Plataforma Solar de Almería

BIANNUAL REPORT 2008-2009

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

TABLE OF CONTENTS

Message from the Director

Diego Martínez Plaza

If there is one thing that marked 2009 it was the start up of "Plan E" for improvement of our facilities. The impact was so great that we even had to postpone the publication of our annual report for 2008 and combine it with the one for 2009 in this book.

Thanks to this significant injection of 10 M€, we have been able to undertake improvement of our Centre in two respects:

- First, we have been able to acquire the equipment necessary to undertake those new lines of R&D that we had already identified as of interest and almost compulsory in order to continue with cutting-edge R&D. For example, research on the use of molten salt as the storage medium for thermal energy collected in the solar collector fields, or studies for optimizing integration of a solar thermal electric plant and a water desalination plant to make use of the waste heat from the first plant to produce drinking water.
- Second, we were able to undertake important improvements in general infrastructure. Our Centre is already about 30 years old and it takes a constant effort to fight deterioration of buildings, streets and so forth. Apart from that, our staff is growing and so is the number of collaborators, involving a need for more buildings and workspace.

Plan E will be completed in a few months, but the "SolarNOVA" Project, funded by the ERDF, will take over and allow us to continue with the effort to remodel and complete our facilities until December 2012.

Since R.D. 661/2007 regulating the special regime for electricity generation from renewable energies was published, solar thermal electric technology has become a major opportunity for reducing this country's dependence on foreign fuel and reducing greenhouse gas emissions, both of which require a greater effort to improve the current situation in our country.

In spite of some "shocks" that rocked the sector in 2009, construction of a total of 2,339 MW_e commercial plants with the right to a "production premium" was finally authorized. Who would have thought it ten years ago?

In this scenario, our Centre has been consolidated as the international reference for R&D and demonstration in this technology, and the number of requests for collaboration with industry is growing constantly.

In another vein, I would like to say that the traditional collaboration with the DLR enjoys good health, stimulated by new lines of collaboration that have arisen at the demand of the solar industry and that are basically related to characterization of the various components of solar collectors: mirrors, absorbent materials, complete collectors, etc.

Collaboration with other solar R&D centers in Europe has also been reinforced due to the award of the European "SFERA" project (Solar Facilities for the European Research Area). This is an "Integrated Initiative", coordinated by the CIEMAT, in which the DLR, PROMES-CNRS (Odeillo), Paul Scherrer Institute, Institute of Energy Technology Zurich (ETHZ), Weizmann Institute and ENEA also participate. The main purpose of this project is to advance toward a greater coordination of the research efforts made by all of these institutes in the solar field, optimizing resources promoting exchange of scientific personnel and making their test facilities available to the European scientific community.

The last paragraphs of this message have to be to remember, briefly but fondly, Juan Antonio Rubio, Director General of the CIEMAT, recently deceased at the time of writing.

Juan Antonio always gave his support to this Centre, from the beginning, and I know that he always declared to the four winds with all his pride that "*the PSA was the CIEMAT's jewel*". We will continue with our work to demonstrate that he was right.

Rest in peace.

Diego Martínez Plaza
Director of Plataforma Solar de Almería

1 General Presentation

1.1 The PSA as a large solar installation: general information

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

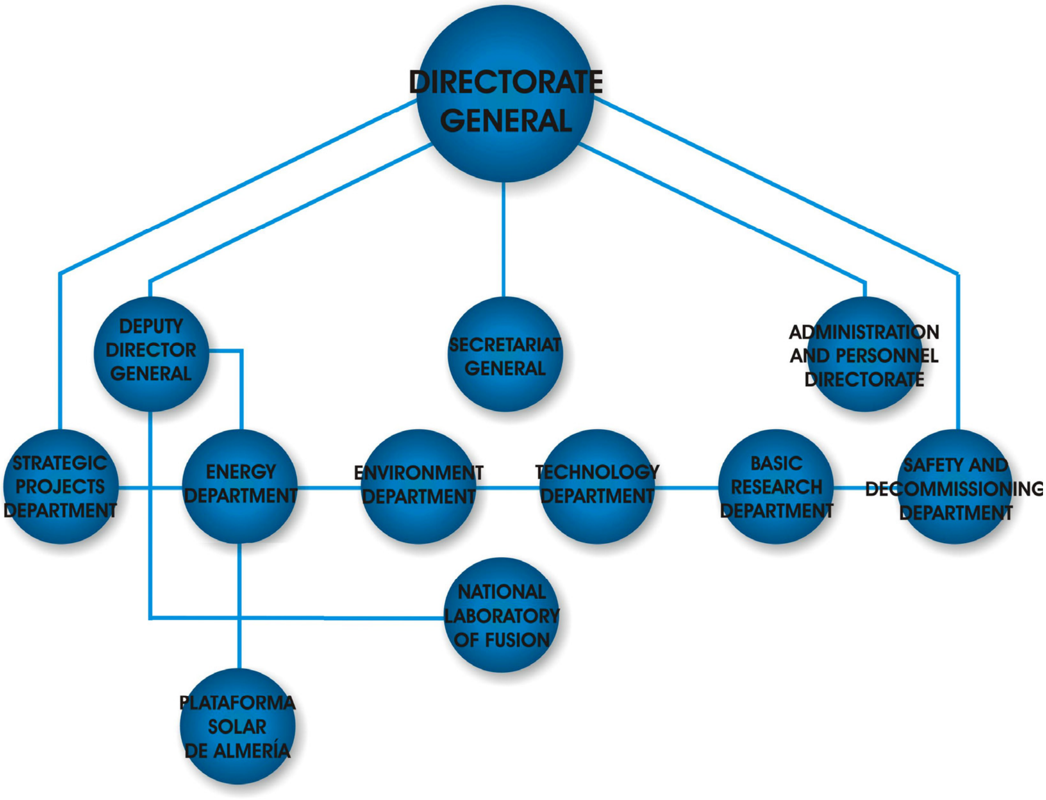


Figure 1.1. Integration of the PSA in the CIEMAT organization

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

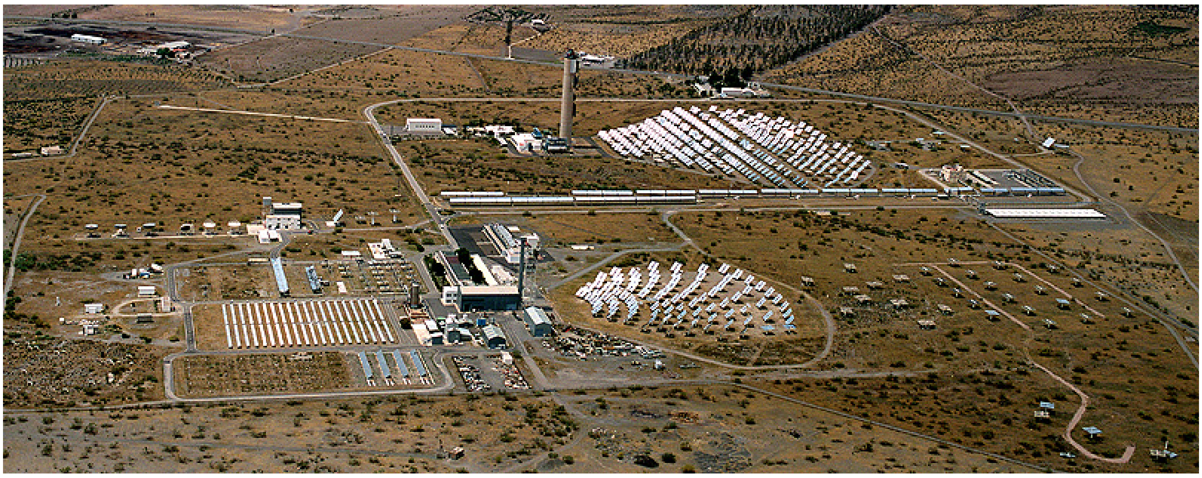


Figure 1.2. Aerial view of the Plataforma Solar de Almería

1.2 Functional Structure

In 2004, research activity at the Plataforma Solar de Almería was 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 2009 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, 17 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.

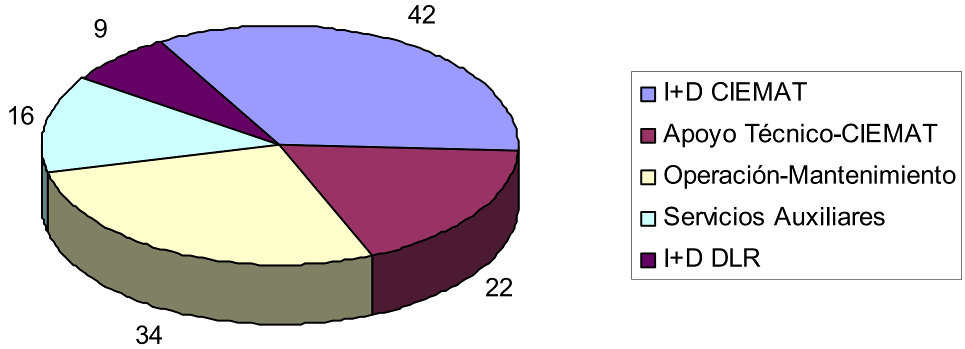


Figure 1.3. Distribution of permanent personnel at the PSA as of December 2009

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 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 CIEMAT contribution was increased during these two years to undertake activities approved under the PSA Infrastructure Improvement Plan 2006-2009. This plan was devoted to major improvements necessary in the main infrastructures, such as buildings, heliostat fields, etc.

The PSA budget in 2008 reached 8.1 million Euros (not including R&D personnel) and in 2009 it was 8.5 million Euros.

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 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.

Figure 1.4. Photo of the 'CIESOL' Bldg.

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.

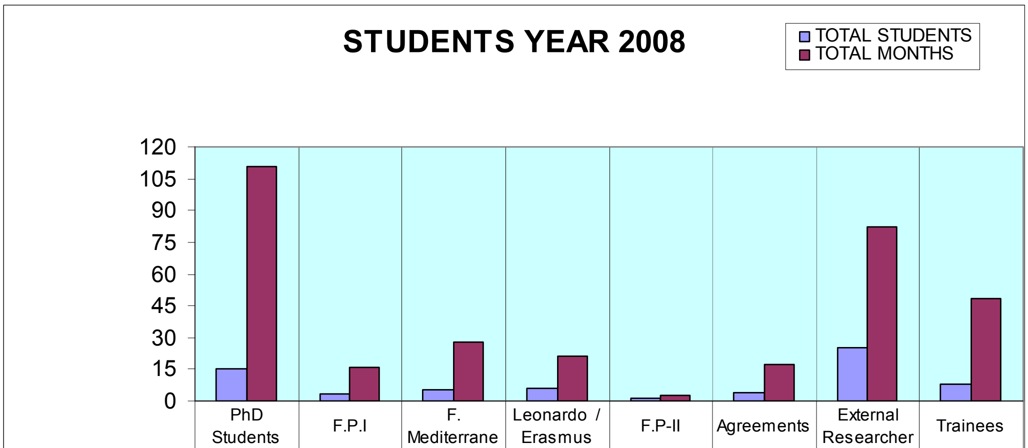
Very recently, ambitious lines of collaboration have been launched with Maghreb countries, specifically, in agreements signed with the Moroccan CNRST and the NEAL (New Energy Algeria) in Algeria.

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.

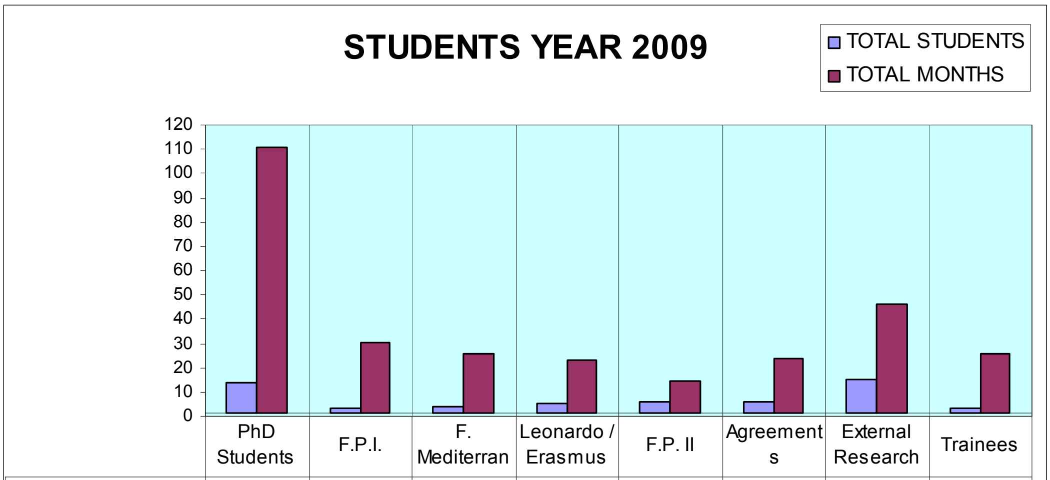
1.5 Training activities

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



	PhD Students	F.P.I	F. Mediterrane	Leonardo / Erasmus	F.P-II	Agreements	External Researcher	Trainees
TOTAL STUDENTS	15	3	5	6	1	4	25	8
TOTAL MONTHS	111	16	28	21,5	2,5	17	82	48,5

Figure 1.5. Fellowships in 2008



	PhD Students	F.P.I.	F. Mediterran	Leonardo / Erasmus	F.P. II	Agreements	External Research	Trainees
TOTAL STUDENTS	14	3	4	5	6	6	15	3
TOTAL MONTHS	110,5	30,5	25,5	23	14,5	23,5	46	26

Figure 1.6. Fellowships in 2009

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 fourth such seminar, organized this time by the PSA, was held from September 10-12, 2008, and from June 22-24, 2009, the fifth one was held in Cologne (Germany).

Figure 1.7. Participants in the semimar held in Almería in September 2008

Figure 1.8. Participants in the seminar in Cologne (Germany) in June 2009

1.6 PSA National Access Activities

In 2005, the National Plan for R&D started a new line of activity for promoting 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 2008, 14 researchers benefited from this program, enjoying a total of 51 weeks of free access to the various PSA test facilities. In 2009 there was somewhat less activity, with 14 researchers, but only 32 weeks of facility access.

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

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

2 Facilities and infrastructure

2.1 General Description of the PSA

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

The PSA is an experimental facility with climate and insolation conditions similar to those in developing solar-belt countries (where the greatest potential for solar energy is found), but with all the advantages of large scientific installations in the most advanced European countries, making it a privileged site for evaluation, demonstration and transfer of solar technologies.

The main test facilities available at the PSA are:

- 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.

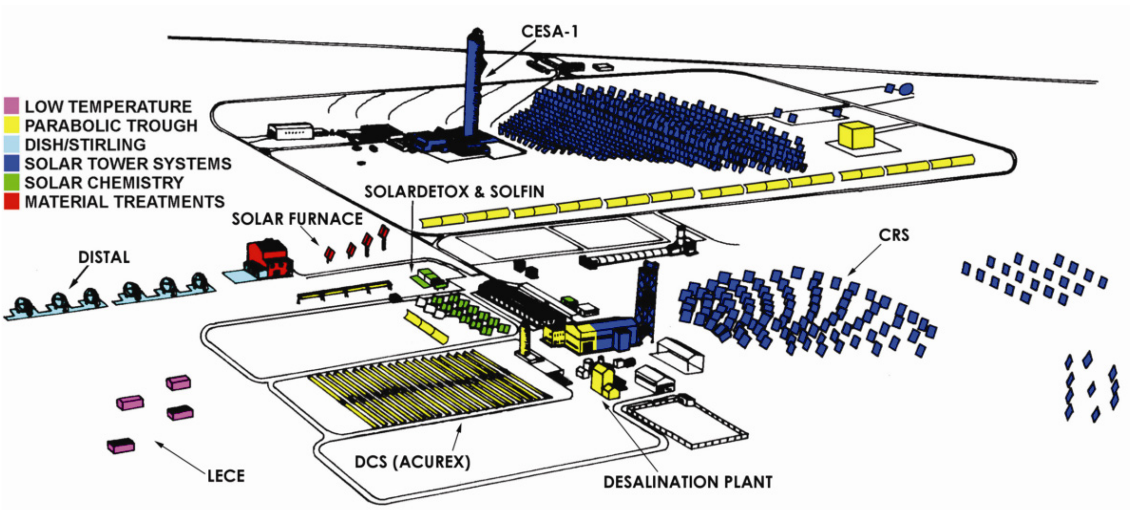


Figure 2.1. Location of the main PSA test facilities

- The parabolic-trough collector system called the "Innovative Fluids Test Loop"
- 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).

