efficiency of the photo-Fenton advanced oxidation treatment to ozonization applied by the Users at their institution.

First photo-Fenton treatment was carried out (50 mg/L of Fe^{2+}) on from garbage dump lixiviate biologically pretreated in an SBBGR reactor (in the user facility). The evolution of dissolved organic carbon (DOC) and the chemical oxygen demand (COD) are shown as a function of H_2O_2 consumption in Figure 4.11 (a), where it may be observed that after total consumption of 25.3 mM of H_2O_2, there is a 59% decrease in DOC and 68% in COD. Second, photo-Fenton treatment was applied to the dump lixiviate after pretreatment by an integrated process comprised of SBBGR and ozonization, to lower the high ozone consumption necessary to reach Italian sewage dumping limits for DOC (160 mg/L). The effluent used for this experiment was taken from the integrated SBBGR/O_2 system available at the user's own facilities at the CNR-IRSA (Italy) and sent to the PSA for this purpose. The results are shown in Figure 4.11

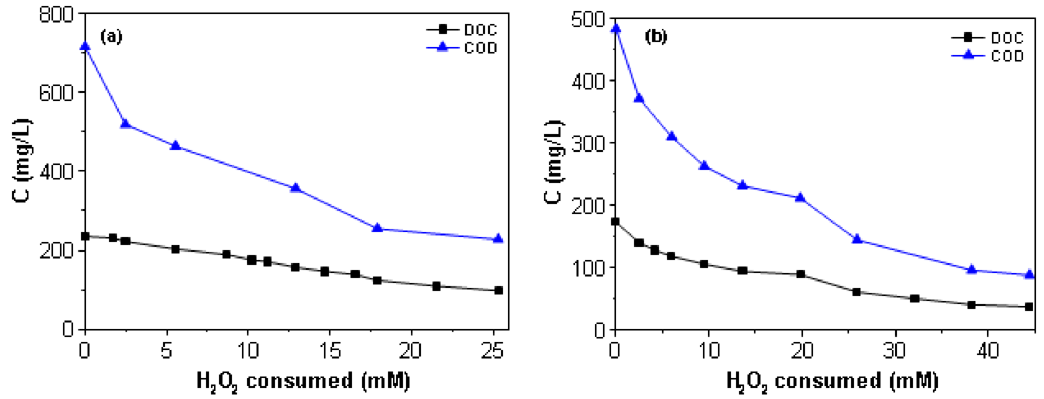


Figure 4.11. Elimination of DOC and COD Turing Photo-Fenton treatment of: (a) Dump lixiviate pretreated in an SBBGR and (b) dump lixiviate pretreated by SBBGR and ozonization.

(b), where it may be seen that after H_2O_2 consumption of 44.4 mM, 79% of DOC was mineralized and COD was reduced 82%.
The results of this Project show that the use of Photo-Fenton as a tertiary treatment is an option of great interest for mineralizing down to the Italian sewage dumping limits. Finally, acute toxicity tests with *Vibrio fischeri* and respirometry with active sludge from WWTP were also carried out in this project. These results show how the use of photo-Fenton as a tertiary treatment of municipal garbage dump lixiviates not only allows DOC dumping limits to be met, but also reduces to or maintains original toxicity levels at a minimum in this waste water.

3) *PHOTOCAT-SODIS: Evaluation of a coated solar photocatalytic reactor for disinfection.* Royal Collage of Surgeons in Ireland (RCSI) and Dublín Institute of Technology (CREST-DIT)

Drs. Kevin McGuigan and Suresh Pillai (supervisors) and Mike Fisher and Donal Keane, researchers, stayed for a total of three weeks. The purpose of this project is the evaluation of a stable photocatalytic TiO_2 coating on the inside wall of glass jars for the degradation of methylene blue and solar water disinfection (SODIS). These borosilicate glass jars were prepared before their evaluation at the PSA. This preparation consisted of their coating with TiO_2 twice by submersion and heating at 600ºC.
The kinetic data corresponding to the decreased absorbance of methylene blue show that the photocatalytic activity of the coated jar is approximately twice the uncoated jar. However, no difference was found in the activity between TiO_2-coated jars doped or undoped with copper or other species.

Study of disinfection activity of these TiO_2-coated jars was also studied by analyzing inactivation of *E.coli* (gram negative) and *E.faecalis* (gram positive) under natural solar radiation. The results show faster inactivation in both species in presence of TiO_2 doped with copper than in the presence of TiO_2 with other dopants, without dopants or uncoated jars.

4) *SOLFED: Evaluation of the disinfection action of photo-Fenton in CPC solar reactor for elimination of pathogens.* Environmental Engineering Dept. Technical University of Crete (Greece).

Drs. Dionissios Mantzavinos and Theodora Velegraki (superisors) and Athanasia Katsoni, researcher, stayed for a total of 4 weeks. The objectives of this project are listed below.

- Train visiting researchers in the basics of photo-Fenton application to disinfection of water and in enumeration and counting protocols for *Fusarium solana* (fungus), *Phytophthora capsici* (fungus) and *Pseudomonas syringae* (bacteria).
- Test the efficiency of solar AOPs: $Fe^{2+}/Fe^{3+}/H_2O_2$/solar UVA for disinfection of water polluted by the abovementioned pathogens, using pilot CPC photoreactor plants.

Figure 4.12 (a) and (b) show the disinfection action of solar photocatalysis in glass jars and in solar photoreactors, respectively. Figure 4.12 (a) shows inactivation of *F. solani* in SWW. The results show that direct sunlight (SODIS) has a fungicide effect, however, this effect is faster with photo-Fenton. This photocatalytic treatment caused a 3-log decrease in *F.solani* viability after five hours. Moreover, Figure 4.12 (b) shows inactivation of *F. solani* in CPC reactors with DW as the matrix. Spore inactivation was complete in four hours of photo-Fenton treatment once the system had received a minimum of 35 kJ/L solar UV energy.

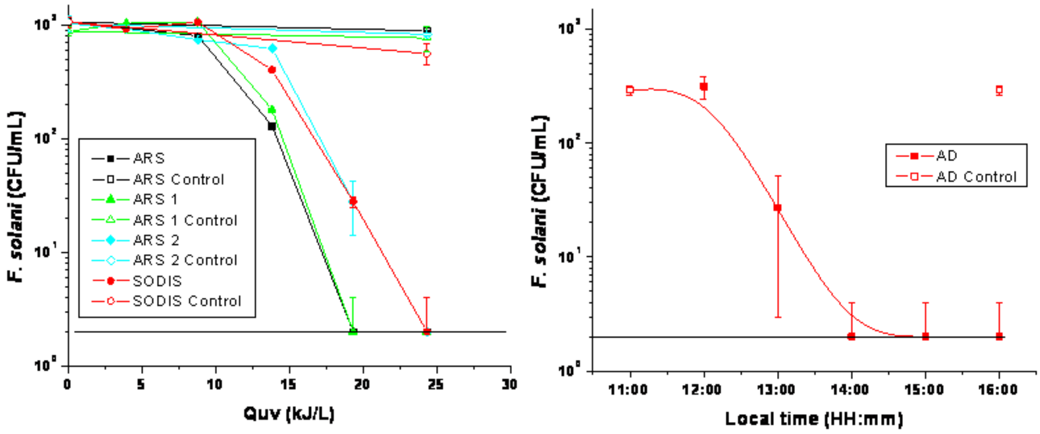


Figure 4.12. Inactivation of *F. solani* by photo-Fenton and solar radiation in : (a) lab-scale, in SWW and glass jars and (b) in DW and pilot CPC solar photoreactor plant.

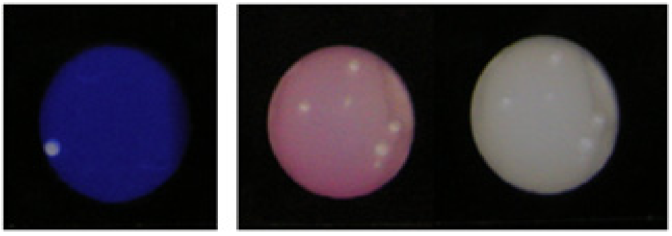
5) *SODIS-SENSOR: Development of a UVA radiation dosimetric sensor for solar water disinfection.* Univ. Ulster (UK), Nanotechnology Dept. and Integrated Bioengineering Centre (NIBEC).

Drs. Anthony Byrne and Patrick Dunlop (supervisors) and Researcher Emma Magee, were here for a total of five weeks. The purposes of this project are listed below:

- Train visiting researchers in the basics of solar photochemistry in the unique PSA disinfection facilities.
- Keeping in mind some of the drawbacks of solar water disinfection (SODIS), such as the variation in efficiency with incident light intensity, the need arises for UVA dosimetric sensors that can show the user when disinfection is complete.

- Determine the active concentration of compound necessary to show a visible color change when the amount of UVA solar radiation absorbed is considered "lethal" for inactivation of a certain microorganism.

The SODIS sensors are base don redox reactions associated with titanium dioxide excited by UVA radiation. The efficiency of these sensors was demonstrated by exposing them to sunlight at the PSA facilties. The time necessary to observe a complete change in color and the UVA dose is calculated using the UVA intensity measured by fixed radiometers located in the PSA detoxification and disinfection facilities. Figure 4.13 shows the change in color observed using the resazurin SODIS sensor. During its exposure to solar radiation the sensor's original blue color changes quickly to pink, showing that the SODIS process has begun. If solar exposure continues, the sensor becomes white, indicating that the UVA dose necessary has been received.



Start **During exposure** **After exposure**

Figure 4.13. Change in color observed during exposure to sunlight of the reaszurin SODIS sensor.

Finally, the UVA dosimetric sensors were used to follow the SODIS process. To do this, well water contaminated by *E.coli* K12 was sampled and exposed to solar radiation in the SODIS CPC solar photoreactors. In addition, a battery of sensors showing color changes at UVA doses from 30 to 60 Wh/m^2 were exposed to the solar radiation during the SODIS experiments. After two hours of exposure to sunlight, the water was completely disinfected. At the same time, the SODIS sensors changed color according to the dose of radiation received, demonstrating their aptitude for predicting the end of solar disinfection.

Publications: [4.32]-[4.33]

4.2.5 Singular Scientific and Technical Facilities Access Subprogram

Participants: Univ. Santiago de Compostela, Univ. Extremadura, Univ. Seville, Univ. Barcelona, Facultad Regional de Buenos Aires (National Technological Univ., ARG).
Contact: Dr. Manuel I. Maldonado. mignacio.maldonado@psa.es
Funding: National RD&I Plan, Ministry of Education and Science.
Duration: 2010

Background: Along the lines of CIEMAT directives to promote knowledge of renewable energies in Spanish society, in 2010, it made the facilities and advice of the scientific-technical personnel at the PSA available to the scientific community, through the National Unique Scientific-Technological Infrastructures Program, Subprogram Design, Feasibility, Access and Improvements in Unique Scientific Facilities and Techniques (ICTS) under the

National Plan for Scientific Research, Technology Development and Innovation 2008-2011 (Ref. ICTS-2009-36).

Purpose: The basic purpose is to provide access to the largest number of researchers possible, both Ph.D. students and researchers in training as well as senior researchers in National Plan projects. In the Water Detoxification and Disinfection Group, it is also our intention that this program serve to increase collaboration with large Spanish installations, by identifying new partners for future projects, making use of ideas contributed by visitors and motivating us to maintain and improve facilities.

Achievements in 2010: The researchers selected by the external evaluators belonging to different large Spanish installations have achieved the following results:

1) *Application of H_2O_2 to solar disinfection of water contaminated by Cryptosporidium.* Lab. Parasitology, School of Pharmacy, Univ. Santiago de Compostela. Researchers: Elvira Ares Mazás.

   The purpose was to study the application of hydrogen peroxide (H_2O_2) to solar disinfection of water contaminated with *Cryptosporidium.* To do this, four 500-mL bottle reactor containing the infective forms of *Cryptosporidium parvum* at a concentration of 10×10^6 oocysts/liter were placed in a mechanical agitator (100 rpm).

   After 2.5 hours of exposure and at the end of the experiment, 15 mL of water was taken from each of the bottle reactors and centrifuged twice at 3000 rpm for 10 minutes. The 100 µL of the sediments from each were incubated at 37ºC for 30 minutes with 20 µL of monoclonal anti-*Cryptosporidium* antibody and 10 µL of propidium iodide (PI), a fluorogenic vital dye indicative of the integrity of the oocysts wall. The oocysts were first identified using epifluorescence microscopy with excitation and barrier filters, and in continuation acquisition/exclusion of the vital dye was observed. At the same time, using phase contrast microscopy, a spontaneous bursting phenomenon was observed, which in the absence of any triggering stimulation other than the temperature inside the reactors, a certain number of oocysts burst open completely or partially and the sporozoites contained inside them are released into the aqueous medium where, outside of the environment that an appropriate host would provide, their survival is impossible. The two known parameters, percentage of IP negative oocysts (potentially viable oocysts) and the percentage of oocysts that did not burst or intact, were used to calculate Overall Viability (OV).

   The *C. parvum* oocyst isolation in the experiments were: Overall Viability 97.62%, IP negative 99.04%, IP positive 0.96%, shells 1.43%, intact 98.57%. In conclusion, the results show that the concentration of H_2O_2 tested did not improve the effectiveness of conventional SODIS.

2) *Pilot plant study of degradation of atenolol, ofloxacin, hydrochlorothiazide and trimethoprim in water by ozonation, TiO_2/sunlight, and ozonation +TiO_2/sunlight.* Chemical Engineering and Physical Chemistry Dept. Univ. Extremadura. Researchers: Gracia Márquez Matamoros and Eva María Rodríguez.

   Method: The effectiveness of degradation systems was studied based on the concentration of contaminants, concentration of TOC and toxicity of samples as a function of variables such as contact time and ozone consumption (during ozonation) and the UV-A radiation dose applied (in the TiO_2/sunlight system). The study was done using distilled water and simulated WWTP wastewater effluent as the matrices.

In the TiO_2/sunlight system, neither the original compounds nor reaction intermediates formed are toxic at these concentrations in the *vibrio fischeri* toxicity test. Compounds were eliminated after 75 min of reaction, except ofloxacin, which seems to be much more reactive to the hydroxyl radicals. 80% of the TOC concentration was eliminated after 180 min of reaction.

During ozonation, neither the original compounds nor the reaction intermediates were toxic at these concentrations in the Vibrio fischeri toxicity test. However, elimination of the compounds was slow and depended on the ozone concentration. With this system, less TOC was eliminated than in the photocatalytic treatment, achieving only 40% degradation under the best conditions.

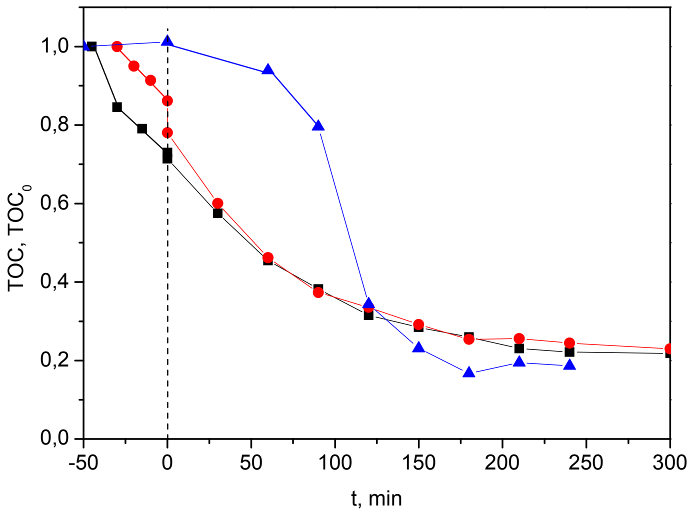


Figure 4.14. Elimination of TOC in the mixture of compounds in water at a concentration of 10 ppm using the sunlight/TiO_2 with and without the preliminary treatment. Symbols: ● elimination of compounds by ozonation; ▲ without preliminary ozonation.

In the combined ozonation+TiO_2/sunlight treatment, TOC concentration is eliminated faster at the beginning of the photocatalytic reaction with a preliminary ozonation stage, as shown in Figure 4.14. Furthermore, fewer phenolic compounds are generated, and they are degraded in a shorter time.

When the simulated WWTP effluent was treated by photocatalysis, the matrix exerted a negative effect on compound elimination, increasing compound elimination time from 15 to 45 minutes. TOC elimination after five hours of treatment was 51.7%. Compound elimination by ozonation was not as affected by the matrix as photocatalysis, and eliminated the compounds in 10 minutes of ozonation, but TOC was only 8% after two hours of ozonation. If the compound mixture is treated by ozonation and then by photocatalysis, the TOC elimination rate is higher in 120 minutes of reaction, and in addition, fewer polyphenolic compounds are generated and the elimination rate is higher.

3) *Electrochemical treatment of emerging contaminants in a pilot plant by solar photoelectric-Fenton.* Univ. Barcelona. School of Chemistry. Dept. of Physical Chemistry. Electrochemistry, Materials and Environment Lab. Researcher: Ignacio Sirés Sadornil.

The dual purpose of this study was to (i) become familiar with the electrochemical-photochemical system as it is a new facility at the PSA and no previous studies have been done with it, so this work is innovative and promising for technology transfer; (ii) carry out preliminary studies on the effect of operating conditions on the destruction of an emerging contaminant (progesterone).

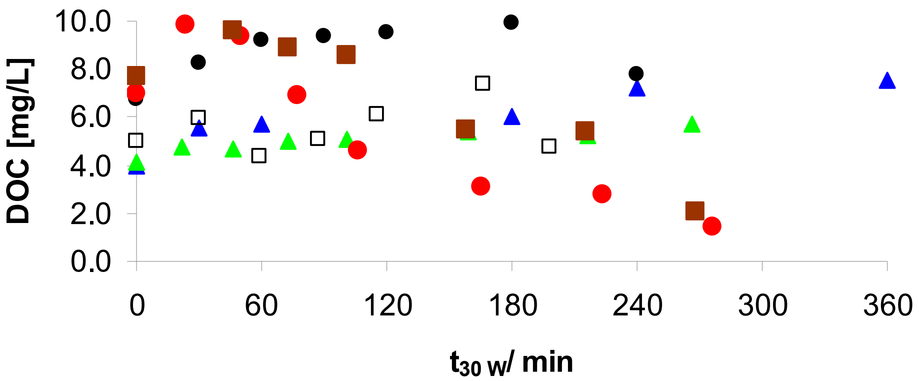


Figure 4.15. Mineralization of progesterone solutions treated under different conditions. Sunlight-only (□),Anodic oxidation (AO) at 10 A (▲),AO+sunlight at 10 A (▲) electroFenton (EF) at 10 A (●), and photo-electro-Fenton (FEF) at 10 A (●) and at 15 A (■).

The electrochemical reactor is described under the EDARSOL project. The following relevant results should be emphasized: (i) The most important point was identification of the critical points in the electrochemical-photochemical system configuration, for which a CPC tank and electrochemical reactor tank were chosen; (ii) The electrochemical reactor showed high capacity for continuous generation of H_2O_2 in sufficient amounts for the Fenton reaction; (iii) The oxidative capacity for mineralization. The photoelectric-solar Fenton treatment is the only one that has demonstrated the ability to destroy all the carbon contained in progesterone solutions (Figure ………). In conclusion, the photoelectric-solar Fenton process is able to quickly destroy progesterone, and gradually and completely mineralize large volumes in solution. In the future, several experimental parameters will have to be optimized, especially the catalyst metal concentration and the intensity of the current applied.

4) *Effectiveness of solar disinfection of water contaminated by enteric virus (hepatitis A, norovirus and rotavirus) and with pilot solar photo-Fenton systems. Univ. Santiago de Compostela. CIBUS-School of Biology. Dept. of Microbiology and parasitology*. Researchers: Jesús López Romalde and David Polo Montero.

The purpose proposed for this study was to determine the effectiveness of solar disinfection (SODIS) in water contaminated with enteric viruses (hepatitis A, norovirus and rotavirus). Experiments were done in triplicate in clear water, evaluating the different of sun exposure times

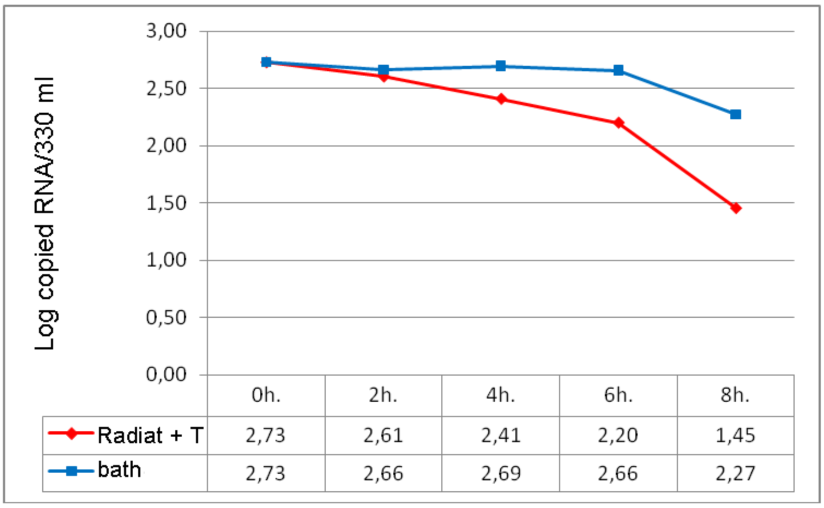


Figure 4.16. Effect of radiation (blue) and radiation plus temperature (red) on the virus concentration in samples.

(2, 4, 6 and 8 hours). The viral concentration was prepared from water samples by filtration. Virus detection and quantification was done in real time using the RT-PCR technique. In the experiments with original concentrations of 10^3 VHA virus particles/ml of water, the data show a clear effect of temperature on detection quantification of the virus. In samples subjected to solar radiation and temperature (red), the decrease is over 90%. Figure 4.16 shows the dynamics observed in the bottles exposed to the sun and kept in a temperature bath in blue.

5) *Treatment of garbage dump lixiviates from RSU by solar photocatalysis using industrial TiO_2 production waste as the active agent*. Univ. Seville. School of Engineering. Dept. Chemical and Environmental Engineering/ Waste Engineering. Researchers: Rodrigo Poblete Chavez; Luis F. Viches Arenas and Emilia Otal Salaverri.

The purpose was to evaluate the photocatalytic potential of waste from the first acid attack by

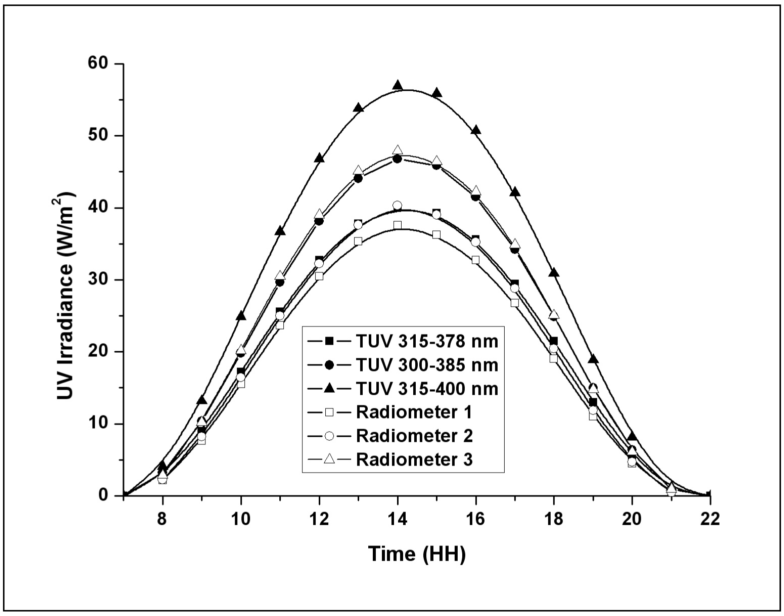


Figure 4.17. Comparison of measurements by radiometers 1 2, 3 and prediction of the TUV 4.1 model on a clear day in August 2010 at the Plataforma Solar de Almeria

ilmenite using sunlight for treatment of garbage dump lixiviates using solar reactors compared to a traditional photo-Fenton process. The results show that using $WTiO_2$ as the catalyst achieves a higher reduction of TOC than $FeSO_4$, 63% and 52% respectively, so it is concluded that $WTiO_2$ has great potential as a catalyst. Its high treatment capacity is due to the two catalyst agents it possesses, generating more oxidizing agents. The results show that the contribution of Fe to the reaction kinetics is much higher than with TiO_2, although the synergy of both is also observed. Complete mineralization was not possible. In the final stages of the experiment, elimination of TOC and COD was very slow, which is understandable given the complexity of the liquid to be treated, garbage dump lixiviates, which have a wide variety of compounds in the matrix, within which there must be some that resist the attack of the hydroxyl radicals.