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 optimum working condition due to a strategic program of continual mirror-facet replacement and drive mechanism maintenance. To the north of the field are two additional areas used as test platforms for new heliostat prototypes, one located 380 m from the tower and the other 500 away from it. The maximum thermal power delivered by the field onto the receiver aperture is 7 MW at a typical design irradiance of 950 W/m^2, 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 CRS heliostat field has recently been improved 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. 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 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-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 distribution parameters can be calculated.

Figure 2.4. Aerial View of the CRS Facility

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

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

2.3.1 The DISS experimental plant

This facility was erected and put into operation in 1998 for experimenting with direct generation of high-pressure high-temperature (100 bar/400ºC) steam in parabolic-trough collector absorber tubes.

The DISS experimental plant 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. It is not only very suitable for the study and development of control schemes, but also for the study and optimization of the operating procedures that must be implemented in direct steam generation solar fields. Other possible applications of this plant are study of the heat transfer coefficients in horizontal tubes through which the two-phase water/steam flow circulates, and testing of components for parabolic-trough solar collector fields with direct steam generation in the absorber tubes.

The DISS plant consists of two subsystems, the solar field of parabolic-trough collectors and the power block. In the solar field, feed water is preheated, evaporated and converted into superheated steam as it circulates through the absorber tubes of a 665-m-long row of parabolic-trough collectors with a total solar collecting surface of 3,838 m^2. The system can produce a nominal superheated steam flow rate of 1 kg/s.

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

Facility operation is highly flexible and can work at up to 100 bar pressure as needed (usually at 30, 60 or 100 bar) and in any of the three basic direct steam generation modes: Recirculation, Injection and Once-Through, or any combination thereof. Furthermore, it is equipped with all the instrumentation required for complete system monitoring.

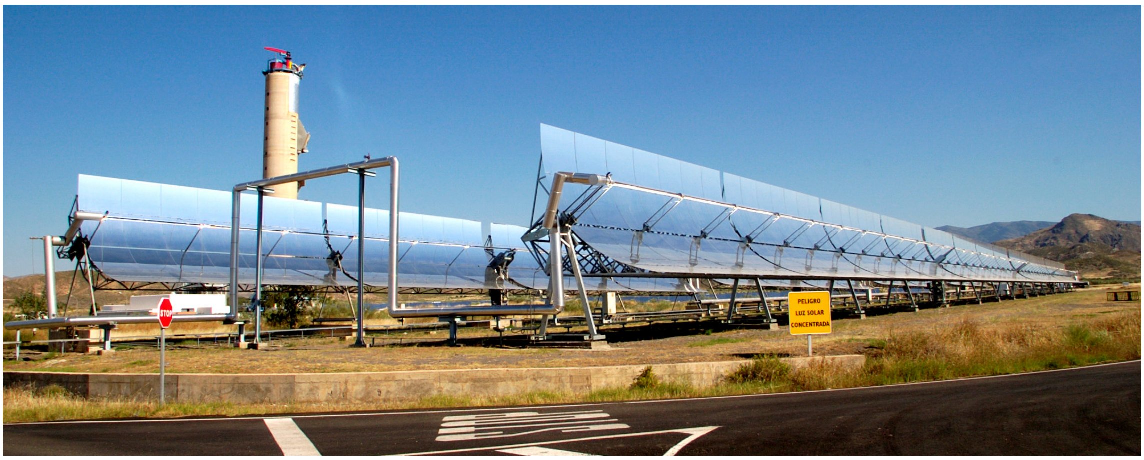


Figure 2.5.View of the DISS plant solar field in operation

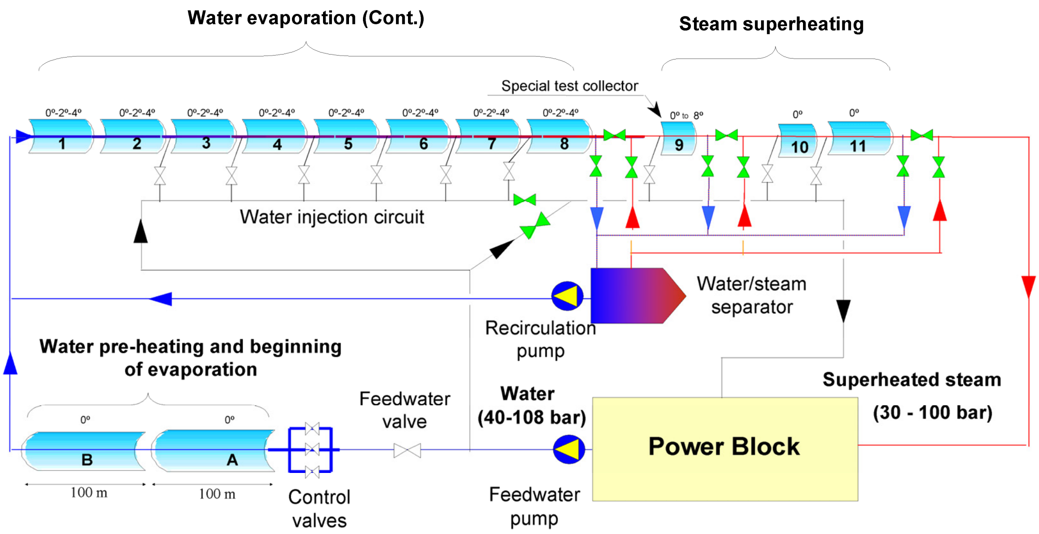


Figure 2.6. Simplified flow diagram of the PSA DISS loop

Figure 2.6 shows a simplified diagram of the DISS loop in which the solar field is shown as one row of 13 parabolic-trough collectors on north-south-oriented rotating axes. The collectors are composed of 12-m-long by 5.76-m-wide reflective parabolic-trough modules. The solar field consists of two parts, the preheating/evaporating section and the superheating section. At the end of the preheating/evaporating section, there is a recirculation pump and a water/steam separator which augments flexibility of system operation. The power block consists of water/steam separators, condensers, chemical dosing system, preheaters, deaerators and water pumps.

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

2.3.2 The HTF Test Loop

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

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

- 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.

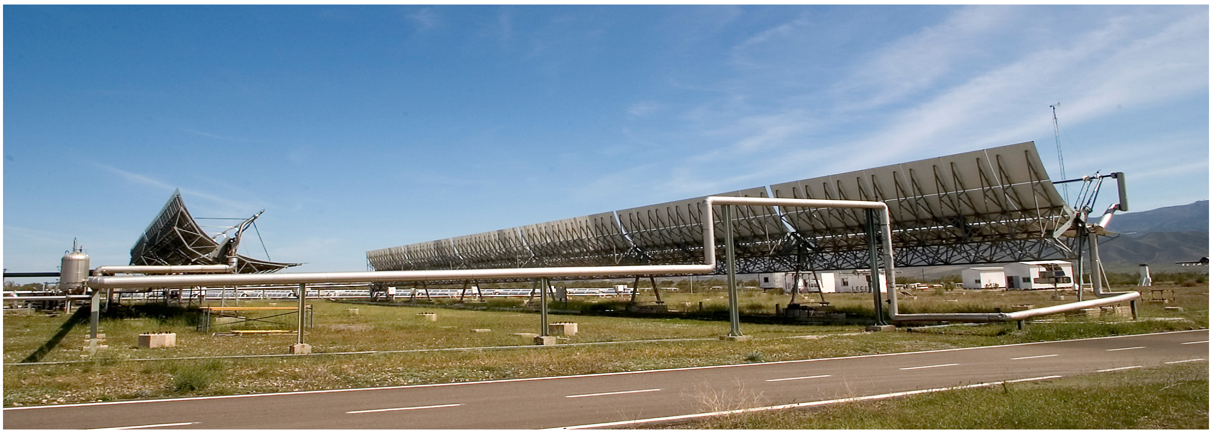


Figure 2.7. General view of the HTF

Parallel to the original HTF solar collector test loop is the EUROtrough collector prototype which was installed later. The EUROtrough collector design was developed by a European consortium which, with the financial aid of the European Commission, designed, built and erected it at the PSA and evaluated it under real conditions. The new parabolic-trough collector is not only apt for solar thermal power plants, but also for other large applications, such as desalination of seawater or industrial process heat in the 150ºC-425ºC range.

At the conclusion of the EUROtrough project, the project partners donated this first prototype to CIEMAT for its operation and maintenance, and it now forms part of the PSA parabolic-trough collector facilities, increasing the system's collecting area has to 685 m^2.

2.3.3 Innovative Fluids Test Loop

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 pos-

Figure 2.8. View of the innovative fluids test loop in operation.

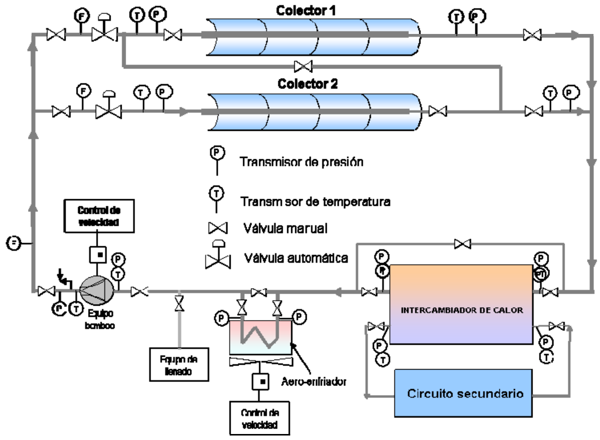


Figure 2.9. Simplified system diagram of the innovative fluids experimental facility.

sible 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 Plant control room. The monitors and central control system for this loop are in the DISS Plant control room. The plant was erected from June 2006 to October 2007, and commissioning activities began immediately thereafter.

The facility, which is prepared to work at pressures and temperatures of up to 100 bar and 400ºC, 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.
- 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.

2.4 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 FRESDEMO 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 on 25 parallel rows spanning the length of the loop.

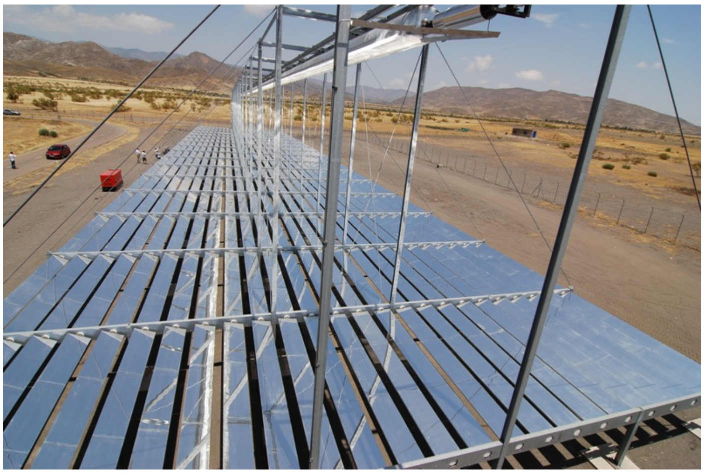


Figure 2.10. Photo of the MAN linear Fresnel demo collector erected on the Plataforma Solar de Almería (PSA).

The collector loop is designed for direct steam generation at a maximum pressure of 100 bar and maximum temperature of 450ºC.

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.

2.5 Dish/Stirling Systems: DISTAL and EUROdish

2.5.1 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.

2.5.2 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 2.11. 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.

2.5.3 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.

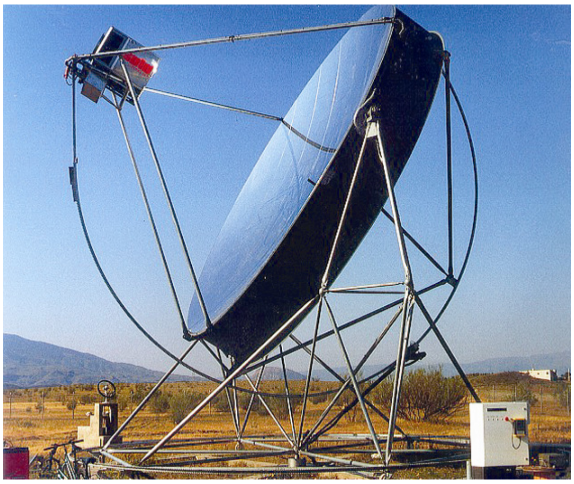


Figure 2.12. DISTAL II unit

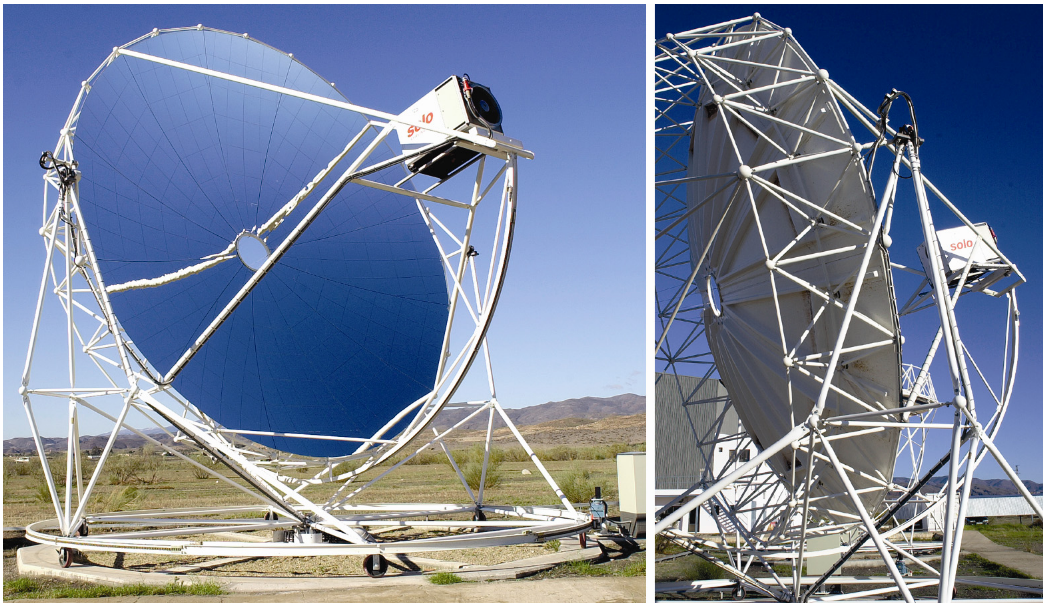


Figure 2.13. Front and back views of the EUROdishes.

2.5.4 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.
- 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.

2.6 Solar Furnace

2.6.1 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.

2.6.2 Components

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

The PSA solar furnace heliostat is made up of 28 3-mm-thick flat silvered facets and has a total surface of 120 m^2. The facets are made of 2^{nd}-surface mirrors which are silvered on the back, which have a 90% reflectivity and are canted together so they form a continuous flat surface reflecting the sunbeams but not concentrating them.

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

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

It is composed of 30 louvers arranged in two columns of 15. In closed position the louvers form a 55º angle to the horizontal and 0º when open.

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

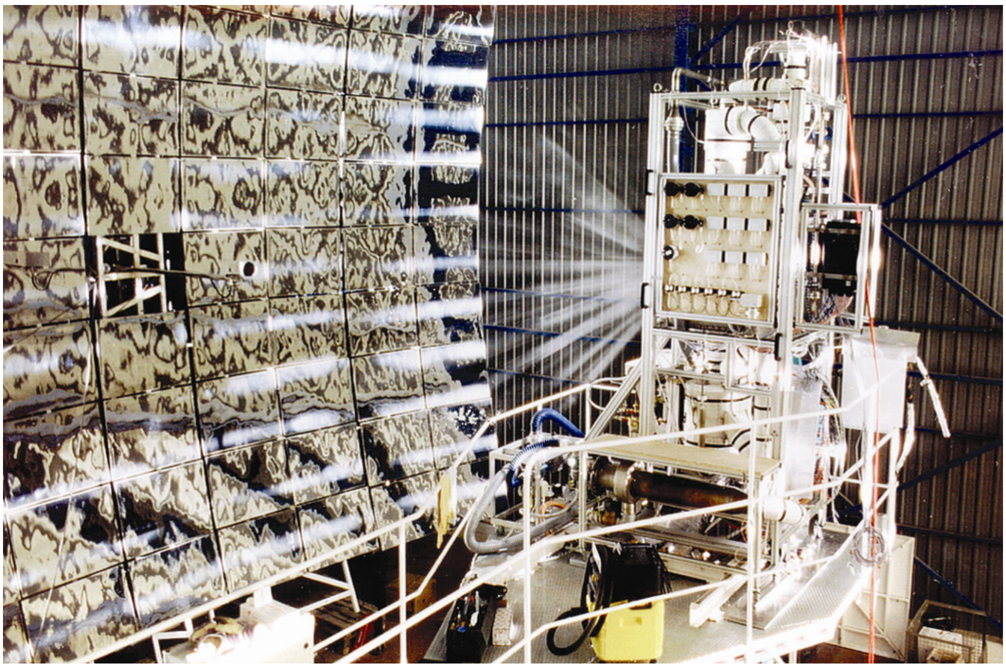


Figure 2.14. Solar Furnace: Concentrator (left) and receiver in operation at the focus (right).

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.

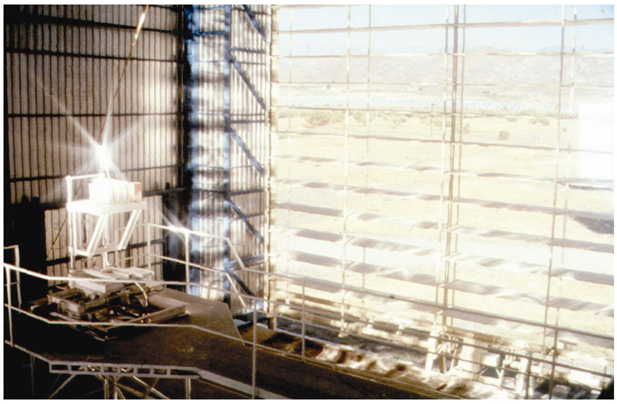


Figure 2.15. The focus and the test table, on the left. On the right, the completely open shutter allows the rays from the heliostats outside to come in.

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, 3000 kW/m^2, total power, 58 kW and focal diameter, 23 cm [Neumann, 1994].

2.6.3 Materials Lab

The Plataforma Solar de Almería, 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.

Figure 2.16. View of the PSA Materials laboratory

The lab's equipment is currently as listed below:

- **Leyca DMI 5000 optical microscope** with Leyca-IM50 image acquisition system and motorized table.
- **Olympus optical microscope** Union MC 85647.
- **Struers micro durometer** Duramin HMV-2
- **Manual durometer**
- **Surface Finish Measuring Unit** ZEISS Surfcom 480 with data processor.
- **Grinder** Remet SM1000
- **Automatic cutoff machine** Struers Secotom
- **Manual cutoff machine** Remet TR60
- **Pelleter** 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 between 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**

2.7 Detoxification and Disinfection Facilities

The PTC (Parabolic-Trough Collector) photochemical pilot plant is presently configured is made up of 1 parabolic trough solar collector (32 m^2) 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.

There are several CPC plants installed at the PSA. The oldest (1994) consists of three 3-m^2 modules tilted 37º from the horizon. The total system volume is about 250 L and the absorber tube holds 108 L (illuminated volume). In 2002, a new 15-m^2 collector for experiments of up to 300 L was installed. It also has small twin 3.08-m^2 prototypes with a 40-L total volume, 22 L of which is irradiated, for parallel experiments. This facility was recently (May 2007) renovated, and the CPCs were replaced with new collectors which can be covered with Plexiglass transparent to Solar-UV, making it possible to work at higher temperatures in photo-Fenton treatments. They may be removed to compare the effect of temperature in an experiment with and without the cover.

These new CPCs can also be mounted and dismounted more easily than the old collectors and they have a wider surface per module, so that only two modules are necessary for a 3.08-m^2 surface, when previously three were required. Since 2004, a new CPC system, with 50-mm-diameter photoreactor, more suitable for photo-Fenton applications, with tank and recirculation pump (75 L), has been hooked up to a 150-L biological reactor based on fixed biomass on an inert matrix, and 50-L ozonization system with ozone production of up to 15 g O_3/h. All of it is monitored (pH, T, ORP, O_2, flow rate, H_2O_2,0_3) by computer. Connected to these photoreactors is The PSA Water Detoxification and Disinfection Group biological water treatment system (Figure 2.17). This biological system consists of three tanks: a 165-L conical tank for conditioning the waste water to be treated, a 100-L conical recirculation tank and

Figure 2.17. Biological system underneath one of the CPC photoreactors

Figure 2.18. Disinfection CPC photoreactors installed in November 2008.

a 170-L flat-bottom fixed-bed 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 is automatically controlled by dose pumps and dissolved oxygen is also automatically controlled.

There are also several prototype collectors for water disinfection applications (0). 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 was installed (Figure 2.18), 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 (1500 mm long, 2.5 mm thick and 50 mm inner dia.). In this system, 45 L of the 60 L total volume are irradiated. The irradiated collector surface is 4.5 m^2. The water is circulated through the tubes to a 60-L tank by a centrifuge pump. The reactor is completed with a pH sensor and another for dissolved oxygen inserted in the piping and connected to a Crison MULTI44 controller with two relays for output for each variable and transmission of 4-20mA input signals for automatic 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. The main difficulty in the use of TiO_2 suspensions is the need to separate the catalyst particles after treatment.

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.

2.8 PSA Analysis Lab

The PSA solar chemistry lab is a 75-m^2 building designed to contain all of the conventional laboratory equipment: work benches, gas extraction hood, storage space for small amounts of chemicals, centralized gas distribution system, UPS, safety systems (extinguishers, shower, eyewash, etc.) precision scales, ultrapure water system, ultrasonic bath, thermostatic bath, centrifuge vacuum distillation system, and many other systems normally used in a chemistry lab. The following analytical equipment is also available for environmental chemistry: 2 liquid chromatographs (quaternary pump with diode array detector and 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 anions, and another configured 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) a UV-Visible spectrophotometer, a solar simulator with xenon lamp, a respirometer (for biodegradability analysis, COD fractionation, nitrification and denitrification tests, etc.) and COD, BOD and toxicity analyses (*Vibro fischeri* and active sludge from WWTP by respirometry). All of these systems are computerized and integrated in a complete information network. For microbiological and catalyst samples from solar disinfection tests, since 2006, a Scanning Electron Microscope (SEM) is also available for analysis of microbiological samples and catalysts used in solar disinfection and detoxification tests. For the preparation of these samples, the system is completed with a metal coater and critical point dryer. There is also a biosafety level-2 microbiology lab with 3 work stations, each with the corresponding microbiological safety cabinet, autoclave, 2 incubators, 2 fluorescence and phase contrast combination optical microscopes with digital camera attachment, spectrophotometer, turbidimeter, microcentrifuge and pH, dissolved oxygen and conductivity multisensor.

2.9 Sol-14 Solar MED-Distillation Desalination Facility

This facility is composed of the following subsystems:

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

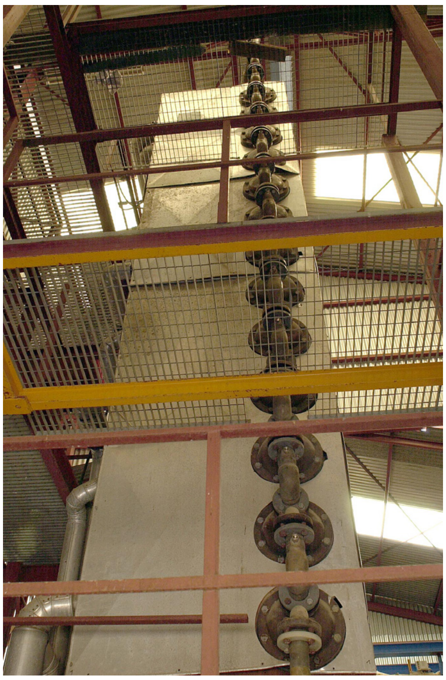


Figure 2.19. The Sol-14 MED plant

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 pressure storage tanks in an open loop. The thermal storage system consists of two water tanks connected to each other for a total storage capacity of 24 m^3. This volume allows the operation sufficient autonomy for the backup system to reach nominal operating conditions.

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

2.10 Membrane Distillation Module Test Platform

This new facility was erected in 2007 in the framework of the European MEDESOL project. The MEDESOL-1 project was designed to analyze a multistage 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 Air Gap Membrane Distillation (AGMD: One of the possible membrane distillation technology configurations) membrane distillation modules manufactured by the Keppel Seghers Group (www.keppelseghers.com). Each one of the modules has a distillation production of 5 to 15 L h^{-1} m^{-2} depending on the operating conditions.

Figure 2.20. View of the MD module test plant

The heat exchanger is specially treated to support the action of hot salty water. The exchanger plates have been treated with a special film, developed

Figure 2.21. Characterized membrane distillation modules in the plant; at the left: Scarab AB module; at the right: Keppel Seghers module.

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[1]) 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 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 2.22 shows a diagram of the facility.

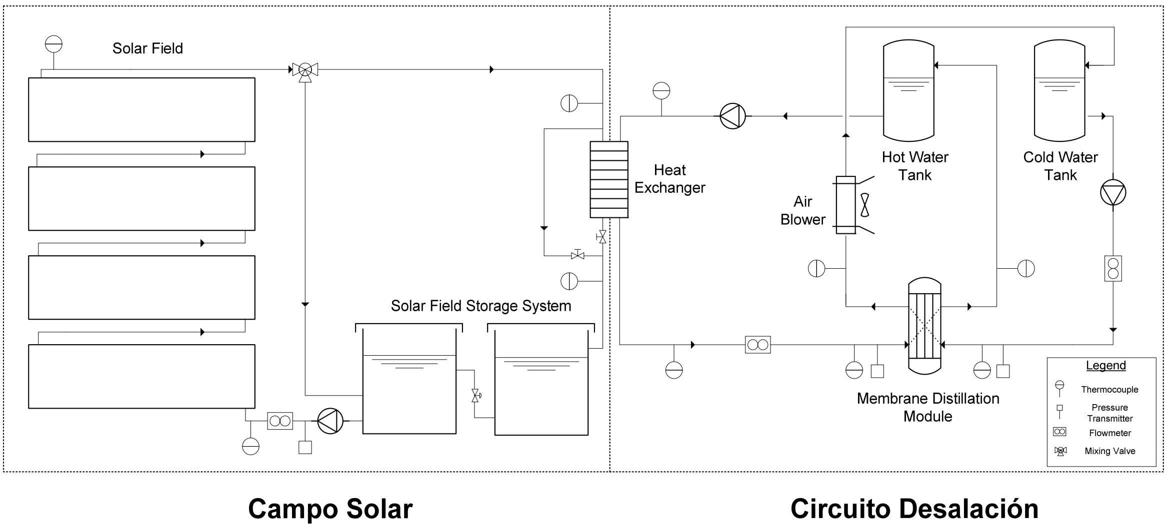


Figure 2.22. DM plant flow diagram

[1] 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.

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.

2.11 Solar ORC Facility

This installation, built in 2009, consists of a prototype organic Rankine cycle generator manufactured by the Swiss company Eneftech. The generator has a rated electrical power of 5 kW, and operates with a scroll turbine and Solkatherm SES36 heat transfer fluid. The system requires thermal input power of 25 to 30 kW, with evaporator inlet temperature of around 200ºC. It is a unique prototype for several reasons: (i) the turbine, a Scroll expander, is specially designed for this type of machine, instead of operating one of the turbines usually used as compressors in cooling machines in reverse; (ii) the cycle inlet temperature is higher than other similar ORC facilities, and therefore, the organic fluid used is different.

Figure 2.23. Solar ORC experimental facility

The machine is connected to the thermal oil tank in the Acurex parabolic-trough collector solar field by a very simple circuit controlled by an automatic control valve. As the connection to the solar field is indirect, input thermal power conditions can be stabilized. Inside the machine, the heated fluid is evaporated in the evaporator and the steam enters the expander to activate generator rotation. When the outgoing steam is exhausted, it is cooled and condenses in the condenser to close the cycle with the pump, which returns the compressed liquid to the evaporator. The machine also has an internal reheater, but requires a cooler to keep the condenser cold. This is done by a water circuit which uses water from the fire extinguishing system tank next to it. The three-phase electricity generated, once measured and the wave analyzed, is dissipated through a system of resistances that is also cooled by the water circuit.

2.12 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.

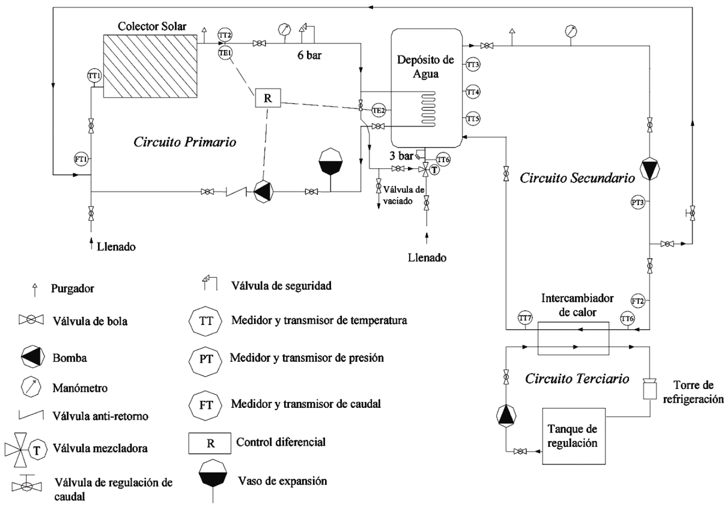


Figure 2.24. General layout of the stationary solar collector test platform

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.

2.13 Environmental Applications of Solar Radiation in Air

The Environmental Applications of Solar Radiation in Air Group laboratories are equipped for synthesizing photocatalysts (dip-coating thin-film deposition system, digestion pumps for hydrothermal synthesis, heaters, kilns, centrifuges, water distillers, etc.) for the evaluation and optimization of photocatalytic systems for the detoxification and disinfection of air.

They have a multitude of laboratory reactors of different sizes and designs that employ solar radiation, artificial radiation sources of different types, or combinations of both, alternately or simultaneously. The solar reactors are lo-

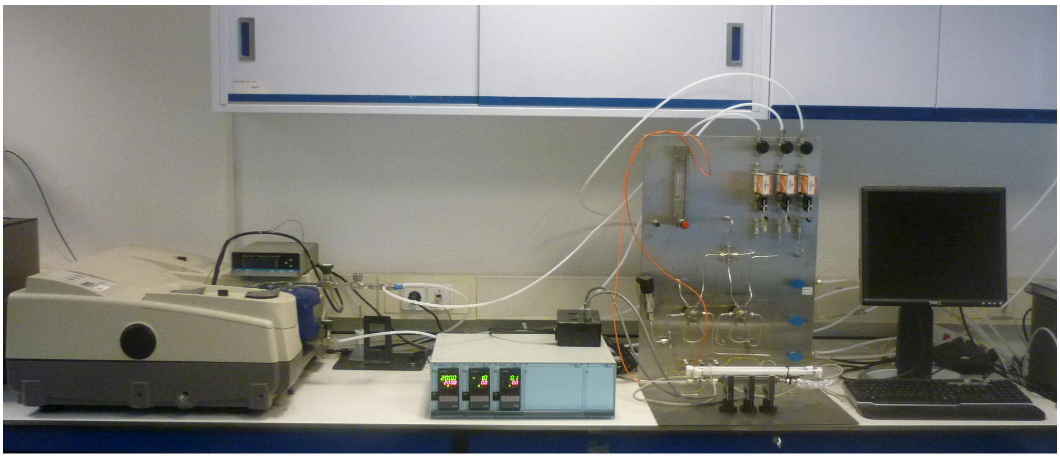


Figure 2.25. Photocatalysis test bench with gas analyzer and FT-IR spectrometer

cated immediately above the laboratory on the roof of the building, enabling their connection with the analytical equipment and its continuous automatic control.

For the chemical analysis of gas and/or air streams in interiors, there are a gas microchromatograph with thermal conductivity detector (microGC), two chromatographs with FID and TCD, automated thermal desorption gas chromatography mass spectrometry (ATD-GC-MS) and FT-IR spectrometer provided with a multiple reflection gas cell. Other accessories of the FIT-IR spectrometer are ATR and DRIFTS cells connected to a reactor with three windows for analyzing what is occurring on the photocatalyst surface during operation

Figure 2.26. Hybrid solar/lamp reactor with CPC

For the biological characterization of air, there is a separate laboratory equipped with a biological safety cabinet with vertical laminar flow for working with microorganisms and preparing culture media under sterile conditions, an autoclave for sterilizing media and laboratory materials, a colony counter with camera connected to a computer, 63X magnifying glass will optic fiber illumination and camera, cooled centrifuge, two heaters for incubation and two refrigerators with freezer for sample conservation. There are also single and two-stage air impacters for sampling and follow-up of the photolytic air disinfection capability.