Publications: [4.34]-[4.39]

4.2.6 INNOVA -MED. Innovative processes and practices for wastewater treatment and re-use in the Mediterranean Region http://www.idaea.csic.es/innova-med/home.htm

Participants: CSIC (Coord., E), INRGREF (TN), CITET (TN), BZU (PS), PWA (PAL), SCU (EGY), ANKU (TR), IAVCHA (MA), RAMSA (MA), CIEMAT (E), BOKU (A), ECOLOGIC (D), EFF (D).

Contact: Dr. Damiá Barceló, dbcqam@cid.csic.es
Dr. Sixto Malato, sixto.malato@psa.es

Budget: EC, VI-FP. International Co-operation Programme (INCO)-Co-ordination Action (CA); 797.3 k€. CIEMAT: 41.4 K€.

Duration: January 2007 – May 2010

Background: The need to introduce treatment and decontamination technologies in the water cycle has been widely recognized by the European Commission in its Fifth and Sixth Framework Programs. Several research projects directed at improving wastewater treatment techniques by optimizing and minimizing the environmental impact they cause have been financed by these programs. National initiatives are also being carried out both in the European Union and in countries in the Mediterranean Basin. However, the communication gaps between scientists and local communities (final water users), as well as the lack of connection among Mediterranean countries, are the main obstacles for a more efficient use of the knowledge acquired. The INNOVA-MED Coordinated Action includes seven EC-funded projects related to treatment and reuse of waste water and water management.

Purpose: The main purpose of the INNOVA-MED Project is to coordinate EU and national research activities underway in wastewater and activated-sludge treatment and dumping technology development projects. It will also coordinate application of innovative practices for the reuse of recovered water, as well as facilitate knowledge and technology transfer and use in partner countries in the Mediterranean Basin. This means facilitating efficient diffusion/exploitation of information on treatment and reuse of waste water and improved efficiency of knowledge and technology transfer to the less favored regions, providing access to information from databases relative to treatment and reuse of water in the Mediterranean region, counteracting fragmentation of research and in general, improving diffusion of its results, as well as promoting public awareness of the sustainability of water.

Achievements in 2010: The PSA (CIEMAT) is the coordinator of Experts Group 2 (WP2), which has 10 members. This group undertakes advanced technologies for wastewater and activated sludge treatment, and is therefore related to water treatment technology engineering for development and application, scale-up from laboratory to pilot plant, then to demonstration and industrial scale. The following activities were carried out under WP2 and the rest of the project: (i) set up a common forum for information exchange among INNOVA-MED project partners and associated projects; (ii) prepare a critical summary of the state of the art of wastewater and activated sludge treatment, writing a report entitled, "Overview of innovative technologies for wastewater treatment, including an informative package proposing solutions to actual problems or a friendlier alternative to actual treatments in Mediterranean Partner Countries", which will form part of a chapter of a book entitled, "Wastewater Treatment and Reuse in the Mediterranean Region" by D. Barceló and M. Petrovic (eds.), Springer-Verlag, Berlin-Heidelberg, Germany; (iii) set up an information exchange platform to provide a common perspective on the subject among INNOVA-MED project groups and outside experts; (iv) prepare a recommendation package for application of the scientific and technological achievements developed for integrated management of waste water reinforcing existing perspectives in Mediterranean Basin countries.

4.3 Air Detoxification and Disinfection Group

4.3.1 NANOTITAN

Participants: CIEMAT_PSA
Contact: Dra. María D. Hernández Alonso; mdolores.hernandez@ciemat.es
Funding: Ministry of Science and Innovation. Total Budget 76 k€
Duration: January 2009 – December 2011

Background: The recent discovery of a simple synthesis method for the preparation of TiO_2 nanotubes under very gentle conditions has opened a new potential route for preparation of highly effective photocatalysts, which in the last five years has acquired enormous relevancy.

There are a multitude of reasons for the growing interest of the scientific community in these nanotubes. On one hand, the TiO_2 nanotubes have a high specific surface are (of up to 400 m^2/g) and fine distribution of pore sizes. Furthermore, the close structural relationship between titanates and TiO_2 makes it possible to make reversible transformations between nanotubes, nanofibers and nanoparticles by very gentle methods, contributing excellent versatility to nanometric assembly of photoactive elements. Finally, titanates have a loaded laminar structure which provides the ionic exchange contributed to the synthesis a flexibility which TiO_2 lacks. Titanates, given their capacity for ionic exchange, could be used as intermediates to widen the spectral response of TiO_2, by incorporating cations capable of absorption in the visible band.

Purposes:
1) Acquire the maximum control of synthesis in order to optimize the one-dimensional TiO_2 nanostructure production process.
2) Evaluate the photocatalytic activity of synthesized nanotubes.

3) Develop a synthesis methodology for depositing TiO_2 nanotubes and nanofibers as thin films on the most suitable substrates for their use as photocatalysts in continuous operation.
4) Make use of the capability for cationic exchange of titanate nanotubes for synthesizing nanostructured photocatalysts with visible-band activity.
5) Synthesize titanate nanotubes that incorporate cationic organic sensitizers as a way of making use of any synergies between semiconductors and photoactive molecules.

Achievements in 2010: In 2010, second year of the project, study has concentrated on achieving 2), apart from initiating preliminary tests for 3) to 5). Previously, in the first stage of the project, a study on synthesis optimization had been done in which the influence of the various process parameters on the chemical-physical characteristics and morphology of the materials, was analyzed by electronic transmission microscopy (ETM), X-ray diffraction and N_2 adsorption isotherms. In the second stage of the project, performed in 2010, photocatalytic activity of the one-dimensional structures synthesized, taking into consideration the effect the various parameters of synthesis on the photoactivity: TiO_2 phase used as precursor, the temperature and duration of the hydrothermal treatment, post washing treatment, stage which has been shown to be critical in the process of nanotube formation, as well as the calcination temperature employed. The purpose of the study was to select the optimum synthesis conditions that provide the best photocatalytic activity.

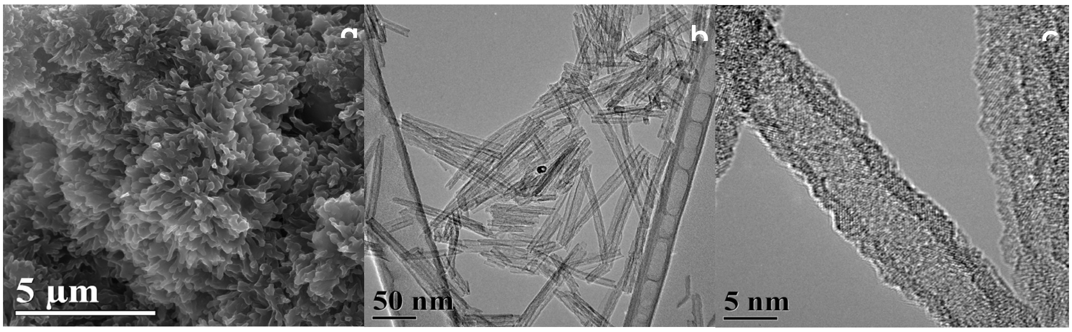


Figure 4.18. (a) SEM Image (b) and (c) ETM micrographs of one of the materials synthesized

Trichloroethylene (TCE) was chosen as the model volatile organic compound (COV). In absence of steam, this compound could not be completely mineralized, causing formation, in addition to CO_2, of highly toxic phosgene. Furthermore, under certain reaction conditions, dichloroacetyl chloride (DCAC) or CO_2 can be generated. Therefore, a highly CO_2-selective photocatalyst combined with strong conversion is very desirable.

In this study, we found that it is possible to modulate the photoactivity of the TiO_2 nanotube structures by varying synthesis and post-synthesis conditions., high conversion rates were achieved with the samples synthesized compared to the reference photocatalyst, Degussa P25, and simultaneously improving CO_2 selectivity.

Publications: [4.40]-[4.41]

4.3.2 CEDETI-COMSA

Evaluation and development of photocatalytic construction materials for use in air decontamination

Participants: CIEMAT-PSA, COMSA EMTE
Contact: Dr. Benigno Sánchez; benigno.sanchez@ciemat.es
Funding: COMSA EMTE, 90 k€
Duration: January 2010 – December 2011

Background: In recent years, photocatalytic decontamination treatment based on the use of TiO_2, has been reaching a stage of growing commercial development. One of the fields in which this technology is experiencing the greatest expansion is in the use of architectural components with TiO_2 incorporated in them. Photocatalytic coatings provide self-cleaning properties and can also act as passive systems (no maintenance) for treatment of air pollution. In this sense it should be emphasized that photocatalytic construction materials represented a business volume of over 300 million Euros in Japan in 2004. On this basis, the COMSA EMTE Group contacted the Environmental Applications of Solar Radiation to Air Group for the purpose of assessing the effectiveness of different photocatalytic systems prepared by their associated companies.

Purpose:
1) The main purpose is to assess the effectiveness under real conditions of photocatalytic construction materials manufactured by the company
2) For this CIEMAT shall test plates on laboratory scale.
3) Test controlled surfaces exposed outdoors.
4) Finally, the company will request characterization and monitoring of a larger surface in an urban environment in the city of Barcelona.

Achievements in 2010: During the first year of the project, construction materials delivered by the company were characterized and assessed. Testing of their photocatalytic activity for degradation of trichloroethelene (TCE) was done as the first stage of materials evaluation, and later activity of the materials was analyzed by degrading nitric oxide. In addition to this compound, possible formation of other undesirable reaction products, such as nitrogen dioxide (NO_2) and nitrous oxide (N_2O) was also analyzed. The

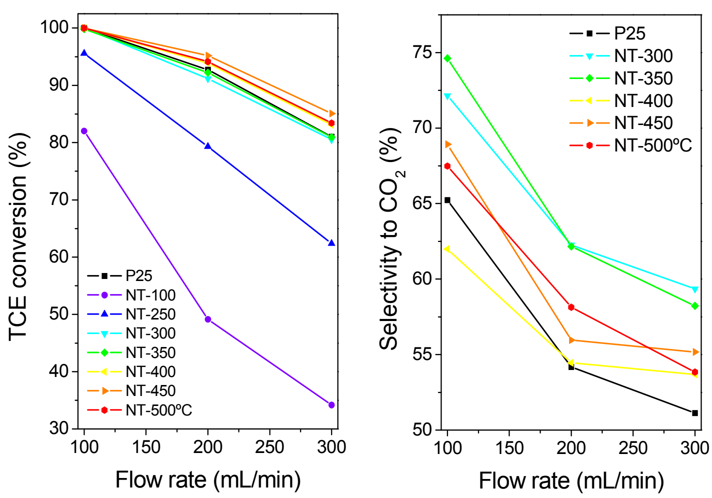


Figure 4.19. Effect of calcination temperature on TCE conversion and CO_2-selectivity of one of the sample nanotubes synthesized.

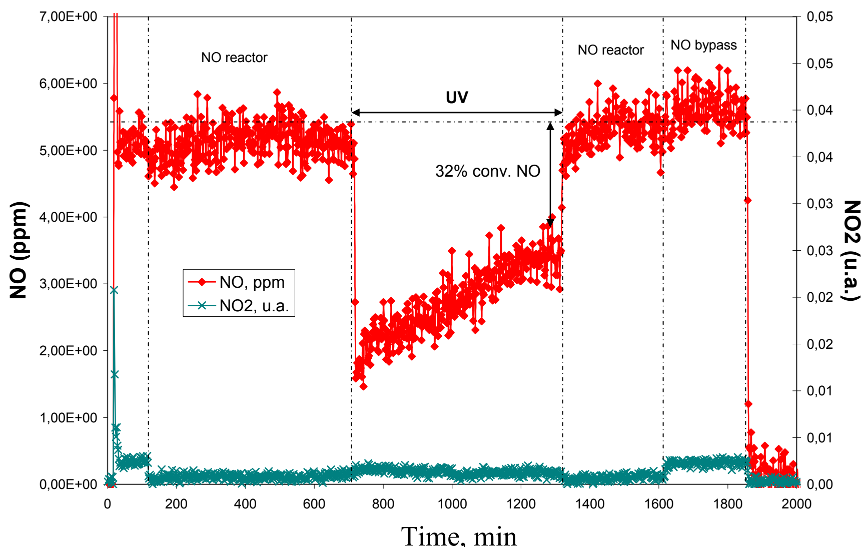


Figure 4.20. Variation in concentration of NO and NO_2 during photocatalytic degradation of NO for one of the photocatalytic asphalts tested.

various tests done have enabled us to find that materials and additives in asphalt are more suitable for elimination of NO. Figure 4.20 shows an example of the tests done with the different samples prepared from commercial materials. The effect of UV radiation on NO degradation with reaction time and scant formation of NO_2 can be clearly observed.

Furthermore, a reaction system is being perfected for evaluating the activity of photocatalytic asphalt plates under real outdoor air conditions.

Publications: Three confidential reports have been made to COMSA-EMTE.

4.3.3 IndoorAir

Treatment of indoor air: Study and optimization of new adsorbents, catalysts and photocatalysts

Participants: CIEMAT, ICP-CSIC,
Contact: Benigno Sánchez; benigno.sanchez@ciemat.es
Budget: Ministry of Science and Innovation: 194 k€
Duration: January 2009 – December 2011

Background: Social perception of air pollution as a severe problem that must be solved to avoid damaging health and the environment is growing all the time. Since the seventies, the change in building construction, which has gone from natural ventilation to mechanical extraction, has caused the appearance of a series of symptoms (headaches, sleepiness, dry cough, itchy eyes, fatigue, etc.) related to the "Sick Building Syndrome". Volatile organic compounds (VOCs) have a basic role in the pollution of indoor environments. The development of effective, yet simple and economical, trace pollutant sampling and analysis methods is a subject of current relevance. There are several control technologies for treatment of VOCs in gas emissions, of which the most commonly used in industry are based on adsorption and catalytic oxidation. Photocatalytic oxidation has been gaining special interest in recent years since it is economical and environmentally-friendly. Many publications in the literature report on photocatalysts for photocatalytic oxidation of different kinds of VOCs, as well as their efficiency for ppm-level oxidation. Nevertheless, when dealing with traces, previous studies are not valid and rigorous analysis of photocatalytic system behavior must be done under these conditions. Development of an analysis method for studying these pollutants and also synthesis of efficient photocatalysts for complex mixtures of pollutants characteristic of indoor air are priority topics for evaluating and improving the quality of indoor air.

The purpose of this project is to acquire the knowledge necessary to define the best strategies for treating VOCs in different indoor environments. The starting hypothesis is that adsorption, catalysis and photocatalysis systems, individually or in combination, are useful for effectively and economically eliminating pollutants in indoor air in buildings with different characteristics, and are environmentally safe.

Purpose:

1) Systematically identify the VOCs in different types of buildings (office, laboratory, factory and home).
2) Acquire in-depth knowledge necessary to develop new adsorbents with improved efficiency in retaining VOCs representative of indoor air. Shape these adsorbents and demonstrate their efficiency.
3) Develop structured hybrid adsorbent and photocatalyst materials.
4) Systematize the information found and propose a method or set of methods for eliminating or reducing selected pollutants.

Achievements in 2010: During the second year of the project, characterization of air pollutants has progressed, as has the development of a suitable technique for their quantification. Different types of environments have been selected for this. On one hand, a wastewater treatment plant (WWTP) has been chosen to represent a real industrial application, where a wide variety of organic and inorganic compounds are emitted. On the other, two CIEMAT buildings have been chosen, one of them, Bldg. 42, is 30 years old, and another recently built bioclimatic building. The purpose is to analyze the influence of the type of construction on the nature and concentration of pollution. Different spaces, such as laboratories, offices, common zones, restrooms, library, among other have been selected. Structured materials for photocatalytic treatment of polluted air and development of reactors for insertion of the photocatalyst and use of solar radiation are well advanced. Figure 4.21 shows an example of the results from one of the photocatalysts developed under the project for elimination of pollutants from a WWTP. To analyze system effectiveness, air samples were collected from primary sludge before and after going through the reactor. The samples are complex, with a wide variety of compounds. Among them it is worth mentioning the presence of sulfur compounds (mercaptans), aromatic hydrocarbons, aliphatic hydrocarbons, and terpenes. The results show the effectiveness of the photocatalytic treatment, and that the system developed is able to eliminate most of the compounds present in air with over 90% effectiveness.

Regarding the analysis of air from buildings, the results identified benzene and derivates, toluene, xylene, siloxanes, and aliphatic hydrocarbons (tetradecane, pentadecane and hexadecane), alcohols and terpenes, such as pinene, alpha limonene, and so on. The concentration of most of them is higher in indoor air than outdoors, which shows progressive concentration of pollutants in building interiors. The results indicate that the concentration of these compounds is, in general terms, higher in the bioclimatic building than in the traditional construction, possibly due to the lack of ventilation or defective recirculation of air in the first.

Publications: [4.42]-[4.44].

4.3.4 TRAGUA
Wastewater treatment and reuse for sustainable management

Participants: CIEMAT, UAH, UCM, UAM, CIESOL and up to 25 different research groups.
Contact: B. Sánchez; benigno.sanchez@ciemat.es
Funding: MEC CONSOLIDER-INGENIO Project, partial: 700 k€
Duration: January 2007 - December 2010

Background: The reuse of waste water generated by wastewater treatment plants (WWTP) is an essential goal for a country like Spain which must confront a continuous water deficit, which is especially dramatic in the regions most influenced by the Mediterranean. However, the generalized use of this resource requires certain sanitary guarantees for water reuse to be a safe, acceptable option. These considerations are reflected in Royal Decree 1620/2007 on reuse of treated water. In this sense, one of the basic purposes of the TRAGUA project is to evaluate the microbiological quality of treated water to determine the presence of emerging micropollutants and establish economically feasible, effective methods for improving the quality of this resource and widen the possibilities for its reuse.

Purpose: The work of the CIEMAT Environmental Applications of Solar Radiation in Air Group, as an integral part of the intensive wastewater treatment area, is to evaluate the use of solar photocatalysis based on the use of immobilized TiO_2 for disinfection and elimination of emerging micropollutants in CPC-collector pilot plants (39 L volume). This work is being done in close co-ordination with the CIESOL Group, which is developing the analytical method for determining the presence of traces of pollutants which are non-biodegradable, and therefore, not eliminated by WWTP biological treatments.

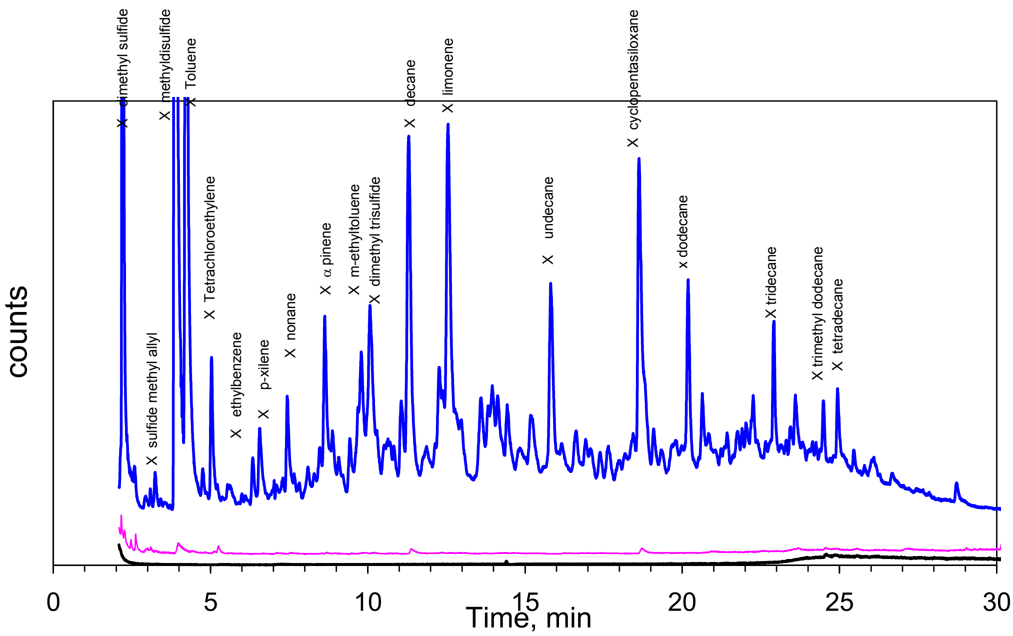


Figure 4.21. Photocatalytic treatment of real air from primary sludge in a WWTP. Chromatograms from air samples taken at the reactor inlet (blue line), and reactor outlet (pink line) and control (black line).

Achievements in 2010: In 2010, the Consolider Tragua Program received one of the awards granted by the IWQ in the framework of “"Prizes for Excellence in Sustainable Urban Water Management". Specifically, Tragua won the award for innovation in the practical realisation of sustainable urban water management). This prize rewards the project’s innovation and the proposal it makes for management of urban water within a sustainable framework.

The results of photocatalytic activity found by the T9 Group the year before, showed the efficiency of the immobilized TiO_2 system developed under this project for degradation of 15 selected model contaminants in a distilled water, simulated hard water and simulated effluent matrices. In 2010, two important aspects for optimizing the photocatalytic system were studied in more depth. On one hand, the characterization of the catalyst developed to establish a relationship between its physico-chemical properties and its photocatalytic activity. On the other, and given that the purpose is reuse of treated water for irrigation of greenhouses, golf courses, public gardens, etc., system behavior has been studied using real water. To do this, water from a secondary biological treatment at the El Ejido (Almería) WWTP (COD≅13 mg L^{-1}) was used. Variation in the concentration of the 15 compounds selected over time during the first and fifth cycle, using CPC collectors is shown in Figure 4.22.

The results show that 53% of the compounds were degraded after 60 min. This percentage rose to 73% after a reaction time of about 150 min. Only

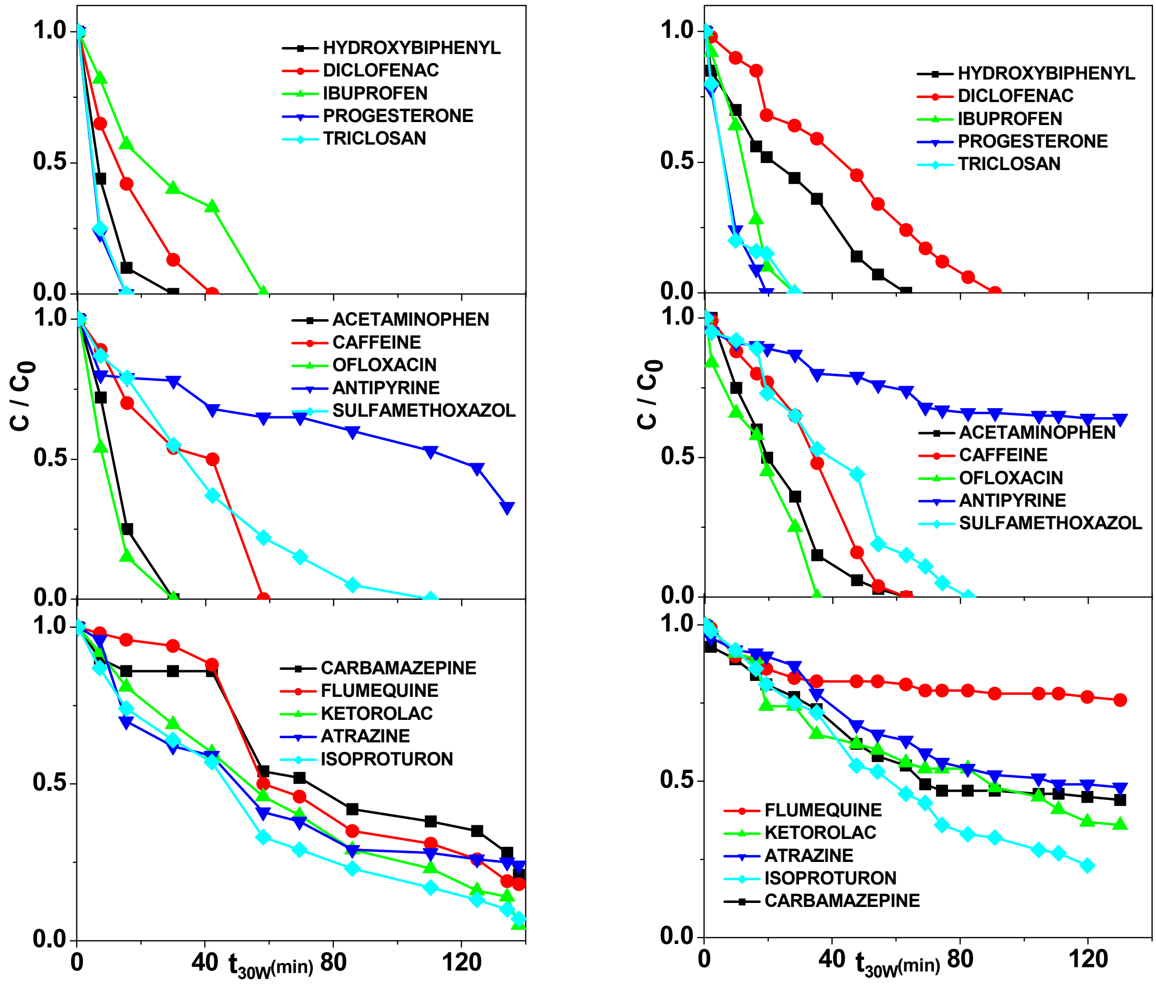


Figure 4.22. Degradation of the 15 selected compounds in real water after the 1st cycle (left) and after the 5th cycle (right).

antipyrine, atrazine, flumequine and carbamazepine were not completely degraded. As expected, degradation of the compounds after five cycles in a row using the catalyst is noticeably slower, but effective for 60% of the selected compounds. The results of characterization of the material show that this is related to blocking of active TiO_2 centers by species adsorbed such as nitrates, phosphates and sulfur and chloride compounds, and not because of loss of the active phase.