Figure 2.27. ATD-GC-MS for analysis of air in interiors

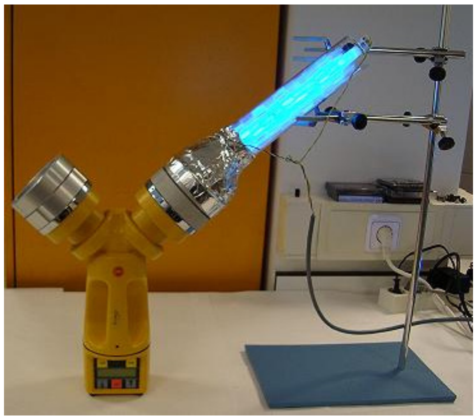


Figure 2.28. Air impacter for biological sampling connected to a photocatalytic disinfection reactor

2.14 *Accelerated ageing and durability materials test laboratory.*

Solar thermal power plants are at the beginning of their mass commercial deployment. One of the greatest challenges of the technology consists of decreasing as much as possible the risk of its main components, such as the solar receiver. These components are subjected to high solar fluxes of up to

1200 k"/m^2, and temperatures from 300º to 1200ºC depending on the heat transfer fluid. The greatest technological risk in this type of plant is associated with selection of the materials the receiver is made of, especially concerning their durability under real operating conditions, without losing sight of the 20-25 year life cycle of this type of plant.

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

The CIEMAT is therefore installing an accelerated ageing and materials laboratory to cover a demand that is beginning to be important in the field of solar concentrating systems.

The accelerated ageing laboratory is divided into facilities located at the Plataforma Solar and in CIEMAT-Moncloa and has the following capacities:

- A proper laboratory equipped with the instrumentation necessary for thermal cycling: two kilns, a high-temperature furnace, a weathering chamber, an air-cooled volumetric receiver test loop and the associated instrumentation; and analysis of materials: optical and electronic microscopes, microdurometer, thermal scale, X-ray diffraction analysis, etc. Construction on this laboratory began in 2009 and is due to begin operation in the second semester of 2010.
- 4 parabolic dishes (Figure 2.29), three are DISTAL-II with a total thermal power of 50 MW and two-axis tracking; and 1 is DISTAL-I type with a total thermal power of 40 MW and polar one-axis tracking. The Stirling motors on the 4 dishes have been replaced by different types of test platforms for subjecting materials or scaled receiver prototypes to highly concentrated solar energy for testing. These platforms cover a wide variety of applications, from testing materials to air-cooled volumetric receivers (metal or ceramic) scaled receiver prototypes with or without heat transfer fluid, etc.
- A 4-kW solar simulator installed at CIEMAT-Moncloa (Figure 2.30) made up

Figure 2.29. General view of parabolic dishes used for the ageing and durability laboratory.

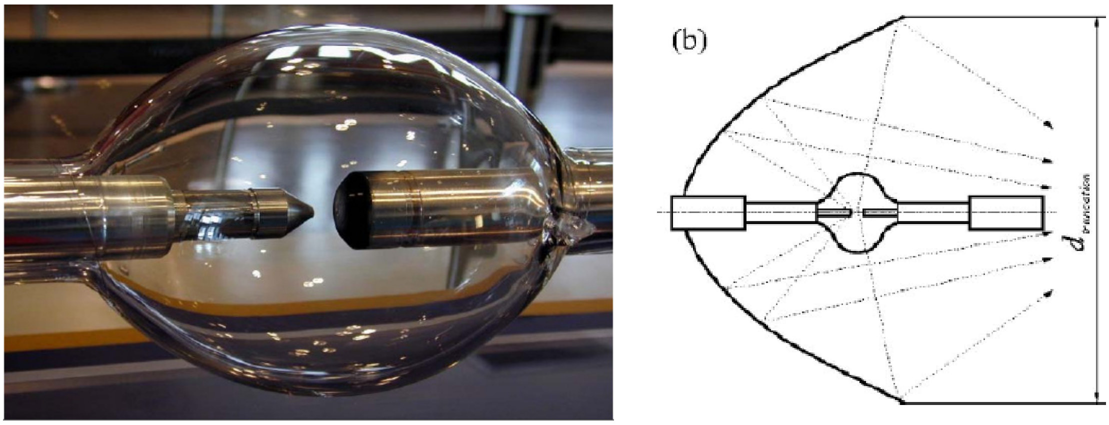


Figure 2.30. Xenon lamp used in the solar simulator and configuration of the lamp and concentrator.

of a xenon lamp and a parabolic concentrator which can reach fluxes of up to 1400 kW/m^2.

2.15 Radiometry Laboratory

The PSA Radiometry Laboratory was born of the need to verify important radiometric magnitude measurements associated with solar concentration. These magnitudes are solar irradiance ("flux" in the solar concentrating jargon) and the surface temperature of materials (IR detection).

Different measurement systems are used at the PSA for high solar irradiances on large surfaces. In these systems, the basic component is the radiometer, which depends for its correct use on the measurement of the concentrated solar radiation power incident on the aperture of the solar receiver. The measurement of this magnitude is basic to determining the efficiency of the receiver prototypes evaluated at the PSA and for defining future central receiver solar power plants.

A black body offers the possibility of being employed as a source of thermal radiation for reference and calibration of IR devices (infrared cameras and pyrometers) which use thermal radiation as a means of determining the temperature on a given surface. It is also used as an irradiance reference for calibrating radiometers.

The Radiometry Laboratory has three black bodies as references for cali-

Figure 2.31. Radiometry Laboratory

brating 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.

2.16 Other facilities

2.16.1 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 2.32. 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:

1) ***Measurement instruments***. The PSA meteorological station instruments are in the highest range of solar radiation measurement. All the radiation sensors are ventilated and heated, and have a temperature measurement sensor. This equipment provides the best information on solar radiation

and more general atmospheric variables, and can be used for filtering input data and validating spectral models. They are used for:

- Measurement of the terrestrial radiation balance. Incoming and outgoing shortwave and long-wave radiation is measured at 30 m
- Solar radiation component characterization: (direct and diffuse) and UV
- Vertical wind profile: wind speed and direction at 2, 10 and 30 m
- Vertical temperature and humidity profile at 2 and 10 m
- Miscellaneous weather information: rain gauge, barometer and psychrometer

2) ***The* Spectroradiometer** is so different that it must be considered an independent installation. It is a prototype developed to CIEMAT specifications by *Instrument Systems*. This equipment, based on the SP320D, which incorporates a photomultiplier and a lead sulfur detector, records the spectral distribution of the solar radiation over its whole spectral range (from 200 to 2500 nm), compared to the majority of such equipment which works only for a part of the spectrum (generally visible or ultraviolet). The basic equipment is connected to a switch in such a way that it can work with three alternating probes, which are arranged in a solar tracker to record the global, direct and diffuse solar radiation, respectively. Although it is configurable, the equipment has been programmed to record a spectrum (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.

Figure 2.33. Spectroradiometer probes for measuring global and diffuse radiation installed in the solar tracker

Figure 2.34. Spectroradiometer detector with three-probe connector switch

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

The database 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

Figure 2.35. User login for access to solar radiation information.

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.

2.16.2 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.

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

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

Figure 2.36. New Spectral Calibration Laboratory adjacent to the CESA-1 building

Figure 2.37. Views of the LECE: Cells, reference buildings and solar chimney

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

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

2.16.4 ARFRISOL Building

The PSA ‘ARFRISOL’ Building 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 Project is to demonstrate that it is possible to save from 80 to 90% of conventional energy through proper application of active and passive solar technologies, by adapting building design to its surroundings and climate. There are five buildings in the PSE- ARFRISOL Project, built in different climates within Spanish territory: Almería (2), Madrid, Soria and Asturias.

Figure 2.38. ARFRISOL Building

The PSA building includes the following "active" measures:

- 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 photovoltaics 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 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.

2.17 Plan 'E'

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.

By decision of March 26, 2009, the Secretary of State for Research transferred to the CIEMAT 10 million Euros for the construction of new infrastructures associated with the PSA. This decision was revised on July 27th setting September 30, 2010 as the deadline for execution of the proposals approved.

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

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

2.17.1 Actions Related to the Experimental Facilities

Prototype for Development of a Parabolic-Trough Collector (PTC) without Ball Bearings

The current configuration of the PTC loops requires connection of the collector modules using ball bearings. This type of joint deteriorates under very adverse conditions, high temperatures and pressures, and frequent very severe transients during operation. It is therefore necessary to develop new solutions for these connections between modules, in order to make use of the advanced technology at higher working temperatures and pressures and to improve the thermodynamic performance of the process.

Furthermore, the fact that these higher temperatures and pressures will be achieved through the use of working fluids different from the usual synthetic thermal oil, such as superheated steam (PSA DISS loop) or other more innovative fluids such as CO_2 OR N_2. Obviously, the use of gases involves potential problems with leaks in a component such as the ball bearing between modules in the solar field.

It is intended then, to study the feasibility of a collector in which the ducts where the working fluid circulates through the focal line remains as firm and stable in space as possible, while allowing the reflector to move as necessary for solar tracking.

New Control and Data Acquisition System for the DISS Direct Steam Generation Test Loop.

The DISS experimental solar plant is the first and only plant in operation in the world devoted to research in Direct Steam Generation in parabolic-trough collectors under real solar conditions.

This system went into operation in 1999 and has been a test bench for studies undertaken in the framework of the international DISS, INDITEP and DISTOR Projects, funded by the European Union and in which mostly German and Spanish research centers and industry.

The studies done in this system are of different types: heat transfer and pressure drops with the dual phase flow in the receiver tubes of the solar collectors, process control with different solar field configurations, thermal behavior of the solar field components under high pressure and temperature conditions (up to 100 bar and 400ºC), etc.

As the facility occupies a large area (the collector loop is 700 m long), and it is an experimental plant in which process monitoring is fundamental in a multitude of different points in the installation, many more than in a commercial plant, the control and data acquisition system consists of a series of cabinets distributed around the solar field. Each cabinet contains input/output cards connected to the sensors (thermocouples, flow meters, pressure transmitters, level meters, solar radiation sensors, etc.) and equipment (pumps, automatic valves, collector solar tracking systems, etc.) installed in the experimental plant receiving up to 450 different signals from the field.

This system was installed in 1998 and is currently subject to a high rate of failures, which makes normal progress of tests planned in the plant impossible. Therefore, the hardware and software of the data acquisition and control system is being completely renovated.

New CSP Plant Molten-Salt Thermal Storage Technology Laboratory

An experimental molten-salt thermal-storage system for solar thermal power plants that use molten salt as the energy storage medium is being developed for research and development under real operating conditions.

Flexibility is a critical factor in designing the system required, not only concerning the type of energy stored (sensible heat vs. latent heat), but capacity for:

- Testing hydraulic components: valves, pumps, materials, etc.
- Study and optimization of specific components, such as heat exchangers, design concepts, etc.
- Optimization and testing of auxiliary heat systems
- Testing of instrumentation necessary to control molten salt systems
- Study and optimization of control, operating and maintenance strategies for molten salt systems

The system will be connected to the DISS loop which will supply steam under real solar operating conditions.

In addition to the system described above, a laboratory with equipment for thermochemical characterization of the salt is going to be set up for evaluating the quality of the salt used in the system above, the point of phase change of the salt, and hysteresis at those points, important for defining the optimal charge-discharge process of the storage system, its thermochemical stability, etc.

Scientific Equipment for the New Line of International Collaboration in Characterization and Certification of Solar Receivers (CIEMAT-DLR "Certification")

A current problem for the solar thermal power industry is the lack of standardization and certified solar components on the market, so the investor cannot make a satisfactory decision based on the properties of one product compared to another.

This problem may slow down commercial deployment and even lead to risk situations in existing plants.

From our position as a worldwide center of reference for this technology, it

Figure 2.39. Foundations of the new 'Kontas' installation for characterization of PTCs

Figure 2.40. The new solar furnace under construction

is our obligation to launch the initiatives necessary to mitigate this problem. At this time, there are several concrete initiatives underway, specifically, in the framework of Spanish-German cooperation, CIEMAT and DLR are going to erect/adapt some test facilities for the QUARZ-CSP Project.

This project involves the need for test facilities and evaluation procedures of the following CSP components:

- Complete parabolic-trough collectors: KONTAS experimental rotating module
- Adaptation of two DISTAL-II parabolic dishes for accelerated aging of absorbent materials for solar receivers.
- Photogrammetric characterization of mirrors

These new facilities will be jointly managed by both institutions within this international initiative. One of the goals pursued is to acquire certification capacity for certain components, backed by the international recognition of CIEMAT and DLR in this field.

New Solar Furnace for Very High Concentration for High Temperature Thermochemical Processes (e.g. Hydrogen Production)

Construction has begun on a new facility to house the PSA-CIEMAT's 98.5-m^2 McDonnel Douglas concentrator able to concentrate incident radiation 3000 times with a power of 68ºkW. It will be used as a test facility for prototypes generating solar heat for industrial processes and high temperature waste treatment (over 1000ºC).

This concentrator makes it possible to develop pre-industrial prototypes for generating solar process heat, a new line begun at the PSA-CIEMAT four years ago, on the basis of different reactor models show their feasibility of the industrial processes studied. Results show that concentrated solar energy can be effectively applied to high-temperature industrial processes, such as those related to the ceramics and metallurgy industries or elimination of persistent toxic waste.

New Cogeneration Facility for Studying Combination of Solar Thermal Power and Desalination by Making Use of Waste Heat

This initiative includes acquisition of the equipment necessary to study the technical possibilities of this combination.

The CIEMAT is the entity that represents Spain in the International Energy Agency Implementing Agreement called SolarPACES (Solar Power and Chemical Energy Systems). This is a forum where the international scientific community meets regularly to exchange information and even to launch new joint research tasks in the field of concentrated solar energy.

In view of the growing interest in this type of cogeneration applications, in 2007, a new SolarPACES task called “Solar Energy and Water Processes and Applications” was created, which is going to be devoted to concentrating, spreading and promoting research and demonstration activities related to the application of solar energy to water processes and technologies. This new task (SolarPACES Task VI), is led by the head of the PSA Environmental Applications Unit (which co-ordinates it), and will have an initial duration of five years starting on January 1, 2008.

The construction of this new experimental infrastructure will make Spain the unmistakable leader in the technological development of this type of solar application.

New experimental solar facility for applications de polygeneration and process heat

A small experimental field of mid-temperature parabolic-trough collectors is going to be added to the current solar desalination facilities (made up of the SOL-14 multi-effect distillation plant, double effect heat pump, membrane distillation test platform, the Organic Rankine Cycle facility and the above mentioned CSP+D test bench).

Figure 2.41. New collectors for generating saturated steam

This field of 8 *Polytrough 1200* collectors manufactured by the Australian company NEP Solar Pty Ltd., has a total aperture area of 230 m^2 and will use Therminol 55 thermal oil as the working fluid at a maximum temperature of 220ºC.

- Aperture: 1.2 m
- Module length: 24 m
- Height: 1.58 m
- Focal distance: 0.65 m
- Module weight: 900 kg (32 kg/m^2 aperture area)

This facility will be used for solar process heat for polygeneration applications, with solar desalination holding a primary position among them.

New Solar Water Detoxification, Desalination and Disinfection Scientific Instrumentation and Research Facilities

New laboratory equipment is being acquired for this line of work in the Environmental Applications of Solar Energy Unit.

2.17.2 ACTION RELATED TO GENERAL INFRASTRUCTURE AND CIVIL ENGINEERING WORK

Transformation of an old Office Building into a Laboratory Building

The old technical and scientific personnel office building (SSPS Bldg.) is being rehabilitated. Rehabilitation includes relayout of its dependencies for use as a laboratory building. The building where the laboratories are currently located will be torn down and the area will be reurbanized.

Figure 2.42. Rehabilitation of the old office building for laboratories

URBANIZATION AND LANDSCAPING OF THE GROUNDS

The PSA was originally conceived as a solar thermal power technology demonstration project with a limited lifetime. Because of the investments made in the test facilities, the rest of the infrastructures were only temporary, and over the years have required a continued investment program to provide the center

Figure 2.43. Paving roads on the PSA grounds

with an image in tone with its prestige.