These experiments show that emerging contaminants in μg L^{-1} in water can be degraded by a photocatalytic system with immobilized TiO_2 using solar irradiation as the excitation source, not only in simulated WWTP effluents, but in real water. These results open the field of application of photocatalysis to reuse of treated water. It should be mentioned that the main purpose is to eliminate emerging compounds, and the presumably less effectiveness of the immobilized catalyst compared to TiO_2 suspension systems is not a problem as demonstrated. In fact, it is advantageous from the viewpoint of eliminating TiO_2 from treated water, as filtration, which in addition to being complicated is makes the overall process prices considerably more expensive.

Publications: [4.45]-[4.47]

4.3.5 Development of hybrid photocatalysts for elimination of COVs in gas streams

Participants: CIEMAT, ICP-CSIC
Contact: Silvia Suárez; silvia.suarez@ciemat.es
Budget: Ministry of Science and Innovation: 6 k€
Duration: March 2008 – March 2013

Background: Society's development involves increasingly high consumption of natural resources which with current technology generate enormous amounts of polluting gases and subproducts that are discharged uncontrolled into the environment. Therefore, this entirely unsustainable growth model requires the use of renewable energies along with ever-cleaner technologies, to reduce the emission of pollutants into the air. Among the most important air pollutants are the Volatile Organic Compounds, COVs, not only because some of them are carcinogens, but because of their involvement in tropospheric ozone production and their resistance to physical, chemical or biological degradation. The paint and pigment industries and combustion are some of the most important sources of emissions. Oxidative photocatalysis, the use of luminous or photon energy of a certain wavelength, is an attractive, clean, effective and environmentally-friendly alternative for eliminating these compounds by oxidation. If in addition, solar radiation is used for this, then a renewable energy is also employed. TiO_2 is the photocatalytic material of excellence. Among its main characteristics are its inherent outstanding photoactivity, low price, availability, innocuousness and physicochemical stability. Photocatalysis is based on the excitation of a semiconductor material by UV radiation (λ< 380 nm) with the consequent creation of electron/hole pairs. However, photocatalysis has some important practical limitations. This technology is better suited to treatment of small flows, with a low concentration of pollutants. The use of small-sized TiO_2 particles in industrial processes is technologically unfeasible, since filter processes would be necessary to remove the catalyst which would be too expensive. The synthesis of catalysts that simultaneously combine high activity and easy separation is a priority subject.

Purpose: This project undertakes the development of *hybrid materials* that produce a synergic effect between adsorption and photocatalysis, which involves:

1) Developing easily manipulable shapes were from a porous adsorbent material coated with a TiO_2 thin film.
2) Optimizing the method of incorporating TiO_2.
3) Analyzing the influence of the reactor configuration on COV degradation using a compound parabolic collector (CPC) enabling more efficient use of diffuse radiation. The use of solar photoreactors, which increase the percentage of $\lambda < 380$ nm solar radiation available to activate the TiO_2, is of great interest.
4) Analyzing photocatalytic system efficiency and the influence of the configuration of the hybrid material on process selectivity with model compounds such as trichloroethylene, toluene, formaldehyde, and H_2S, etc.

Achievements in 2010: In 2010, the influence of the configuration of the hybrid material on photocatalytic process selectivity was analyzed with two model compounds, one organic, trichloroethylene (TCE), and another inorganic, H_2S, working with different reactor configurations allowing the use of UV-opaque materials. The new experiments with TCE in a tube reactor with a CPC collector continued along the line of previous years, demonstrating the benefit of using adsorbent materials to buffer the effect of solar intermittence in addition to improving mineralization capability. The experience acquired in the DETOX-H2S program (Madrid Regional Project S-050/AMB/0406), which ended in 2009, was fundamental for the experiments with H_2S. Under that project, the first H_2S experiments with a hybrid ring photoreactor able to operate 24 hours a day were designed and installed. The reactor consists of a non-concentrating CPC and an internal UVA lamp which is turned on as required, so it can operate with solar and/or artificial radiation. An international patent extension (PCT) has been applied for that allows the reactor to be adapted to opaque photocatalysts in simple shapes, such as hybrid adsorbent/photocatalyst material plates. Once it was demonstrated that the use of these materials can solve some of the problems for photocatalytic elimination of H_2S, continuous treatment on a semi-pilot scale of real air from a WWTP containing H_2S and other corrosive compounds and compounds causing foul odors was evaluated with this system. The good results, with treatment capacity and durability improved over photocatalysts deposited on non-porous substrates, as well as an significant delay in the appearance of SO_2 as a sub-

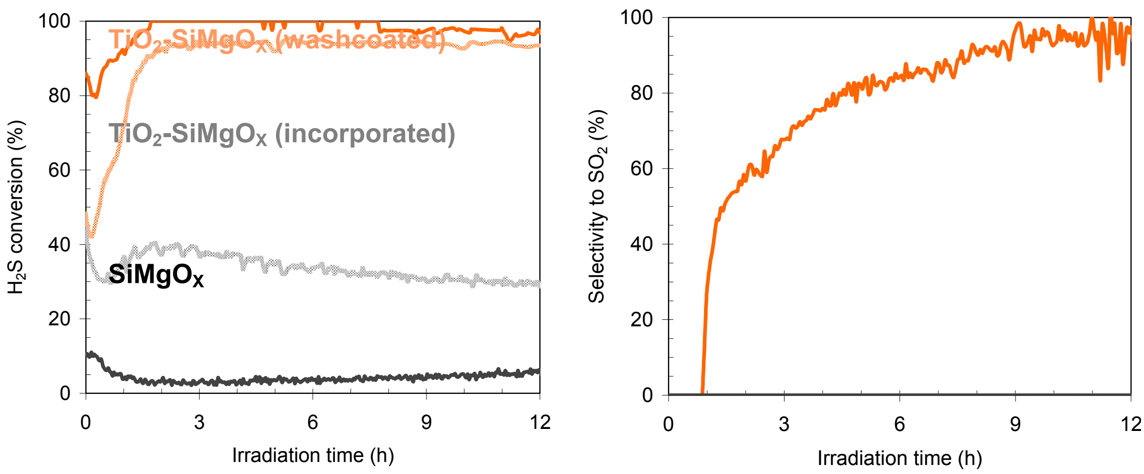


Figure 4.23. Conversion (left) and selectivity (right) during photocatalytic oxidation of H_2S with pure $SiMgO_X$ and P25-TiO_2 or hybrid TiO_2-$SiMgO_X$ incorporated and coated, all treated at 500ºC.

product are very promising and have awakened the interest of business and opened several possibilities for new projects.

Publications: [4.48]-[4.51]

4.3.6 New photocatalytic treatment system for chemically and bacterially contaminated indoor air

Participants: CIEMAT, Aire limpio S.L., CBMSO, UV.
Contact: Dr. Benigno Sánchez; benigno.sanchez@ciemat.es
Funding: Ministry of Science and Innovation. Total budget: 164k€.
Duratión: January 2010 – January 2012

Background: Air pollution has traditionally been related only to the presence of Chemicals in outdoor area. However, in indoor environments, where a large part of the population carries on their daily activities 90% of the time, there are a multitude of foci of pollution among which are volatile organic compounds (COVs) and bioaerosols. These indoor pollutants may be the cause of illnesses such as allergies and asthma which have become known as the "Sick Building Syndrome". In recent decades, authorities have become aware of the severity of the problem, which means poor indoor air quality, and have generated clear legislative attention and a demand for efficient indoor air treatment systems.

In most of the studies related to this subject, one or several compounds or certain varieties of bacteria, defined as "model pollutants". This project poses the challenge of developing a photocatalytic prototype that efficiently reduces most of the chemical and biological pollutants in indoor environments. It is therefore intended to deal with the existing pollutants and identify them before and after treatment of the resistant chemicals and bacteria. This requires sophisticated analytical tools, such as automatic thermal desertion (ATD-GC-MS) for analysis of VOC on ppb levels and molecular biology techniques, such as PCR for the analysis of bacteria and fungi.

Photocatalysis mediated by TiO_2 may be considered an alternative or supplement to conventional indoor air filtering systems, because, contrary to these, they involve the formation of hydroxyl radicals, the oxidizing potential of which is stronger than other traditional oxidants. The selection of a support for immobilizing the photocatalyst is not an easy task, as in addition to maintaining good photocatalytic activity, they must be made of very durable materials that are mechanically highly resistant, to which TiO_2 coating sticks in coated systems and which do not make the final price of the photocatalyst too expensive.

Purpose: This project is intended to demonstrate, and transfer knowledge to industry, the real possibilities of heterogeneous photocatalysis based on immobilized TiO_2 for treatment of COVs and bacteria under real operating conditions. The following goals are set for this.

1) Design, construct and install a first photocatalytic reactor prototype for working under real conditions.
2) Develop, prepare and characterize supports and photocatalysts for photocatalytic oxidation of COVs and bacteria.
3) Study the efficiency for destruction of VOCs and bacteria of the photo-catalysts prepared.

4) Systematically analyze the composition of air (VOCs and bacteria) in different buildings.
5) Test and evaluate the efficiency for destroying VOCs and bacteria of the photocatalytic system designed, constructed and installed by Aire limpio S.L., UV at CIEMAT.

Achievements in 2010: In 2010, the first year of the project, the first air treatment prototype was designed, manufactured with materials usually used in air conditioning systems to make the system competitive from the beginning. The prototype was installed and put into service in CIEMAT buildings. In the first stage, experiments were done without the photocatalyst for the purpose of studying the influence of temperature, photon intensity and spectral selectivity on the bacterial concentrations found. During the tests, continuous monitoring was carried out by Internet of the operating parameters and variables that influence the system (for example, temperature, relative humidity, etc.).

Catalysts were prepared for their insertion in the system. To improve adherence of the photocatalyst, a basic pretreatment was applied to the monolithic aluminum structures provided by Aire Limpio. TiO_2 films were deposited by dip-coating a sol. We have worked on optimizing the variables related to the pretreatment and deposition, which are time, temperature, additive concentration, etc. The catalyst was characterized by such techniques as DRX, nitrogen isotherms and SEM images. Figure 4.24 shows micrographs of the support and the photocatalyst.

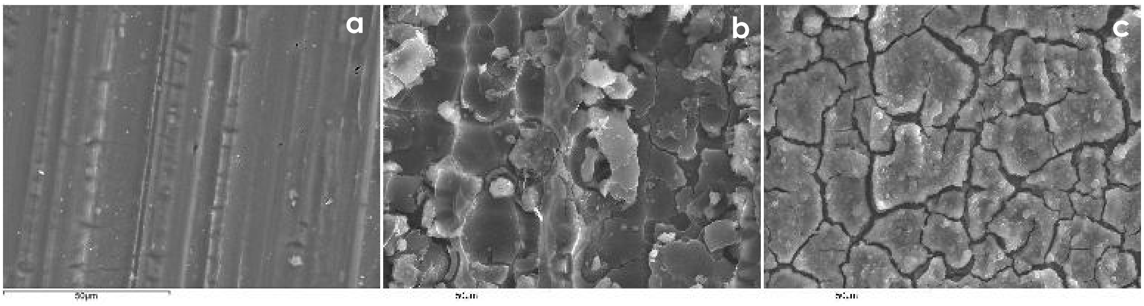


Figure 4.24. SEM images. A) Washed aluminum b) Pretreated aluminum c) Pretreated aluminum coated with TiO_2.

System photocatalytic activity was evaluated, keeping in mind the effect that the different parameters related to pretreatment of the support, such as time and temperature, the amount of tiO_2 deposited, and thermal treatment have on photoactivity. The purpose of the study was to optimize the preparation conditions for the best photocatalytic activity. Trichloroethylene was chosen as the model volatile organic compound (COV). The results show stability of the materials prepared and their highly active mineralization of trichloroethylene. Seasonal sampling of bacteria and COVs was carried out simultaneously at different representative points in two CIEMAT buildings, a recently built bioclimatic building and a building over 35 years old. The results demonstrated the extremely high variability in the number of CFU and of bacterial species identified in both buildings, but this variability is especially high in the old building.