The present investment would conclude the urbanization and landscaping work still needed.

NEW TECHNICAL BUILDING FOR LIBRARY AND COMPUTATION CENTER

With the planned increase in stable CIEMAT staff, as well as temporary personnel (visiting scientists and students) the Center needs a technical services building to provide the necessary educational resources and research support.

This building will receive the current PSA library collection, which is now housed in the old SSPS building. In addition, it will have a "computation center" where high-level computational resources will be located for use by all of the PSA scientific community.

Finally, although no less important, this building will have a classroom with a seating capacity of 30 for seminars and master's courses, continuing the trend to higher demand for training activities by PSA scientists.

Figure 2.44. New library and computation center building under construction

3 Solar Concentrating Systems Unit

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3.1 Introduction

The Solar Concentrating Systems Unit (USCS) is one of the Plataforma Solar de Almería's two R&D research units. Its staff is distributed between the CIEMAT facilities in Almería and Madrid. The main purpose of this unit is to promote and contribute to the development of solar radiation concentrating systems, for both power generation and 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 2008-2009 followed four master lines that are defined as goals:

- Develop new solar concentrating system components with an improved quality/price ratio.
- Develop simulation and characterization tools for this type of solar system.

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- Encourage and promote cutting-edge action in solar concentrating technologies, opening the way to medium and long-term technology improvement, and
- Facilitate development and consolidation of a national solar concentrating system industry through technical-scientific consulting and technology transfer.

The intense promotional and development activity of solar thermal power plants triggered by Royal Decree 661/2007 continued in 2008 and 2009. During the first half of 2008, over 240 solar thermal power plant projects had deposited bank guarantees for a total associated electrical power of over 10 GW, while at the end of 2009, a total of 183 MW_e were officially already in operation in Spain, 1168 MW_e were under construction, 9513 MW_e were in different stages of promotion, and a total of 14730 MW_e had already deposited their compulsory bank guarantees.

This great interest of business in solar thermal power plants propelled both internal R&D projects by the companies themselves and the search for scientific-technical assistance in public R&D centers. This motivated a large number of companies to come to the PSA during 2008 and 2009 for consulting and information. During these two years, over forty companies and entities interested in solar thermal power plant technologies have met with our team at the PSA, and we received a significant number of requests for consulting and technical assistance. All of this brought about a heavy overload of work in some fields of activity in the Solar Concentrating Systems Unit, but we attempted to respond at all times to these requests and usually were able to do so.

Along this line of assistance to the private sector are three new activities started up by the USCS in 2008-2009. In 2009, a standardization activity was begun, which in close collaboration with other national and international entities, has been begun to provide the sector with standards that define the technical characteristics of the various component characterization and evaluation procedures. On the other hand, a national group on molten-salt thermal storage has been set up in collaboration with the CIEMAT Strategic Materials Division. Finally, but no less important, in 2009, in collaboration with the German DLR, the PSA created a solar reflector laboratory for joint studies and projects in this field. These three new USCS activities are described more fully in the following sections.

Continuing the policy of spreading knowledge and in our desire to facilitate development and consolidation of a domestic Spanish industry specialized in solar concentrating systems, in 2008-2009, the course on "Solar Concentrating Systems" was given three times in the main CIEMAT offices in Madrid: November 3-13, 2008, February 2-12, 2009 and November 16-26, 2009. Due to the large number of applications received, the course was given twice in 2009, in both cases the maximum attendance capacity was filled. This course has continued to be received enthusiastically by all sectors (engineers, promoters, equipment manufacturers and research centers) involved in the technological and commercial development of solar thermal power plants. In 2008-2009, participation was also continued in numerous workshops, seminars and courses organized by other institutions for the same purpose of exchanging/refreshing information and contributing to the visibility of the solar concentrating technologies and the USCS's own activities.

The following sections summarize the most important activities and results achieved in 2008 and 2009 in the three Solar Concentrating Systems Unit

R&D Groups, clearly demonstrating the intense activity carried out by all of them in their respective areas.

3.2 Medium Concentration Group

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The activities carried out during 2008-2009 by the Medium Concentration Group (GMC) are framed in several different fields that go from the development of new components for parabolic-trough collectors to research in innovative working fluids for parabolic troughs and providing technical services to business.

It should be pointed out that the number of technical services provided by the GMC, characterizing parabolic-trough collector components and studying the annual production of several different solar thermal power plants grew significantly in 2008-2009 to a total of 31. This increase in third-party services caused GMC activity to go from 100% R&D to having a significant technical services component. Nevertheless, this does not mean that it is abandoning R&D, but that in addition to this activity, technical assistance is being given to companies that request it of us. The technical service that we provide is a very specialized service hard to find anywhere else, because the solar thermal power plant market is not yet sufficiently developed. It is not the intention of the GMC to devote itself largely to third-party services, but the current situation of the technology and the consolidation of a strong Spanish industry in the solar thermal power plant sector at this time require the support of the PSA in tasks that are not exclusively R&D. As soon as the private sector is able to provide the services that are now being demanded of us, it is our intention to leave this activity and concentrate on R&D.

In addition to the technical services provided, meetings were held with many companies during 2008 and 2009 to inform them of the situation of the technology and the main lines of R&D that are currently underway in parabolic-trough collector technology.

During these two years we also continued to work on improving and marketing our developments, especially new selective and anti-reflective coatings for solar thermal systems. Conversations in this sense were held with several different companies interested in these coatings and preliminary agreements for marketing anti-reflective coatings developed and patented by the CIEMAT were signed with two of them in 2009.

During 2009, GMC activity for improvement of the PSA test facilities assigned to this Group was also intense, and new facilities that will increase our mid-concentration R&D capacity considerably were built. Among the facility improvements, it is worth mentioning updating of the data acquisition and control system in the DISS Plant, the first experimental plant in the world for studying direct steam generation (DSG) under real solar conditions. Among the new facilities which were planned in 2009 in the GMC are the new PSA molten salt laboratory and we also collaborated with DLR in the implementation of the KONTAS test facility, which is going to be built at the PSA for testing parabolic trough modules. All of these facilities, as well as the scientific

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equipment acquired (spectrophotometers, weathering chambers, reflectometers, perthometers, etc.) was paid for out of the Plan E budget granted to the PSA at the beginning of 2009.

The activities and achievements accomplished in 2008 and 2009 in the various projects undertaken by the PSA Solar Concentrating Systems Unit's Medium Concentration Group (GMC) are summarized below.

3.2.1 DISTOR – Energy Storage for Direct Steam Solar Power Plants

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

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

Budget: 3,036,650€. Project partly funded by the EC (Contract SES6-CT-2004-503526)

Duration: February 2004 - March, 2008

Background: Direct steam generation in the parabolic-trough collector absorber tubes is a very attractive option for lowering the cost of electricity generated by this type of solar collector. For such solar thermal power plants to be more commercial, they must have storage systems that make electricity generation independent of the hours of sunlight. The thermal storage systems currently available for solar thermal power plants are based on materials that heat up (sensible heat), and do not work in direct steam generation solar systems, so a thermal storage system specific to solar fields with direct steam generation must be developed.

Purpose: Develop a competitive thermal storage system suitable for direct steam generation parabolic-trough collector solar plants. Since most of the thermal energy in steam is released upon condensation, and this is a process which takes place at a constant temperature, storage systems for this type of solar plant must be based on a medium that can absorb heat at a constant temperature, such as the latent heat provided by phase-change materials (PCM).

Figure 3.1 General view of the new PCM storage module to be installed and tested at the PSA in 2010.

Achievements in 2008 y 2009: Even though the DISTOR Project was due to end in October 2007 according to the contract signed with the European Commission (contract SES6-CT-2004-503526), the GMC decided to continue the testing planned in the project until its completion. The delays in 2007 during the manufacturing and erection of the PCM experimental module to be tested at the PSA made it necessary to extend testing beyond the official project completion date. Therefore tests were continued through January of 2008. At that time they were interrupted due to leaks in the tube bundle of the module under testing.

In spring of 2008, the salt module was emptied and inspected, and the cause of the leaks in the tube bundle was found. This inspection of the module provided valuable information for improving future prototypes.

To progress further in the design of PCM thermal storage systems, in the middle of 2008, DLR and CIEMAT agreed to test a new storage module at the PSA. This module was sent to the PSA by DLR in summer of 2009, and erection and evaluation are scheduled for 2010. This new phase-change storage module includes several advantages which are the fruit of the experience gained from the previous module. Installation and evaluation of the new PCM module at the PSA is by specific cooperation between DLR and CIEMAT outside of the commitments initially signed in the framework of the European DISTOR project.

The new storage module has been designed for a maximum of 80 bar and 300ºC, and the medium is still nitrate salt.

Publications: [3.1]

3.2.2 Almería GDV- Puertollano GDV: Pre-commercial solar thermal power plant with direct steam generation

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

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

Purposes: The purpose of this project is the construction of a 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 the interaction among the parallel collector rows to be studied, as well as the best 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 2008-2009: In 2008, after the consortium was reformed in November 2007, the partners decided to undertake the project with their own resources, since the many applications for public financial aid had been unsuccessful. Once the decision was made, permitting and negotiation of a grid connection point were begun for construction of the Almería GDV plant on the PSA grounds as originally planned from the beginning. The corresponding application for registry in the Special Regime was submitted, the connection point for delivery of electricity generated to the grid was applied for to Sevillana-Endesa and the environmental impact report was ordered. Although there was a small environmental problem due to the existence at the PSA of an endemic plant, *Linaria Nigricans*, these problems were overcome by ensuring that the population of this plant at the PSA would not be damaged.

The main problem found was the grid connection point, since the Sevillana-Endesa, company responsible for the local distribution grid, alledged that the medium voltage line to which the electricity produced was to be delivered was overloaded and would not even allow delivery of 1 MW_e, which meant the DSG plant could not be built because its rated power is 3 MW_e. As the only alterntive for delivering the PSA DSG plant's 3 MW_e to the grid was to erect a new medium voltage line, the project partners had no other choice but to give up building the DSG plant at the PSA, since the extra cost of the new electricity line made the project economically unfeasibile.

After considering several different options for new sites, the partners decided to locate the GDV plant in the municipal limits of Puertollano (Ciudad Real) next to the 50-MW_e Ibersol solar thermal power plant, and the name of the project was changed from "ALMERIA GDV" to "PUERTOLLANO GDV".

In August 2009, the consortium promoting the DSG plant was again reformed, leaving the final partners as PERSEO, IDAE, CIEMAT, AGECAM and Navarro Piquer. These partners formed a new company in November 2009, and construction of the PUERTOLLANO GDV plant was begun in October 2010, with commissioning scheduled for mid-2012. The project coordinator is Iberdrola Renovables.

The updated budget of this project at the end of 2009 was 20.8 million Euros. Except for the physical location of the plant, which was moved from the PSA (Almería) to Puertollano (Ciudad Real), all the other characteristics of this DSG plant are the same. The proposed general layout is shown in Figure 3.2.

Publications: [3.2]

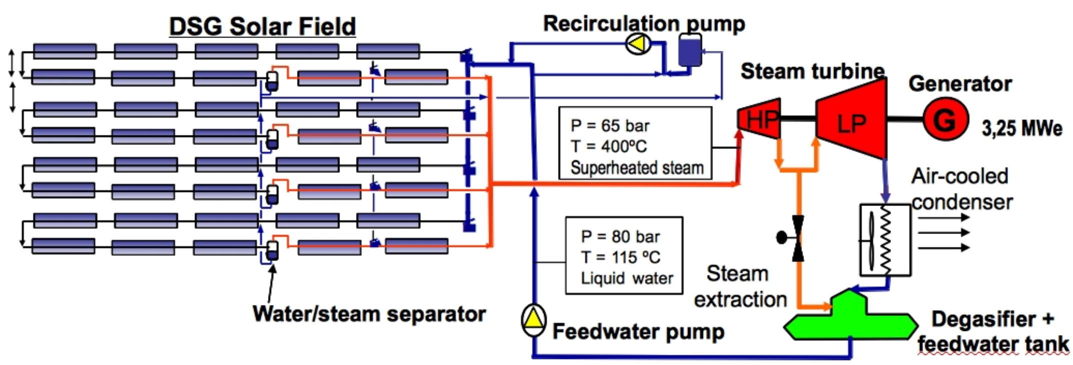


Figure 3.2 Simplified diagram of the Puertollano GDV Plant.

3.2.3 Solgel Selective coatings for absorber tubes

Participants: CIEMAT-PSA, ABENGOA Solar
Contact: Angel Morales, angel.morales@ciemat.es
Budget: 750.000€.
Duration: January, 2008 – December, 2011

Background: One of the most important elements of the parabolic-trough collector is the absorber tube, since that is where the concentrated solar radiation is converted into thermal energy. Due to its high technology, in 2009 only two vacuum absorber tube manufacturers, Schott and Solel marketed this type of absorber tube. Because of the scant offer and high demand, both the price and the delivery period for these tubes are currently a serious barrier to rapid commercial development of solar thermal power plants with parabolic-trough collectors. Therefore, the development of new absorber tubes is very attractive. CIEMAT has been working on the development of new selective coatings for use on this type of absorber tube, and has already patented one. CIEMAT is cooperating with several Spanish companies who are interested in this selective coating to license the patent and begin industrial manufacture of the Solgel selective coatings it has developed.

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

Achievements 2008-2009: The activities and achievements accomplished in 2008 and 2009 are described below in two groups: a) selective coatings for temperatures up to around 500ºC, and b) low-temperature selective coatings

Selective coatings for temperatures up to 500ºC:

During 2008 and 2009, the optical properties and durability of the high-temperature selective absorber were optimized. The high-temperature selective absorber has a solar absorptance of 0.96 and thermal emissivity has been reduced considerably to 0.087 at 400ºC and 0.11 at 500ºC. Figure 3.3 shows the complete high-temperature selective absorber spectrum, optimized in 2008.

Thermal durability tests have been performed on the absorber at 500ºC in air for 6 months with no variation in the optical properties, which confirms the high thermal stability of the absorber and the possibility of its use in receiver tubes without vacuum and or that may have lost their vacuum.

To evaluate the feasibility of the selective absorbent preparation on parabolic-trough collector tubes, 500-mm-long x 70-mm-diameter tubes were prepared in the CIEMAT pilot plant. It was proven that there is no limitation to deposition of films on large samples and homogeneous films with good optical properties were obtained.

At the end of 2009 a new Spanish patent was presented for a significant simplification in the selective absorbent film deposition process. The system consists of a simple device in which the tube is inserted for traditional dip-coating, thereby avoiding preparation of large volumes of precursor solution. This patent was applied for in collaboration with the School of Industrial Engineering of Madrid.

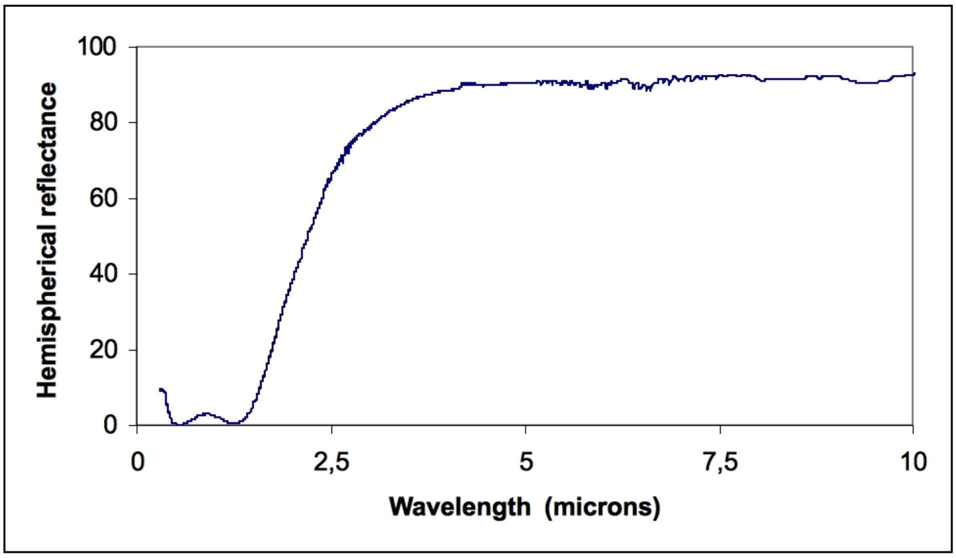


Figure 3.3 Complete spectrum of the selective absorber developed by CIEMAT

Studies directed at reducing the number of absorbent layers from the current six layers, to four, have also been begun to make it more industrially competitive. The first results enabling elimination of one of the absorbent layers are promising, while maintaining its optical properties. Once the number of absorbent layers has been reduced, the thermal durability of the new absorber and the layer thicknesses required to optimize the thermal stability will have to be evaluated.

Low-temperature selective coatings

Low-temperature coating activities in 2008 and 2009 concentrated on scaling up deposition to 30 x 30 cm^2 samples. The three-layer absorbent coating in (Al/CuMnSiOx/ CuMnOx/SiO_2), which had already demonstrated good results in terms of optical properties and durability, was prepared.

Several 30 x 30 cm^2 samples were prepared, some of which were divided into 100 pieces for reflectance measurement and absorptance mapping of each. Figure 3.4 shows the map of one of these samples along with the corresponding histogram. The absorptance interval is αs = 0.925 to 0.955 and the color scale is 0.005.

As observed, the uniformity of the optical properties is very good, espe-

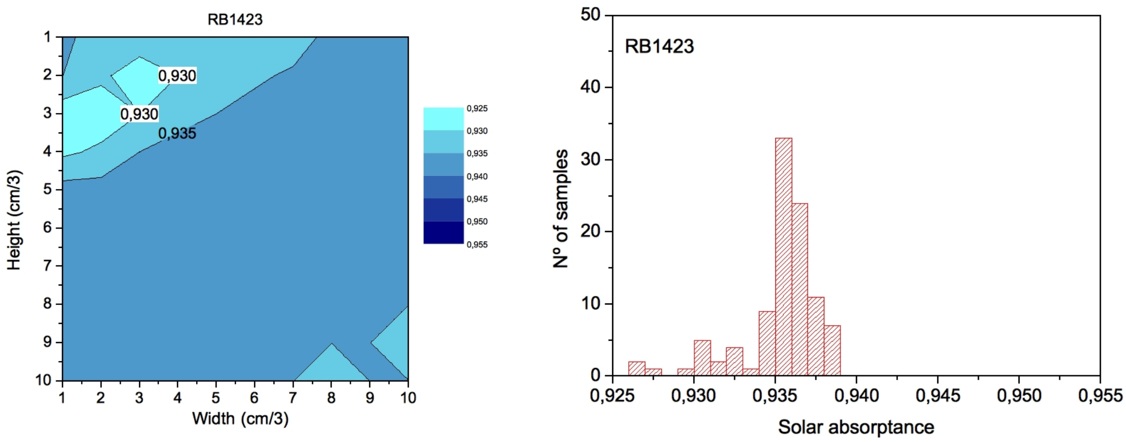


Figure 3.4 Absorptance map (left) and histogram (right) for a 30 x 30 cm^2 sample

cially since it is not easy to control ambient conditions in our laboratory. Even so, the mean absorptance for this sample is 0.935 with a standard deviation of ±0.003. Absorptance values on the map are also lower than expected for a three-layer absorber (i.e., 0.95). This is because the best samples were not used to obtain the maps since it involved cutting them up in pieces, and it was preferred to keep the best samples whole.

Publications: [3.3], [3.4]

Anti-reflective coatings for glass

Participants: CIEMAT-PSA (E), Private Spanish and European business
Contact: Angel Morales, angel.morales@ciemat.es
Budget: 320,000€.
Duration: January, 2008 - December, 2011

Background: Mean weighted spectral transmissivity of glass usually used in solar applications is approximately 92%. Any increase in solar transmissivity of this glass involves an increase of the same magnitude in the useful thermal energy supplied by the solar collector. Using anti-reflective coatings applied on both sides of the glass, transmissivity of the solar radiation can be increased up to a little over 96%, which means an increase of over 4% in the useful thermal energy delivered by the solar collector. Furthermore, manufacture of anti-reflective coatings is not expensive, so it does not penalize the commercial feasibility of the collector. These figures clearly demonstrate how beneficial Solgel anti-reflective coatings on the collector absorber tubes are. The CIEMAT-PSA has developed Solgel anti-reflective coatings with excellent properties, and has patented the manufacturing procedure of these coatings. Although there are anti-reflective coatings already on the market, their durability and mechanical resistance clearly need to be improved and pose an important challenge for R&D.

Purpose: Development of a Solgel anti-reflective coating resistant to weathering, easy to manufacture and which significantly increases the solar transmissivity of glass used in solar collectors.

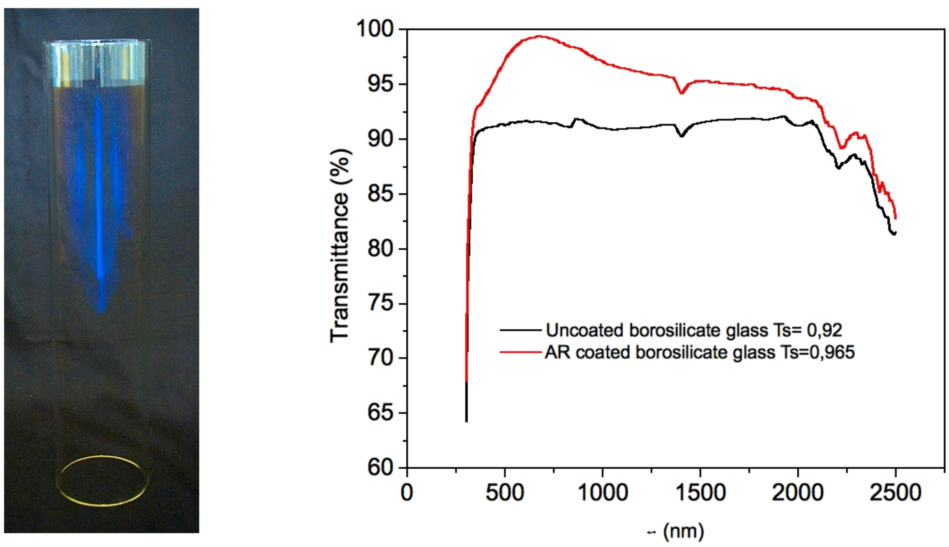


Figure 3.5 Photograph of a borosilicate glass tube coated with the anti-reflective film and transmittance spectra for glass with and without the AR coating.

Achievements 2008 - 2009: In 2008 and 2009, the anti-reflective film deposition process developed by the CIEMAT in previous years was scaled up from depositing films on flat 70x40 mm substrates to covering glass tubes with an inner diameter of 10.4 cm and outer diameter of 11 cm, which are the measurements used in commercial glass covers of parabolic-trough collectors. The tubes were 500 mm long. As observed in Figure 3.5, the scale-up process was successful, forming coatings with the same properties developed at lab scale. Uniformity over the tube was also very high. The top of the tube is uncovered, so the anti-reflective effect is clearly observable in the covered area.

In 2009, two preliminary agreements were signed for exploitation of the anti-reflective glass-tube coating patent and tests on 4-m-long tubes were made in pilot plants with excellent results. Glass tubes have been manufactured with transmittance of 0.96 in the solar spectrum, and the feasibility of using the Solgel technique with the formula patented by the CIEMAT for industrial preparation of the anti-reflective films for glass parabolic-trough collector absorber tube covers has been verified.

Moreover, film durability tests have continued with very satisfactory results, as alter two years of exposure to weathering, solar transmittance was still 0.96, with no degradation at all of the coatings (Figure 3.7).

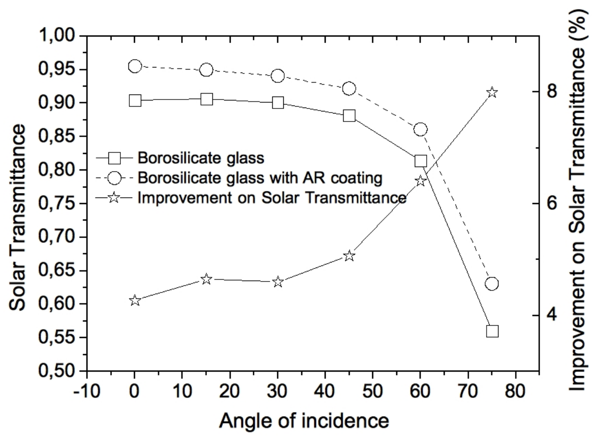


Figure 3.6 Solar transmittance as a funtion of angle of incidence of borosilicate glass with and without the AR coating developed by the CIEMAT

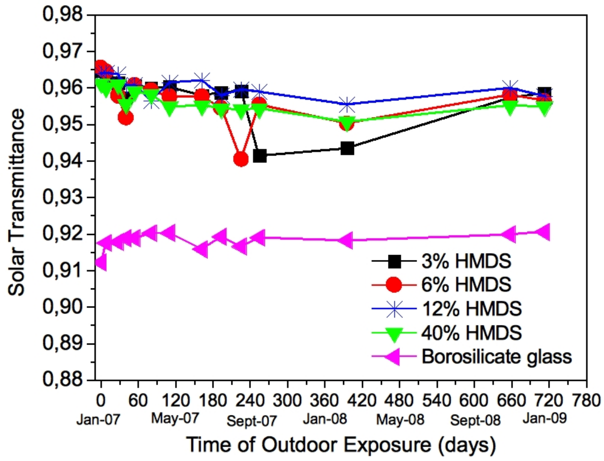


Figure 3.7 Weathering test of a borosilicate glass tube with and without the AR coating developed by CIEMAT.

As the solar radiation on the solar receiver has different angles of incidence, transmittance measurements were made at different angles to evaluate the influence of this parameter. As observed in Figure 3.6, application of the AR film increases solar transmittance of glass at all angles of incidence, and rises with the angle, so it is 4% higher at a 75º angle than at 0º which is an 8% increase in solar transmittance. These results demonstrate the importance of anti-reflective coatings for improving the efficiency of solar collectors.

Publications: [3.5]-[3.7]

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

Participants: CIEMAT, University of Almería, Composites-Sol
Contact: Aránzazu Fernández, arantxa.fernandez@psa.es
Budget: 235 k€
Duration: May 2008 – May 2010

Background: The main reason for this project is to have a solar collector able to cover the demand for thermal energy under 250ºC, with a cost/efficiency ratio making it attractive for competitive penetration in the market, and with geometry and weight that facilitate its installation in industrial, commercial and residential areas.

The processes that can be supplied by solar thermal energy in this temperature range are for industrial process heat, solar refrigeration, thermal energy supply at temperatures below 110ºC for high-consumption facilities (domestic hot water or heating of large buildings and industrial bays, hospitals, schools, sports facilities, pools, prisons, airports, etc.) and other applications, such as pumping, desalination or detoxification of water or generation of electricity by Organic Rankine Cycles.

Purpose: The purpose of this applied research project is to design, manufacture, evaluate and market a parabolic-trough solar collector to produce thermal energy at temperatures up to 250ºC which cover the demand for industrial process heat or air heating/cooling in buildings and for those which currently have no commercial solution taking advantage of solar energy with an adequate cost/efficiency ratio. To achieve this goal it is essential to establish the following specific goals.

- Design a parabolic-trough solar collector with weight, size, cost and performance characteristics which make it a technically and commercially feasible product.
- Manufacture a prototype series meeting the specifications
- Develop a set of tools and installations for thermal and optical evaluation of this type of solar system.
- Test and evaluate prototypes manufactured using the tools and installations developed.
- Determine improvements in the design and manufacture of solar collectors based on the results of their evaluation.

Achievements 2008 - 2009: In continuation of the CIEMAT's activities in previous years in the scope of the internal FASOL Project, at the beginning of 2008, funding was granted by the Ministry of Science and Innovation under the Collaborative Applied Research Projects Program for the CAPSOL project (Reference CIT-440000-2008-5).

In 2007, the conceptual design of the new solar collector was completed with the geometric configuration and associated parameters. After the initial design phase in 2007, in 2008, the first prototypes were manufactured and a test facility was erected to evaluate them.

Fabrication of the first two prototypes, called CAPSOL-01, was done by Composites y Sol S.L. with the technical supervision of CIEMAT personnel, based on the design resulting from the first stage. To do this, the commercial components meeting the technical specifications were selected (metal absorber tube with selective surface, glass tube cover, flat glass cover and reflector) and those collector components with no commercial solution (parabolic-trough concentrator made of composite materials and joints between components) were developed.

Because of the importance of the optical quality of the concentrator, both the mold and the first concentrator manufactures were geometrically evaluated by photogrammetry at the PSA in 2008. In view of the satisfactory results, the collectors were mounted, and a series of improvements that could be made in following prototypes were found. Figure 3.8 (left) shows a picture of one of the prototypes manufactured.

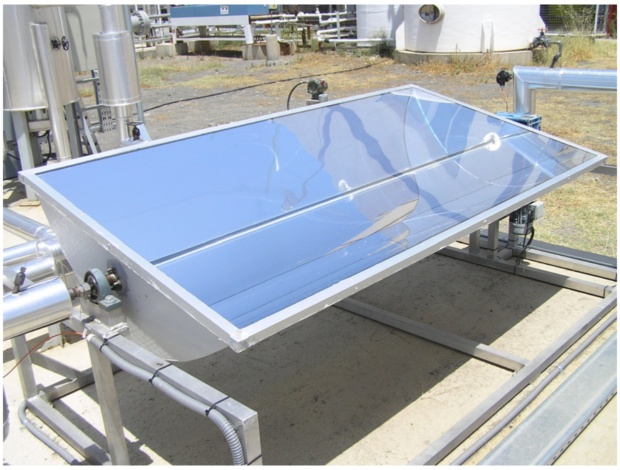


Figure 3.8 CAPSOL-01 Prototype (left) and CAPSOL test facility (right)

The design and construction of the test facility was done entirely by the CIEMAT in 2008. The main criterion was for the facility to enable tests to be performed with the highest precision possible, so high-precision instrumentation was installed and top quality equipment. The test plant, located at the PSA, was designed for use with pressurized water as the heat transfer fluid, under maximal operating conditions of 25 bar pressure and about 230ºC. This test plant not only allows the collector performance parameters to be found, but also analyze technical factors under real operating conditions, such as materials durability, structural resistance, assembly of components, air tightness of the collectors, etc. Figure 3.8 (right) shows a photo of the facility erected at the PSA in 2008.

In the first quarter of 2009, the CIEMAT commissioned all of the equipment, instrumentation and data acquisition system in the CAPSOL test facility built in 2008, and also the monitoring system for the first two units of the CAPSOL-01 collector installed in it. Once all of the systems were functioning properly, testing of these two collectors began.

During testing, a large number of experiments were performed to determine the basic parameters of collector operation: time constant, peak optical performance, thermal losses and incidence angle modifier. Furthermore, during testing, a series of possible improvements to be implemented in future CAPSOL prototypes were found.

Late in 2009, Composites y Sol proceeded to the fabrication and assembly of two units of the second prototypes, CAPSOL-02, including the improvements proposed in view of the results found in both photogrammetry tests and in performance testing. These new prototypes were also evaluated at the PSA by photogrammetry, with very satisfactory results, since the improvement proposed based on the photogrammetry data from the first prototypes and mold increased the intercept factor of the collectors considerably.

The two CAPSOL-02 prototypes were installed in the PSA test bed at the end of 2009 and are to be evaluated in 2010.

Publications:[3.8]-[3.10]

3.2.5 Innovative working fluids for parabolic-trough collectors

Participants: CIEMAT, Polytechnic University of Madrid
Contact: Eduardo Zarza, eduardo.zarza@psa.es
Budget: 950.000€.
Duration: December, 2005 - December, 2011

Background: The parabolic trough collector is at present the most developed commercial technology for solar thermal power plants, with over 3.5 million m^2 of collectors in routine operation at the end of 2009, and with a rated electrical power over 500 MW_e. In spite of its commercial maturity, new ways to reduce costs and increase performance must be found for this technology to make it more competitive with conventional power plants. One of the possible options for reducing costs and increasing performance is attempt to find new working fluids for the solar collectors used in these plants. To date, all the commercial plants use thermal oil as the working fluid, but this oil has clear drawbacks. Some of these drawbacks are the risk of polluting the environment in case of leaks, risk of fire and limitation of the maximum temperature that can be reached in the solar field. Since to avoid these problems, the thermal oil currently used 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 must all be studied under real operating conditions.