Publications: [4.52]

4.4 Solar Desalination Group

Interest in solar desalination of seawater and brine has been experiencing strong growth throughout the world in recent years. This is motivated, on one hand, by the constant increase in demand for desalinated water, and on the other by its implications for energy. International Desalination Association data available show production at the end of 2010 of 65.2 million m^2/day and a contracted capacity of 71.7 million m^3/day. Although these data alone are excellent, even more relevant, if possible, is the fact that world desalinated water production has literally doubled in the last decade and all the forecasts indicate that this production is going to continue growing at the same rate in the coming years. According to 2010 data from the same source, about 62% of the desalinated water is produced by membrane technologies and the remaining 38% by thermal technologies. Since the need to increase available water resources usually coincides with high solar irradiation in the same geographic area, sustainable initiatives for development of desalination applications must always include the solar option among those of most interest.

For all of these reasons, the PSA activity in this field is particularly intense, attempting to develop in the different projects in which we are participating, the widest possible spectrum of technologies to supply existing desalination processes by solar energy as the primary source. A parallel objective pursued in this initiative is for the PSA to have an integrated solar desalination research facility that includes most of the existing processes and technologies and also make the PSA an international reference in research in this field.

The main projects and activities carried out in 2010 in this area are described below.

4.4.1 MEDESOL
Solar seawater desalination by membrane distillation http://www.psa.es/webeng/projects/medesol/index.html

Participants: CIEMAT_PSA (Coord.), Univ. de la Laguna, Acciona Infraestructuras S.A., Aguas de las Cuencas Mediterraneas, S.A., and Iberinsa S.A. (E)., AOSOL (P), Univ. Stuttgarrt (D), Tinep S.A. de C.V. and Centro de Investigacion de Energia – Universidad Nacional Autónoma (MEX), Kungliga Tekniska Högskolan Stockholm and Scarab Development AB (S)

Contact: J. Blanco, julian.blanco@psa.es
E. Guillén, elena.guillen@psa.es

Budget: VI-PM. Global Change and Ecosystems: 1,375 k€.
CIEMAT: 417 k€

Duration: October 2006-September 2009

Background: Development of robust, low-energy desalination systems for small isolated populations where the lack of central utilities and services affects their possibility of installing other desalination systems. Membrane distillation is a low-temperature thermal process which operates between 60-100ºC, so process heat can be supplied by stationary solar collectors with minimum maintenance, and the desalination process itself is simple and easy to operate. The process is based on a pressure difference in the steam on either side of a microporous membrane formed by applying two streams of water at different temperatures. This gradient causes steam to evaporate from a hotter solution through the membrane and condense on the cold side where it is collected free of salt and macromolecules as highly pure distillate.

Purpose:

1) Learn about the desalination process and study the way to increase system efficiency

2) Develop heat recovery process concepts and increase efficiency
3) Develop and/or improve individual system components, including development of a stationary solar collector optimized for the operating temperatures and advanced heat exchanger plate surface treatments to reduce scaling
4) Develop a complete system with several cubic meters per day capacity
5) Develop a stand-alone system with a capacity of a few hundred liters/day

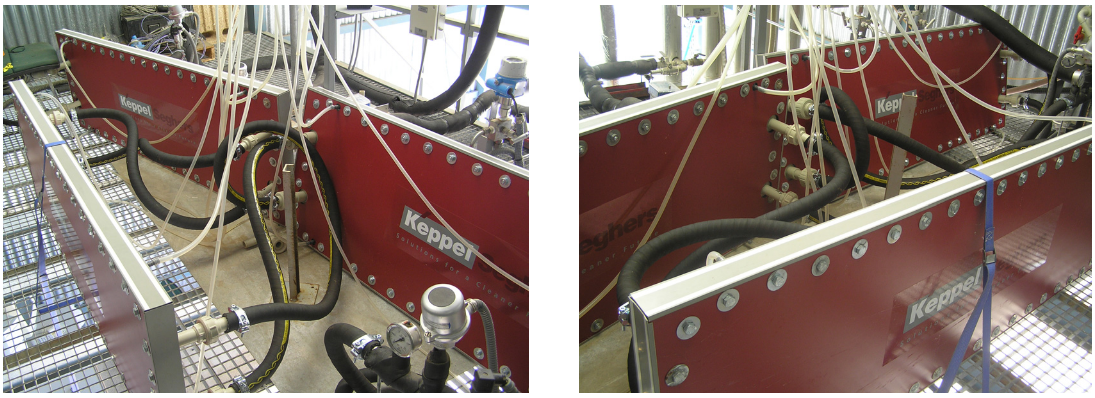


Figure 4.25. Second membrane distillation prototype (Keppel-Seghers, Singapore) tested at the PSA facility.

Achievements in 2010: In 2010, a third module prototype was evaluated (a second prototype from Keppel-Seghers in Singapore). The system tested consisted of three of these new modules arranged in series to maximize heat recovery. The flexibility of the DM facility made it possible test new prototypes with a minimum of modifications. Some of the results found during the experiments were the following:

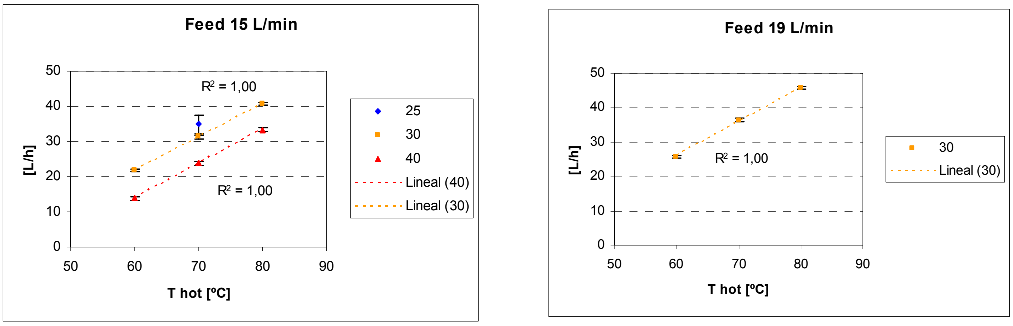


Figure 4.26. Production of permeate as a function of feedwater temperature at different flow rates. Three modules operating in series.

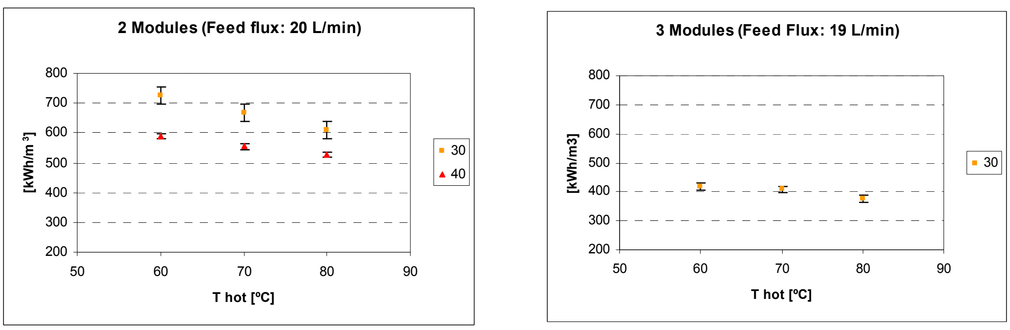


Figure 4.27. Specific thermal energy consumption [kWh_t m^{-3}]. Results operating with 2 and 3 DM modules in series.

The MEDESOL Project formally ended this year during it, the project final reports were being written. One of the final results was a detailed economic study of the combination of DM and solar energy, in this case with stationary solar collectors (http://www.psa.es/webeng/projects/medesol/results.php). Some of the main conclusions the consortium arrived at concerning the current state of the art of membrane distillation for desalination, are:

- The results of the precommercial technologies evaluated are far from values found in the literature. The real thermal consumption reached is around 1000 kWh/m^3.
- Connection of this technology with solar thermal energy is not considered feasible until the specific consumption drops below 200 kW.
- Specific energy consumption affects linearly the finally cost of water produced, so recovery of waste heat in the is essential either internally or externally in a multi-stage concept.
- Combination of this technology with solar thermal energy is not considered feasible until module cost is below 1000 Euros per unit. At less than 1000 Euros/unit, the DM mules influence the final cost of water less.
- The specific production of this technology is still very low and is very far from the productions achieved by other mature desalination technologies such as RO (around 14 L/m^{2}h) or the lab scale results in the literature (80 L/m^{2}h at 60ºC).
- The combination of the three factors, production cost reduction, reduction in thermal energy consumption and specific water production (per m^2 membrane) is therefore basic for solar desalination by DM to become commercially feasible.

Publications: [4.53]

4.4.2 MEDIODIA
Multiplication of efforts for development, innovation, optimization and design of advanced greenhouses
http://www.cenitmediodia.com

Participants: Repsol YPF, Acciona Solar (CIEMAT-PSA como organismo subcontratado), Ulma Agrícola, Ulma Packaging, Acciona Agua, Ulma Handling Systems, Fundación Cajamar, Agrobio, Biomiva, Grupo AN, Ingeteam

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

Budget: 24 M€; Ministry of Industry, Commerce and Tourism CENIT Project, INGENIO Program.

Duration: January 1, 2007 –December 31, 2010

Background: Intensive agriculture is one of the most important agricultural sectors in Spain. So R&D activities should be carried out which move Spain into the vanguard of the agrofood technology, going from a buyer of technology to a European and worldwide reference. The results that could be obtained in this field will transcend the agrofood sector itself, leveraging other industrial activities and services.

Purpose: The general purpose of the Project is to do strategic research in the field of agriculture under plastic that develops a new advanced greenhouse

concept, highly automated, efficient in use of energy and water and that enables diversified, profitable crops any time of the year in different Spanish climates, using an integral production system.
In the specific case of the PSA, this generic goal of the project has the following specific objectives:

1) Erection and evaluation of a mi-temperature parabolic-trough collector for process heat applications
2) Erection and evaluation of an Organic Rankine Cycle (ORC) that can be used in combination with the above collector in polygeneration process schemes (electricity, cooling, water, heating)
3) Obtain an effluent from application of solar disinfection technologies that meets the parameters of the reuse regulation for treated water (RD 1620/2007) for pathogenic organisms

Achievements in 2010: A field of 8 parabolic-trough collectors have been designed, acquired and constructed to supply about 125 kW_{th} for application in polygeneration and multi-effect desalination at the PSA.

The small, low-cost parabolic-trough collector, Polytrough 1200 prototype, by the Australian company, NEP-Solar, has been identified as ideal for mid-temperature thermal applications. It has a nominal efficiency of 55% in the 120-220ºC range with 1000W/m^2 of normal direct radiation and a nominal production of 15.8 kW per module with a mean collector temperature of 200ºC.

Testing of the solar field has begun and the results show that the field achieves and maintains the expected temperatures as required for the schemes studied. Therefore, the field has the potential for use in systems that make use of mid-temperature heat, such as polygeneration, water pumping for irrigation or desalination.
Publications: [4.54]

4.4.3 PRODES
Desalination of sea water with solar membrane distillation Systems
http://www.psa.es/webeng/projects/medesol/index.html
http://www.prodes-project.org

Participants: WIP, Fraunhofer Gesellschaft ISE and Tinox (D); Centre for Renewable Energy Sources (CRES), Capital Connect and Hellas Energy (GR); Univ. Palermo and European Desalination Society (EDS) (I); INETI and Ao Sol (P); CIEMAT-PSA, Befesa and Instituto Tecnológico de Canarias (ITC) (E); AquaMarine Power (UK)
Contact: Michael Papapetrou, WIP, michael@papape.com
Budget: 1,023 k€, from the European Commission Intelligent Energy in Europe Program
Duration: October 1, 2008 –September 30, 2010

Background: In the south of Europe, desalination is an activity of growing importance in the energy demand. Use of renewable energy for desalination, whether in isolated systems or connected to the grid, will allow better load control and thereby more use of renewable energies in those regions. The project promotes the use of renewable energies in remote areas where the grid cannot be adapted to high consumption of intermittent sources.

Purpose:
1) Assemble the actors in desalination with renewable energies and coordinate their activities
2) Set the basis for training specialists
3) Assist technology providers to find market niches
4) Facilitate the capital flow for developing products and projects
5) Promote improvements in the current regulatory framework conditions
6) Increase knowledge of the technologies

Achievements in 2010: In the last year of the project a Roadmap was prepared for use of renewable energies in desalination by consulting with over 100 specialists in industry and research all over the world. The document was distributed and may be downloaded from the Web or hard copies are also available. A work group has also been set up in which the PSA participates and annual meetings will be held to define, propel and supervise the implementation, development and diffusion of desalination with renewable energies.

Furthermore, a database of educational and informative materials on renewable energy desalination has been prepared for use by SMEs and professionals in the water and renewable energy industries, in addition to courses given in 1010 in Gran Canaria (Canary Islands) and Faro (Portugal).

For marketing, a database of SMEs and professionals in the water and renewable energy industries has been prepared, as well as a publication of renewable energy desalination products available, which has been distributed at four events. The one in Spain was in Gran Canaria (Canary Islands).

Finally, an analysis of the conditions surrounding renewable energy desalination in Spain crystallized in a report on the legal and institutional framework in the power and water industries, as well as requirements and procedures necessary for a renewable energy facility in Spain. The document includes evaluation of weak points and a series of suggestions on power and water policies to leverage renewable energy desalination, which were discussed and presented at a meeting with IDAE authorities in Madrid.

Publications: [4.55]

4.4.4 CONSOLIDA Solar R&D consortium http://www.cenit-consolida.es/

Participants: 20 Spanish companies led by Abengoa Solar with 18 subcontracted OPIs (public research centers).
Contact: Alfonso Rodríguez, Abengoa Solar, alfonso.rodriguez@solar.abengoa.es
Budget: 24 M€; Ministry of Industry, Commerce and Tourism INGENIO program CENIT Project.
Duration: January 1, 2008 –December 31, 2010

Background: In spite of the importance of R&D in the lowering the cost of solar thermal technologies, the number of scientists and engineers involved in its technological development is relatively small. The International Energy Agency recommends that R&D teams be multidisciplinary, including optics, materials science, heat transfer and storage, instrumentation and monitoring techniques and energy process engineering.

Purpose: The main purpose of the project is to establish an R&D infrastructure that consolidates Spanish leadership in concentrating solar technologies. Solar thermal energy can contribute to fulfilling EU strategic policies for climate change, e.g., commitment to reduce CO_2 emissions by 20% by 2020.

Achievements in 2010:
Multi-effect distillation: During the previous stages of the CONSOLIDA Project, among the connection configurations of a solar thermal power plant and a multi-effect distillation plant (MED), two were identified as being of interest, a low-temperature MED plant (LT-MED connected to a field of stationary evacuated-tube solar collectors (ETC), and a thermal compression MED plant (TVC-MED) fed by a field of parabolic-trough collectors (PTC). A third plant concept is based on hybridization of the two aforementioned with a solar LT-MED plant working in thermal compression mode when operating with fossil fuel.

During 2010, models were computed for the above configurations based on physicochemical principles developed in previous stages of the project. This has enabled the design of the solar field and desalination system depending on the different desalinated water production capacities required. The models included energy storage to increase the solar fraction of the plant as well as hybridization with fossil fuels to ensure continuous 24-hour operation.

In 2010 an economic analysis was also made of all the systems proposed, finding the specific cost of desalinated water at different electricity costs. This made it possible to determine the best configurations for detailed design during the second stage of the Project.

Publications:[4.1]

4.4.5 HISPAMED
Multi-effect desalination with solar thermal energy
http://www.psa.es/projects/hispamed

Participants: CIEMAT-PSA, ASSYCE INGENIEROS S.L.
Contact: Dr. Julián Blanco, julian.blanco@psa.es
Budget: Cooperation Agreement
Duration: March 2009 – February 2011

Background: Development of desalination technologies based on renewable energies is not only a very promising initiative, but also provides important opportunities for current business in certain areas of the planet. Because of solar energy's strong potential, not only in Spain, but in the whole Mediterranean and Persian Gulf, the use of the multi-effect distillation technology (MED) is one of the best adapted to the use of low-temperature solar thermal energy.

Purpose: The purpose of this project is cooperation between the CIEMAT and ASSYCE INGENIEROS to develop a native MED technology which integrates all of the technological elements necessary for a complete seawater desalination plant.

Achievements in 2010: During 2010, a first prototype, made up of two effects was designed. One had a preheater and the other was connected to a condenser simulating the final condenser of a conventional MED plant. Two designs were proposed and evaluated for two different energy sources, hot water and steam, in the first effect, although in the end the steam supply option was chosen, since it enables simulation of any of the cells in a later multiple unit.

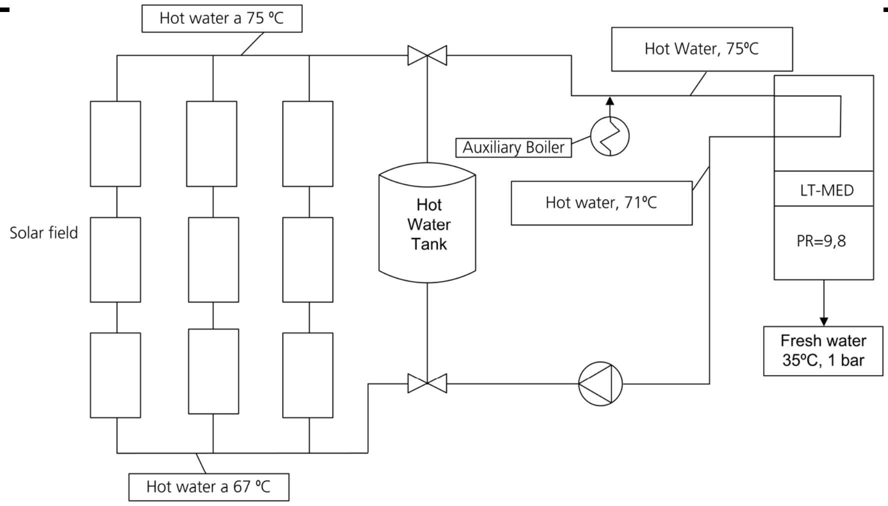


Figure 4.28. Diagram of the system made up of an LT-MED plant connected to a field of ETCs.

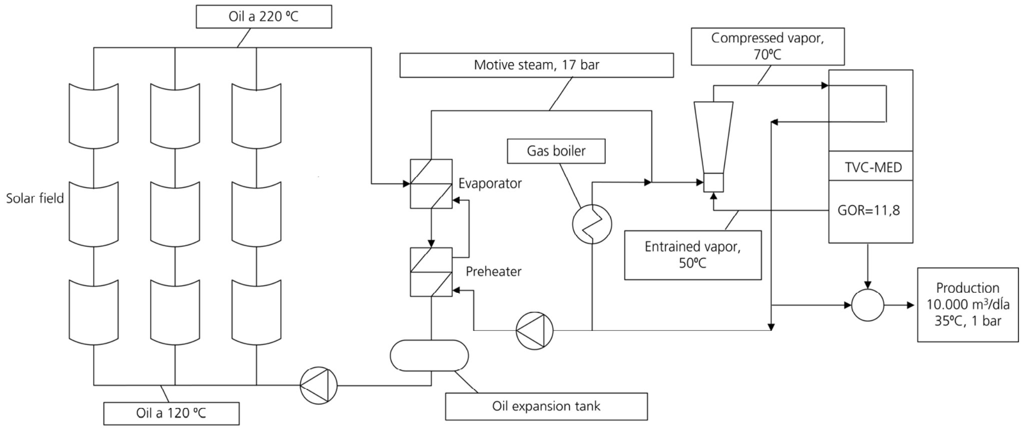


Figure 4.29. Diagram of the system made up of a TVC-MED plant connected to a PTC solar field.

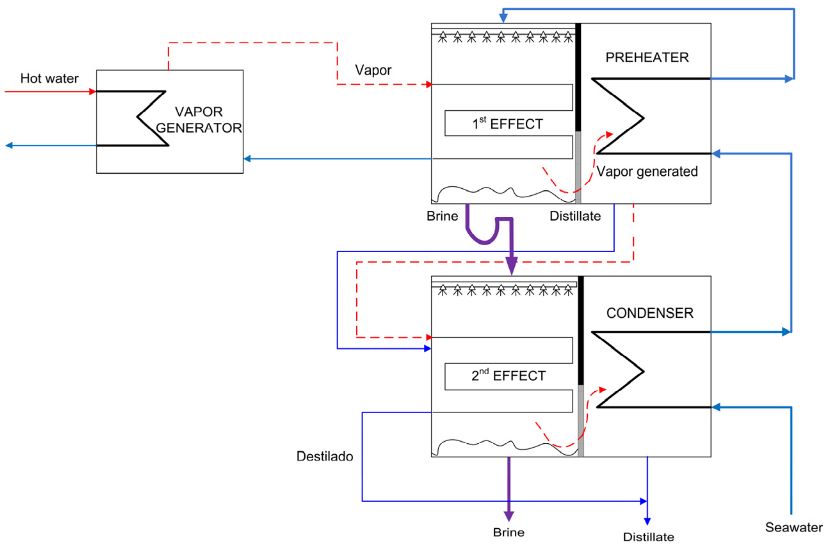


Figure 4.30. Results of a simple distiller that uses steam as the thermal energy source.

Figure 4.31. Double-effect absorption heat pump (LiBr-H_2O) at the PSA

Also in 2010, the materials were chosen and detailed prototype plans were drawn to proceed with construction and experimental evaluation.

Publications: [4.57]

4.4.6 TECOAGUA Development of Sustainable Technologies for an Integrated Water Cycle

Participants: BEFESA (CIEMAT-PSA as a subcontractor), Canal de Isabel II, Emasesa, Agua y Gestión, Inclam, Fagor Electrónica, Deimos Imaging, Terranova, Micronet Porous Fibers, ITC, Inabensa

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

Funding: 18 M€, Ministry of Science and Innovation, CENIT-E Program CENIT Project

Duration: September 17, 2009 – December 31, 2012

Background: The latest world reports on fresh water availability show severe water stress affecting a growing number of places. The effects of climate change have led to an increase in temperature and change in rainfall regime, which clearly affect its availability. During the 20th century, the world population multiplied by four, energy consumption by sixteen and water consumption by nine. All of this has led to a series of environmental consequences, the most obvious effects of which are water shortages, increased waste and dumping and augmented climate change. In view of this, an integrated sustainable water cycle is necessary.

Purpose: The main purpose of the project is to generate knowledge and develop new technologies and processes for the integrated water cycle that contribute to ensuring availability and quality of a sustainable water supply, which means limited resources must be managed efficiently, alternative resources generated and associated CO_2 emissions lowered.

At the PSA, these activities are framed within a sustainable integrated water cycle strategy, under its Activity 11 (Application of renewable energies to the water cycle). The purpose of the scientific work done by the PSA is to study application of solar thermal energy to a multi-effect distillation system connected to a double-effect absorption heat pump.

Achievements in 2010: Design and operating parameters for connecting the multi-effect distillation and double-effect absorption heat pump already at the Plataforma Solar de Almeria were pre-selected. These parameters enabled the functional specifications of the solar system required to supply the high-temperature generator of the heat pump to be determined.

A concentrating solar technology was selected to supply the power (100 kW) to provide the heat pump energy required (180ºC saturated steam), and a commercial parabolic-trough collector for industrial heat applications up to 225ºC (PolyTrough 1200) was identified for it. Construction of a solar field made up of eight PolyTrough 1200 collectors (four rows of two collectors in series) with a total aperture surface of 230 m^2 was carried out in 2010. The efficiency of this collector is around 55% for a direct normal radiation of 1000ºW/m^2 and an output temperature of 220ºC. The working fluid will be thermal oil (Monsanto Santotherm 55) which will supply a steam generator installed in the desalination plant and feed the heat pump.

Publications: [4.58]-[4.60]

4.4.7 PROYECTO ZCR
Zero Carbon Resorts
http://www.zerocarbonresorts.eu

Participants: Gruppe Angepaste Technologie GrAT (A) (Coord.), Philippine Green Building Council PhilGBC (PH), Palawan Council for Sustainable Development PCSD (PH), CIEMAT-PSA (E), Asia Society for Social Improvement and Sustainable Transformation ASSIST (PH).

Contact: Dr. Guillermo Zaragoza, guillermo.zaragoza@psa.es
Dr. Robert Wimmer, rw@grat.at

Funding: Switch-Asia, EU: 2.1 M€ (80%).
Presupuesto CIEMAT-PSA: 300 k€

Duration: Nov 2009 – Nov 2013

Background: For isolated settlements, that is, on islands, energy supply currently depends strongly on the fossil energy (basically gas-oil generators). The Philippines, which has over 7000 islands, is a typical example, and tourism, with its high consumption of water and energy, is one of the industries causing the most impact on the country's environment.