Purpose: The experimental study of pressurized gas as a working fluid for parabolic-trough collectors, evaluating their behavior under different real operating conditions and analyzing their advantages and disadvantages compared to the thermal oil in current use or other possible innovative working fluids. This final goal will be achieved through two partial goals: 1) Design and construction at the PSA of a test loop for experimental study of new working fluids with parabolic-trough collectors, and 2) Experimental study under real solar conditions using different pressurized gases as a working fluid in the test loop erected at the PSA. CIEMAT activities in this project are directed by Prof. Carlo Rubbia.

Achievements in 2008 and 2009: When construction of the test loop required for the experimental study of pressurized gases as a working fluid in parabolic-trough collectors at the PSA had been completed in 2007 (see PSA Annual Report 2007), these experiments were carried out in 2008 and the first half of 2009, using pressurized CO_2 as the working fluid. Figure 3.9 shows a general view the PSA test loop installed at the end of 2007.

Figure 3.9 View of the experimental loop used in 2008 and 2009 to study pressurized gas in parabolic trough collectors

Among the experimental results, the following are worth mentioning:

- The two collectors that comprise the experimental loop have been operated in series and in parallel. It has been verified that the outlet gas temperature in both collectors when operating in parallel is easily maintained, but the gas flow is too low and could put the integrity of the absorber tubes at risk during strong solar radiation transients, as tube cooling may be insufficient. Therefore, after some testing in parallel, it was decided to continue testing with only the in-series configuration.
- With the in-series configuration, the outlet gas temperature in the loop is maintained well in the 400ºC±5ºC range, even with strong solar radiation transients. Figure 3.10 shows the results of July 2, 2009, where it may be observed how the loop control system maintains the gas temperature (red line) even with the solar radiation transients (yellow line).
- The time required to reach nominal conditions alter the startup of the loop is rather long (over 1 hour), but in a commercial plant, it would be much shorter because there is quite a long length of passive piping.
- The ball joints with graphite seal developed considerable leakage after a short period of operation. Although there are several hypotheses that could explain their weakening, none has been demonstrated. It does seem clear that the same ball joints used with thermal oil are not practicable in fields with pressurized CO^2.
- Ball joints from several different manufacturers were tested, all of them with graphite seals, and all of them had the same problem, and started leaking after a short time. This result demonstrated that for solar fields with pressurized CO_2, another type of joints will be needed. In view of this, collaboration agreements have been made with several different companies for development of joints other than ball joints.
- Optimization of the piping layout and equipment design in the pressurized gas loop is very important to reduce pressure drops to a minimum.

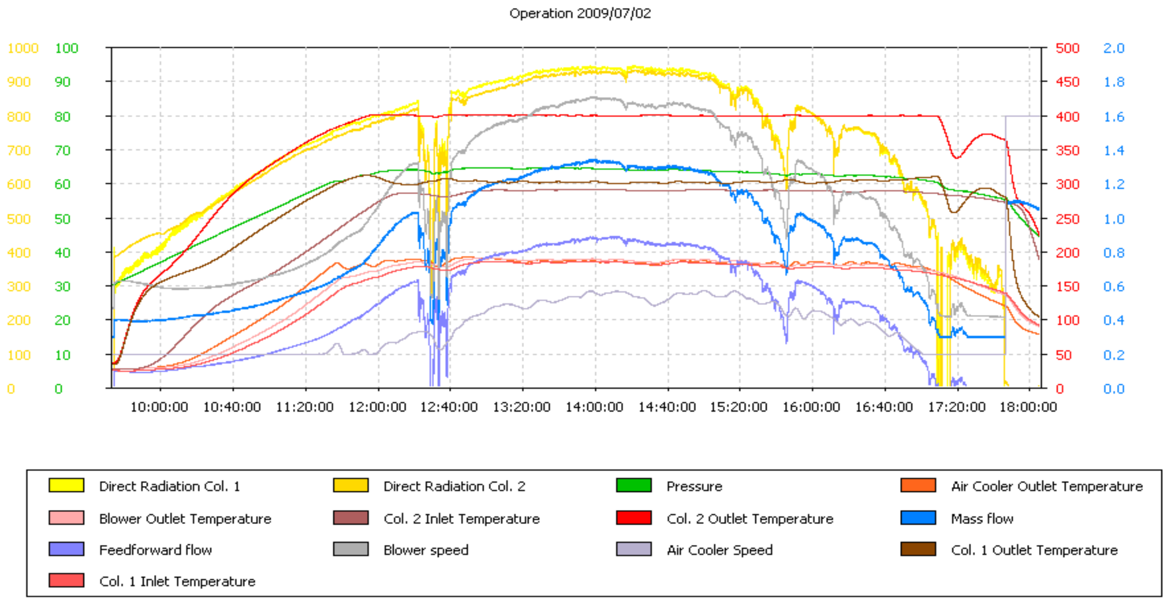


Figure 3.10 Resultados experimentales obtenidos el dia 2 de julio de 2009 con el control de la temperatura del gas a la salida del lazo de ensayos.

At the end of 2008, a test loop modification was designed to increase its operating temperature to 525ºC and technical specifications were written for connecting it to a small molten salt thermal storage system, which would allow it to operate with charge/discharge cycles. The molten salt storage system is expected to be completed in autumn of 2010.

The modification to increase the gas test loop operating temperature from 400ºC to 525ºC, which began in autumn of 2009, is due to conclude in March 2010.

In 2009, the CIEMAT contacted several Spanish companies to study the possibility of construction of a pre-commercial plant using this new technology which is now in the experimental stage at the PSA. Such a plant would validate the technical and economic feasibility of using pressurized gas as the working fluid in large solar thermal power plants.

Publications: [3.11]

3.2.6 Characterization and analysis of durability of solar reflectors.

Participants: CIEMAT and DLR
Contact: Aránzazu Fernández García, arantxa.fernandez@psa.es
Budget: 400k€
Duration: January 2009 – December 2012

Background: This Project is motivated by the need to study the materials used in solar reflectors as one of the main components of solar concentrating systems. The reliability and durability that solar concentrating system reflectors must have make it recommendable to test their qualities previously. The continual appearance on the market of new types of reflectors makes it necessary to have a laboratory equipped with specific instrumentation for evaluating their behavior under a diversity of working conditions, and also define specific tests for these materials.

Purpose: The purpose of this project is to characterize and analyze the durability of reflector materials used in solar concentrating systems. The following specific goals are within this general goal:

- Study of degradation of materials to environmental variables and their effect on solar concentrating system performance.
- Find physical experimental equations for degradation of certain relatively important reflector materials, in order to predict their mid-to-long-term behavior.
- Determine any correlations between testing under accelerated conditions and exposure of materials to real weathering.
- Set the standards and protocols for standardizing tests related to solar concentrating system reflectors.
- Perform tests for companies who so request when necessary to the development of concentrating solar systems.

Achievements in 2008-2009: In the early months of 2009, the first steps in the project were carried out, participants, goals and tasks were defined. The first task undertaken consisted of defining the equipment required for achieving the goals above and designing the reflector materials test laboratory in which this equipment is to be housed. We then proceeded to acquisition of most of the equipment proposed, employing Plan E funds awarded to the PSA in 2009 for its scientific infrastructure and equipment.

Testing and measurement was done in the laboratory for complete characterization of reflector materials, determining the values of their main parameters and any deterioration. The lab has a portable specular reflectometer, a 3D microscope and a spectrophotometer with integrating sphere (see Figure 3.11 left) for this. Furthermore, the laboratory, when complete, will be able to perform controlled accelerated ageing tests on these materials, applying environmental variables causing reflector deterioration when exposed to outdoor conditions, either separately or in combinations. The equipment acquired in 2009 for this end will consist of: weathering chamber with controlled temperature, humidity, solar radiation and rain (see Figure 3.11 right), salt mist chamber, ultraviolet chamber, kilns with and without special atmospheres, and thermal cycling devices.

A series of preliminary accelerated aging tests were also performed on several reflector materials in 2009. Numerous conclusions were obtained con-

Figure 3.11 Perkin Elmer Lambda 1050 spectrophotometer (left) and Atlas SC340 weathering chamber (right) in the solar reflector materials lab.

cerning the durability of these materials thanks to these tests, and progress has been made in writing test protocols for this application.

3.2.7 Thermal storage for solar thermal power plants

Participants: CIEMAT-PSA (E), Spanish and European companies, international research centers
Contact: Esther Rojas, esther.rojas@ciemat.es@ciemat.es
Budget: 3.2000.000€.
Duration: May, 2008 - December, 2012

Background: Red Eléctrica Española (Spanish Electricity Grid) in its report "Additional information necessary for assessment of grid access: evaluation of manageability of solar thermal power plants" of 26/07/2007 stated that this type of plants had to have 4 hours of storage to be considered manageable. The group of companies promoting this type of plants and research centers experts in solar thermal power plants, CIEMAT among them, expressed the high risk of such a requirement, as at present there are many technical and scientific uncertainties associated with large thermal storage systems. This led to a reduced thermal storage requirement in March 2008, when it became feasible. Knowing that this consideration is provisional, it is indispensable that the most relevant technical aspects be solved in the near future in order to assure reliable and competitive thermal storage for solar thermal power plants.

Purpose: Develop and optimize effective, economical thermal storage systems, mainly for use with solar thermal power plants, although industrial applications for process heat are not discarded.

Achievements in 2008-2009: activities in 2008 and 2009 on thermal storage for solar thermal power plants may be grouped in two lines of research:

a) *Design and optimization of thermal storage system components*

The experimental results of a 100-kW nitrate salt PCM storage prototype tested in 2007 were analyzed. This analysis identified possible improvements in the design, manufacture and future developments based on this concept. Deficiencies or limitations of current analytical models proposed for simulation of this type of storage in latent heat have also been identified.

A study has been performed on different salt/oil heat exchanger models for double-tank molten-salt storage systems using commercial CFE programs. The safest and most effective design in terms of the fewest dead zones and best energy transfer was identified. This design was studied in detail and a series of strategies were proposed for reducing and managing the risk associated with the zones where solidification of salts is most likely and which, due to erosion, may be subjected to greater stress. This study was done under the framework of ConSOLida (Consorcio Solar de I+D) CENIT Project.

b) *Experimental evaluation of components, equipment and procedures*

To date, experience in characterization and evaluation of components and charge/discharge processes is limited to a few particular components and storage connected to central receiver solar systems (most of the solar thermal plants currently being promoted or under construction have parabolic-trough collectors, so the operating conditions are different). Thermal power plant promoters and engineering firms find that the specifications of the components to be used do not fit the expected operating conditions in molten-salt thermal storage systems, so they need to find out how they behave. Furthermore, there is no standard procedure for this characterization, and any laboratory around the world which at some time or another has done something of the kind, has employed its own methodology. To assist in solving these problems, the CIEMAT has designed and is building at the PSA with funds provided by the Spanish Plan E, an experimental plant for thermal storage using molten salt (Figure 3.12). It is a system where molten salt thermal storage components, equipment and operating strategies can be tested. The plant is designed to be fed by either a high-temperature or mid-temperature energy source. The plant components are large enough for the results to be applicable to commercial power plants, and sufficiently flexible for them to cover a wide range of research.

The plant is complemented by a laboratory and a dynamic test loop for materials in contact with salt.

Characterization of the components and equipment for storage systems is an important subject critical to engineering firms and promoters of solar thermal power plants. The Solar Concentrating Systems Unit has kept up close contact with such businesses, and in May 2009, a collaboration agreement was signed by 11 companies and the CIEMAT for evaluating the compatibility of structural materials with molten salt in thermal storage systems, to be done by the CIEMAT Structural Materials Division.

The need to establish adequate molten-salt hydraulic component and equipment characterization procedures has been recognized by other national and international research centers. CIEMAT is therefore participating, along with other solar research centers, in the European 7th Framework Programme SFERA Project, the general purpose of which is standardization of characterization methodologies for solar thermal power plants, including thermal storage systems. The CIEMAT also participates in the ASME Solar Thermal Power Plant Committee (PTC-52) and in the national committee for solar thermal power plant component standardization. Both of them have a specific working group for thermal storage.

Publications: [3.12]

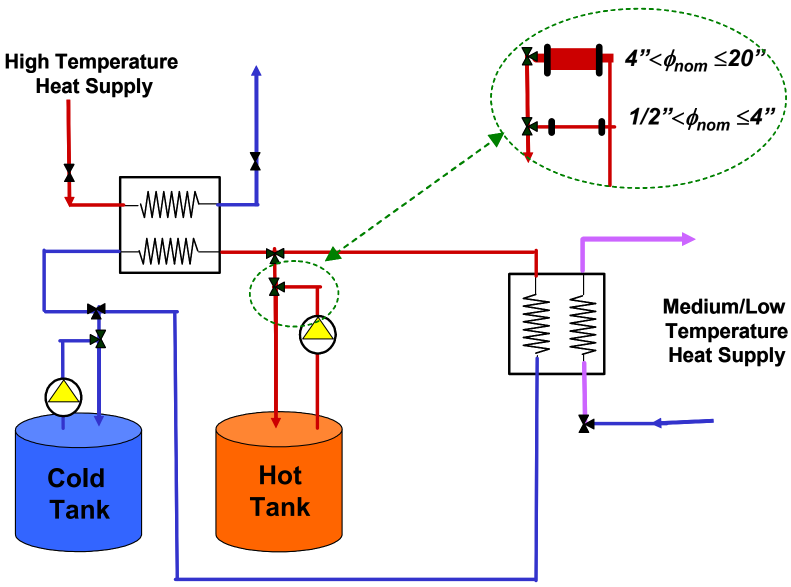


Figure 3.12 Flow diagram of the thermal storage test plant to be installed at the PSA.

3.2.8 Other Medium Concentration Group Activities in 2008 and 2009

In addition to the R&D activities described above, the Solar Concentrating Systems Unit's Medium Concentration Group has carried out other activities in 2008 and 2009, such as:

- Improvement of the modeling and simulation software for solar thermal power plants with parabolic-trough collectors and direct steam generation using the Matlab programming environment.
- Evaluation of new components and parabolic-trough collector designs: the confidential nature of this type of work makes it impossible to provide any concrete information on the work done by the PSA in 2008 and 2009 with regard to these subjects.
- Dissemination of the parabolic-trough collector technology: participation in numerous conferences and courses on renewable energies. In this field, the most significant contribution of the Medium Concentration Group was our participation in the three "Concentrating Solar Systems" courses given in Madrid in 2008 and 2009.
- Consulting for promoters, component and equipment manufacturers and engineering firms involved in the parabolic-trough collector technology. The number of Spanish and foreign companies interested in this technology continued its strong growth in 2008 and 2009. The reason for this great interest is the premium established by RD 2007/661 for electricity generated by solar thermal power plants. This made business interested not only in promoting commercial projects, but also in the manufacture of some of the main components (absorber tubes, solar reflectors, solar tracking drive units, etc.). Following the trend already begun in 2006 and 2007, in 2008 and 2009, many companies have come to the PSA for information and consulting. Given the logical limitation of available resources in the Medium Concentration Group, it was sometimes impossible to attend to all of the requests that we received from national and foreign companies. But, as always, it is our intention to continue giving business all the assistance possible.
- One of the biggest deficiencies experienced worldwide in industry related to solar thermal power plants is the lack of standards defining the technical characteristics that the various components and systems in this type of plant must have, as well as characterization, monitoring and evaluation procedures that must be applied to them. To solve this deficiency, several initiatives have been put into practice in the United States and Europe to draft such standards. In the United States, the ASME has created Working Groups on the various subjects related to solar thermal power plants (ASME Committee PTC-52). In SolarPACES steps are also being taken directed at drafting standards in this same field. In Spain, the CTAER, CENER and CIEMAT have started up, in collaboration with AENOR, an activity for writing national standards that respond to the current vacuum. In Spain, this initiative will also have the support of PROTERMOSOLAR. The PSA is present in all of these standardization initiatives, having joined committees and technical groups recently set up in 2009. This activity began to take its first steps in 2009 and will become stronger in the coming years.

3.3 High Solar Concentration Group

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

Activity in the High Solar Concentration Group concentrates mainly on Central Receiver Systems, but also includes activities related to other Systems that provide high solar flux such dish/engine or solar furnace. The commercial deployment in Spain of solar thermal power plants with central receiver systems progressed slowly in 2008-9 with connection of the PS-20 Plant (20 MW_e) and beginning of construction of Gemasolar (17 MW_e). Nevertheless, international interest has renewed (with projects underway in the US and Israel). Until startup of PS10, in full commercial operation since March 2007, the solar thermal power tower "learning curve" was based on testing of over 10 experimental tower facilities around the world, both complete systems and a wide variety of components (heliostats, receivers and storage devices).