Purpose: The purpose is to substantially improve energy efficiency and sustainability in the tourist industry, especially in the region of Palawan, reducing its carbon footprint by, (i) bioclimatic architecture, (ii) use of renewable energies to generate electricity and water, (iii) sustainable consumption of energy and water. The project proposed is intended to stimulate local economy, enabling local tourist SMEs to develop the capacity to achieve these goals. They are being trained for this in a series of courses and workshops in addition to a demonstration tourist resort implementing sustainable practices and using locally available green materials, resources and technologies.

Achievements in 2010: During the first year, the project began to spread information about itself among the tourist SMEs in Palawan in search of volunteer establishments for selection as the study group. To do this, workshops were held in three places on Palawan Island (Puerto Princesa, El Nido and Coron) where the main environmental problems in Philippine tourist facilities

Figure 4.32. ZCR Conference in Puerto Princesa (Palawan, Philippines) Novembre 2010.

Figure 4.33. Participants in the 1st ZCR Project Workshop in the Philippines, March 2010.

were discussed, proposals made and volunteers signed up to participate in the project. Energy audits were carried out at the establishments in the study group and a first course on basic concepts emphasizing reduction in energy and water consumption was given in Puerto Princesa. At the same time, possibilities for applying renewable energies were evaluated, such as a series of small parabolic-trough collectors to generate process heat usable in organic Rankine cycles to generate electricity, in cooling by solar absorption for HVAC or in membrane distillation systems to desalinate brackish and sea water.

Finally, a first project conference was held in Puerto Princesa in which the first advances and results in lowering consumption were reported and will be compiled in a manual which will be made available to tourist agents.

4.5 Publications

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10). Corfu, Greece. July 5th -10th, 2010. Plenary Lecture. Book of abstracts, 48-49.

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[4.6] N. Miranda-García, M. Ignacio Maldonado, J.M. Coronado, Sixto Malato. Degradation study of 15 emerging contaminants at low concentration by immobilized TiO_2 in a pilot plant. Catalysis Today, 151, 107–113, 2010

[4.7] M. Jiménez, I. Oller, M.I. Maldonado, S. Malato, A. Hernández-Ramírez, J.M. Peralta-Hernández, A. Zapata. Solar Photo-Fenton Degradation of a Mixture Containing Partially Aqueous Soluble Pesticides. Evaluation of Ecotoxicity and Biodegradability. Poster presentation. Proceedings of the 6th European Meeting on Solar Chemistry and Photocatalysis: Environmental Applications. Praga, 13-16 Junio de 2010. Josef Krysa (Ed.). ICT Prague Press, Praga. ISBN 978-80-7080-750-7. pp. 462-463.

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[4.9] M.M. Ballesteros Martín, J.L. Casas López , I. Oller, S. Malato, J.A. Sánchez Pérez. A comparative study of different tests for biodegradability enhancement determination during AOP treatment of recalcitrant toxic aqueous solutions. Ecotoxicology and Environmental Safety, 73, 1189–1195, 2010.

[4.10] J. L. Casas López, A. Cabrera Reina, E. Ortega Gómez, M. M. Ballesteros Martín, S. Malato Rodríguez, J. A. Sánchez Pérez. Integration of Solar Photocatalysis and Membrane Bioreactor for Pesticides Degradation. Separation Science and Technology, 45, 1571–1578, 2010.

[4.11] Ballesteros Martín, M. M.; Garrido, L.; Ortega Gómez, E.; Cabrera Reina, A.; Sánchez, O.; Más, J.; and M. I. Maldonado; "A reliable process for pesticide degradation: Photo-Fenton and membrane birreactor combination". VII ANQUE Internationall Congress. Integral Water Cycle: Present and Future "A Shared Commitment". Oviedo (Spain), 13-16 Junio 2010. Póster (T8-030).

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[4.19] A. Zapata, S. Malato, J.A. Sánchez-Pérez, I. Oller, M.I. Maldonado. Scale-up strategy for a combined solar photo-Fenton/biological system for remediation of pesticide-contaminated water. Catalysis Today, 151, 100–106, 2010.

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5 Events

Diego Martínez Plaza

On February 23, a conference entitled,

"Conference on Policies to Promote Renewable Energy in Europe"

was held at the PSA as part of the program of events organized by the Spanish Government under the EU Spanish Presidency during the first half of the year.

The following people took part in the conference:

Luis Crespo Rodríguez	Director General Centro Tecnológico Avanzado de Energías Renovables (CTAER)
Antonio Hernández Garcia	Director General for Energy and Mining Policy, (MITYC)
Pedro Roque Molina Garcia	Rector University of Almería
Isabel De Haro Aramberri	Secretary General for Development of Industry and Energy, Junta de Andalucía
Carlo Rubbia	Nobel Prize in Physics, CERN
Cayetano López Martínez	Director General del CIEMAT

6 List of Acronyms

A..........	Austria
ACTP......	acetaminophen
AENOR...	Spanish Association for Standardisation and Certification
AGMD	Air gap membrane distillation
AMES.....	Environmental Applications of Solar Energy Unit (PSA)
ALG	Algeria
AOP	Advanced oxidation process
AOS.......	Average oxygen state
AR.........	Anti-reflective
ARG.......	Argentina
ASME.....	American Society of Mechanical Engineers
ASP	Active Server Pages
AT	Agitated tanks
ATD	automated thermal desorber
ATD-GC-MS	automated thermal desorption gas chromatography mass spectrometry
ATL........	atenolol
ATR	Attenuated total reflection (Spectrometer accessory)
AUS	Australia
BLG	Bulgaria
BOD.......	biological oxygen demand
BRA	Brazil
BSRN	Baseline Surface Radiation Network
BZU	Birzeit Univer (PS)
CDTI......	Centre for the Development of Industrial Technology
CEA	Atomic Energy Commission (FR)

CENER ...	Centro Nacional de energías Renovables
CENIM ...	Centro Nacional de Investigaciones Metalúrgicas
CENIT....	Consorcios Estratégicos Nacionales en Investigación Técnica (CDTI)
CFE	compound finite elements
CFU.......	Colony forming units
CH	Switzerland
CHA	Spanish German Agreement
CIEMAT .	Centro de Investigaciones Energéticas Medioambientales y Tecnológicas
CIESOL..	CIEMAT-UAL Mixed Center for Solar Energy Research'
CITET	Tunis International Center for Environmental Technologies
CNR	Istituto de Ricerca Sulle Acque
CNRST...	National Center for Scientific and Technical Research (MA)
COD	chemical oxygen demand
CPC.......	Compound parabolic concentrator
CREST-DIT	Dublin Institute of Techology
CREVER .	Centre of Technological Innovation in Heat Upgrading and Refrigeration - University Rovira i Virgili (ES)
CRS	Central Receiver System
CRT.......	central receiver technology
CSIC	Consejo Superior de Investigaciones Científicas
CSIR	Council for Scientific and Industrial Research (Za)
CSP+D ..	Integration of desalination Technologies in solar power plants
CTAER ...	Centro Tecnológico Avanzado de Energías Renovables
DAD	diode array detector
D	Germany
DISS	Direct Solar Steam
DIW	Dionized water
DK	Denmark
DLR.......	Deutsches Zentrum für Luft- und Raumfahrt e.V. (DE)
DNI.......	direct normal irradiance
DOC	Dissolved oxygen concentration
DRIFTS..	Diffuse Reflectance Infrared Fourier Transform Spectroscopy
DSG	direct steam generation
DZ	Algeria

EAWAG ..	Swiss Federal Institute of Aquatic Science
EC.........	European Commission
EEIG......	European Economic Interest Grouping
ENEA	Agency for New Technology, Energy and the Environment (IT)
ERDF	European Regional Development Fund
ESED	environmental secondary electron detection
ETHZ	Federal Polytechnic Institute of Zurich (CH)
E..........	Spain
EU.........	European Union
FID........	flame ionization detector
FP	EC Framework programme
FPI	Ph.D. research fellowship (Formación de Personal Investigadora)
F	France
FT-IR	Fourier transform infrared (Spectrometer)
GACS.....	Grupo de Alta Concentración Solar (PSA)
GIQA-URJC	Grupo de Ingeniería Química y Ambiental- University Rey Juan Carlos
GDV.......	Generación directa de vapor (Direct steam generation o DSG)
GMC	Medium Concentration Group (PSA)
GPS	global positioning system
GR.........	Greece
HPLC	High performance liquid chromatography
HSCG.....	High Solar Concentration Group
HVAC.....	Heating, ventilating, air conditioning
IBR........	Immobilized biomass reactors
ICP-AES .	inductively coupled plasma atomic emission spectroscopy
ICP-CSIC	Instituto de Catálisis y Petroleoquímica -CSIC
ICROSS..	International Community for Relief of Starvation and Suffering
ICTS	Singular Scientific and Technical Facilities
ICV-CSIC	Instituto de Cerámica y Vidrio - CSIC
IDAE......	Instituto de Diversificación y Ahorro de Energía
IL	Israel
IMDEA ...	Instituto Madrileño de Energías Alternativas

IMP	information module profile o interface message protocol
INCO	Programme for RTD Cooperation with third countries and international organisations
INETI	Instituto Nacional de Engenharia (P)
INRGREF	National Institute of Research on Rural Engineering, Water and Forestry (TN)
INTA ... A	Instituto Nacional de Técnica Aeroespacial (ES)
IPHE......	International Partnership for the Hydrogen Economy
IRSA	The Water Research Institute (I)
I	Italy
JRC	Joint Research Centre (EU)
JTI	Joint Technology Initiative (EU)
KEN	Kenya
LCA	Lifecycle analysis
LC-MS-TOF	Liquid chromatography, mass spectrometry, time-of-flight
LEC	Levelized energy cost
LECE	Laboratory for Energy Testing of Building Components
LPG	Liquid petroleum gas
MA	Morocco
MBR	Membrane reactors
MD	membrane distillation
MEC	Spanish Ministry of Education and Science
MED	Multi-effect desalination
MEX	Mexico
MICINN..	Spanish Ministry of Science and Innovation
MNSV	melon necrotic spot virus
MOF	metal-organic framework
NASA	National Aeronautics and Space Agency (USA)
NEAL	New Energy Algeria
NL.........	Netherlands
NTU	Nephelometric Turbidity Units

OPI	public research center
ORC	organic Rankine cycle
ORP	oxidation reduction potential
P	Portugal
PCM	phase-change materials
PDVSA ...	Petróleos de Venezuela, S.A.
PEG	polyethylene glycol
PET	polyethylene terephthalate
POL	Poland
PS	Palestine
PSA	Plataforma Solar de Almería
PSI	Paul Scherrer Institute (CH)
PTC	Parabolic-trough collector
PVDSA ...	Petroleos de Venezuela, S.A.
RCH	Chile
RCSI	Royal College of Surgeons in Ireland
RT-PCR ..	Reverse transcription polymerase chain reaction
RU	Russia
S	Sweden
SBBGR ...	batch biofilter granular reactor
SCC	stress corrosion cracking
SEM	Scanning electron microscope
SIE	Natural water
SME	Small and medium enterprises
SODIS ...	Solar disinfection
SolLab....	Alliance of European Laboratories on Solar Thermal Concentrating Systems
SQL	Structured Query Language
SSPS	Small Solar Power Systems Project
STP	Solar thermal power
TCD	thermal conductivity detector
TEM	Transmission electron microscopy
TEMA BEU	Tubular Exchange Manufacturer's Association-Bonnet (integral cover), one-pass shell, U-tube bundle heat exchanger

TN	Tunisia
TOC	total organic carbon
TR.........	Turkey
TSS.......	total suspended solids
UAL.......	Univ. Almería
UCLM	Universidad de Castilla La Mancha
UK	United Kingdom
UL.........	University of London (UK)
UNED	National Univ. for Distance Education (ES)
UENF.....	Universidade Estadual do Norte Fluminense (BRA)
UPLC.....	Ultra performance liquid chromatography
UPS.......	uninterrupted power system
URJC.....	Univ. Rey Juan Carlos
USACH ..	Univ. Santiago de Chile
USC	Univ. Santiago de Compostela
USCS	Solar Concentrating Systems Unit (PSA)
UU	Univ. Ulster
UV	Ultraviolet
VOCs.....	volatile organic compounds
WP........	Work package
WTP o WWTP ...	Wastewater treatment plant
XRD	X-ray diffraction
ZA	South Africa
ZSW	Zentrum für Sonnenenergie und Wasserstoff Forschung (D)
ZW........	Zimbabwe

PLATAFORMA SOLAR DE ALMERÍA
Carretera de Senés s/n
Apartado 22
04200 TABERNAS (Almería), Spain
Switchboard: +34 950 387900
Fax: +34 950 365300
e-mail: info@psa.es