Experience accumulated has served to demonstrate the technical feasibility of the concept and its capacity to operate with high incident radiation flux (typically from 200 to 1000ºkW/m^2), which makes it possible to work at high temperatures (from 250 to 1100ºC) and integrate them in more efficient cycles, from Rankine cycles with saturated steam to Brayton cycles with gas turbines. It has also been demonstrated that they easily admit hybrid operation in a wide variety of options, and have the potential to generate electricity with high capacity factors using thermal storage in systems which today can surpass 4500 equivalent hours per year. Predictions for system solar-to-electricity conversion efficiency are from 20-23% at design point and 15-17% annual.

Unlike the technological homogeneity observed in the current deployment of parabolic-trough collector technology, central receiver plants offer, on one hand, higher total conversion efficiencies (associated with operation with higher solar concentration) and on the other a wider diversity of design options, with less accumulated experience in implementation of each typology or component. However, the high cost of capital is still an obstacle for full industrial use of its potential. The first commercial applications that are beginning to be deployed still have installed power costs of 2500-9000€/kW (depending on storage size) and cost of electricity generated is around 0.16-0.20€/kWh. A cost reduction and the perception of risk associated with less commercial experience with this technology is therefore essential for the number of commercial applications to be extended.

This goal of reducing electricity production costs is directing R&D efforts, on one hand to improving existing options, and on the other demonstrating the feasibility of new design options, such as: 1) the choice of heat transfer fluid and receiver operating temperature, (choosing from water-steam, nitrate salt or air), 2) optimum plant size (choosing between with single-tower and multi-tower fields, which adds modularity to construction) associated with thermal storage solutions and/or hybridization to make them more manageable, 3) efficiency/cost compromise in the concentrator field (choosing between two opposite trends: larger heliostats of around 100 m^2 and over with good optical quality and lower specific cost of the tracking devices, or small heliostats, of around 10 m^2, with better land use and possibility of moving them in groups).

Aware of the diversity of competing options, with no clear determining criteria for their selection, the High Solar Concentration Group (GACS), in addition to participating ion the first CRT commercial demonstration projects, maintains a permanent line of R&D on technological development of components and systems in order to generate information that could help reduce the uncertainties and analyze the technical feasibility of the various options.

In 2008-9, in addition to contributing to the general USCS activities, such as improving our own R&D capabilities and technical training for 3rd parties, the GACS has carried out three basic types of activity:

- Collaboration in system development, which at this moment, with the current 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).
- Participation in central receiver component development through the initiative or collaboration in national projects (such as CENIT-CONSOLIDA) or international (such as SOLHYCO).
- Improve the experimental capabilities and quality procedures (with the startup of the International SFERA Project, the continuation of activities in the Radiometry and High-Temperature Lab and perfecting capabilities for accelerated ageing with high solar flux and high temperatures).

3.3.1 SOLAR TRES: Molten-Salt Solar Thermal Power 15-MW_e Demonstration Plant

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

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

Budget: EC-DG TREN (ENERGIE Programme, Ref.:NNE5/369/2001): 5 M€

Duration: December 2002-December 2008

Background: This project accumulates previous experience in the Solar Two Project, but joint developments by Sener and CIEMAT and technical conditions imposed on solar thermal energy by Spanish legislation have also led to design innovations. The original Solar Tres project was predesigned to applicable Spanish legislation in 2000. During project development, legislation in renewable energies underwent some changes and there were also some changes in partners, which led to reorientation of the project, and the consortium promoter. In 2005, the final consolidated team was made up only of European companies and led by Sener. At the same time, Sener and CIEMAT had signed an agreement for development and analysis of a new heliostat concept and a molten salt receiver prototype with better thermal performance able to operate with higher flux without compromising its durability.

Purpose: The purpose of the SOLAR TRES Project is to build and operate a 17-MW commercial-scale demonstration power plant, using heliostat field, tower and energy storage with molten salt. As a demonstration project, the EC funded engineering and plant construction (finally called Gemasolar). Some technological design options, improved from its predecessor, Solar Two,

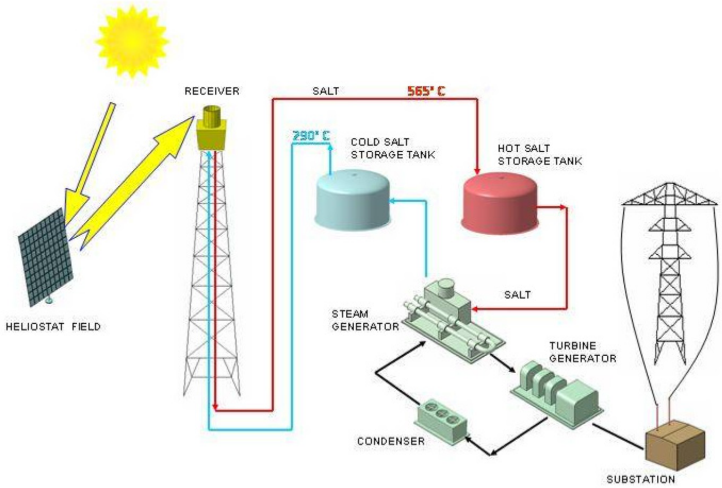
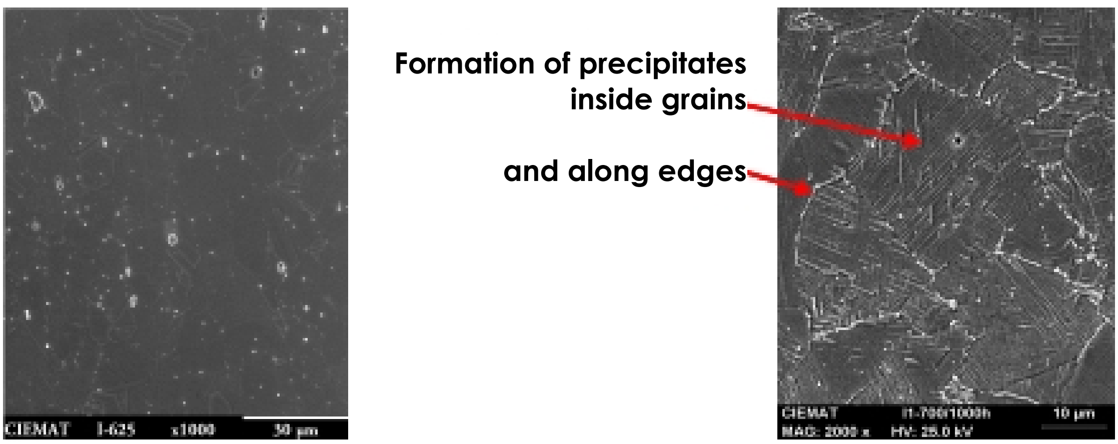


Figure 3.14 Flow diagram of the Solar Tres/Gemasolar Plant

such as the receiver and other equipment associated with operation with molten salt are expected to be validated.

Achievements in 2008-2009: GACS activity in the last stage of the project focused on consulting in selection of solar receiver materials by testing and characterizing the options. In 2008-2009, lab tests simulated molten-salt-cooled tower receiver operating conditions on different metal alloys selected as suitable for this use due to their composition and mechanical properties. These tests included a progressive microstructure study and mechanical behavior due to thermal ageing from exposure to high temperatures and the heat transfer fluid, 60:40 $NaNO_3/KNO_3$ of differing purity. The tests done were: thermal ageing in air at 600, 650 and 700ºC, mechanical characterization of materials at reception and after thermally ageing in ambient air and at 600º, corrosion in mixtures of nitrates at 550 and 565ºC and u-bend tube stress corrosion cracking (SCC) in molten salt at 550ºC. Samples were examined after different accumulated test times and at the end, using such techniques as optical microscopy and scanning electron microscopy (SEM) X-ray diffraction (XRD) microanalysis.



a) Upon receipt b) After 2000 hours at 700^{o}C

Figure 3.13 Effect of thermal ageing. Appearance of one of the alloys tested as seen by scanning electron microscope

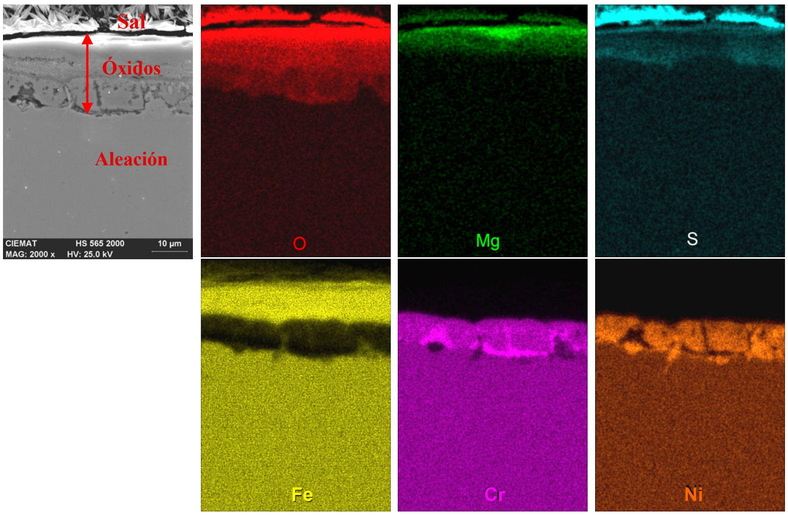


Figure 3.15 X-ray mapping of elements in the oxide film formed on the surface of the alloy in contact with the heat transfer fluid. Effect of the presence of Mg and S impurities in the salt

As a result, different alloys could be compared to selection criteria for use in the absorber in solar thermal power plants using molten nitrates as the coolant.

Publications: [3.13], [3.14]

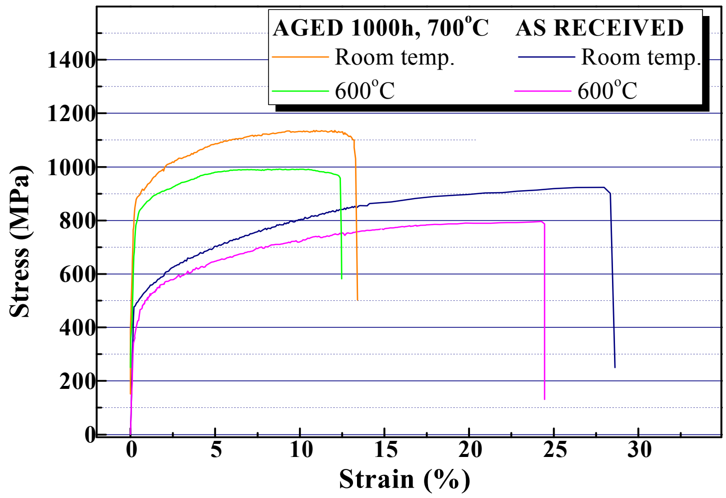


Figure 3.16 Effect of thermal aging. Influence on mechanical behavior.

3.3.2 Molten-salt receiver development for a solar thermal power plant

Participants: SENER Ingeniería y Sistemas, S.A., CIEMAT-PSA; [CIEMAT participates ein this project in two Divisiones: a) CIEMAT-PSA, b) CIEMAT- Structural Materials Division].

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

Budget: 7 M€ from Sener, Ciemat and CDTI-PIIC.

Duration: November 17, 2005 - December 31, 2007 (Extended to October 2009)

Background: In 2004-2005, Boeing withdrew its bid for construction of the Solar Tres plant receiver, compromising continuation of the project for lack of an alternative commercial offer. In view of this situation, SENER decided to undertake engineering and development of the Solar Tres salt receiver on its own. Nevertheless, to reduce the risk, it requested that CIEMAT share in the design and validation of a tube salt receiver, including design, construction and testing of a receiver panel, prior to the fabrication of the Solar Tres receiver, made up of a set of 16 panels. In the second half of 2005, SENER and CIEMAT signed a collaboration agreement for validation of the receiver technology (with SENER-CIEMAT technology), and for definition of operating and control strategies that ensure and prolong the life of a molten-salt receiver for solar thermal power plants (beginning with GEMASOLAR).

At the beginning of 2007, the CDTI approved its support of the Salt Receiver Development Project as an Industrial Research Agreement Project lasting until December 2008, to increase design reliability and reduce risks in the GEMASOLAR receiver. This was extended to October 2009 by an appendix to the collaboration agreement signed by CIEMAT and SENER.

Purpose: i) Reduce the risk associated with the first self-development of a molten-salt receiver solar power plant, ii) Experimentally validate the design of a receiver applicable to Solar Tres, iii) review the selection of materials and geometries to extend the expected durability of the receiver. Except for the turbine and generator, develop the complete experimental system, including a 4-MW_{th} receiver subsystem, 18-t salt storage tank, 1-MWh evaporator, aero-condenser, electrical tracing system, piping, control and measurement system with around 400 sensors.

Achievements in 2008-2009: After the first test stage in 2007, which led SENER to decide to promote the Gemasolar Plant, testing of the salt loop with the receiver panel was continued to increase confidence in its operability and

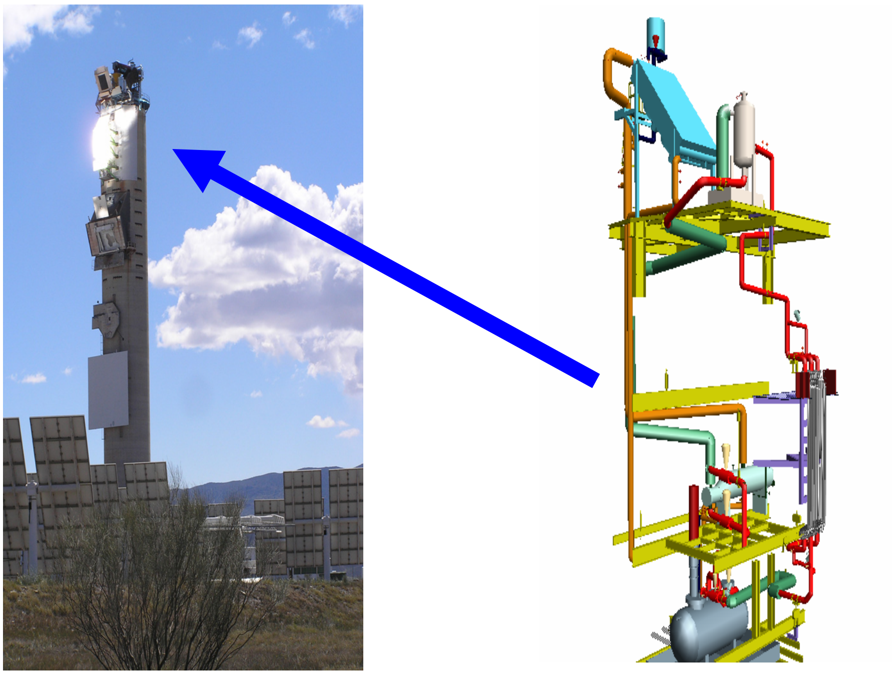


Figure 3.17 Salt receiver panel during testing on the 70-m level of the CESA-1 tower and diagram of the experimental setup.

the durability of its components. This testing was continued with CDTI_PIIC and own funding until October 2009.

This additional testing simulated the real operating conditions that receiver modules or panels would undergo in the Gemasolar plant. Transients in incident radiation, panel temperature, salt flow rate in the panel, and panel exposure to incident power overloads to analyze material resistance and durability.

Taking advantage of salt loop installation, new components were installed for salt melting and freezing tests, to gain confidence in its operability and control. At the same time, valves and instrumentation that could cheapen the cost of future plants and increase their durability were also tested.

3.3.3 Investigation, 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)
Budget: CDTI-TORRESOL. (GEMASOLAR/CIEMAT Agreement). 405 k€.
Duration: August 2009 to December 2011

Background: The good results of construction, testing and evaluation of the molten salt receiver prototype for the Solar Tres project under a development agreement between Sener and the CIEMAT, with support from the CDTI, were determinant for final launching of GEMASOLAR, a 17-MW_e power tower plant with molten-salt coolant and thermal storage, promoted by Torresol Energy in Ecija (Seville).

Purpose: The current project funded by the CDTI now concentrates on the following points: i) Assist Torresol Energy in the installation, commissioning, and operation of the GEMASOLAR plant, ii) Predict and monitor weather data at the GEMASOLAR site (Ecija-Seville), iii) Test new thermal insulation materials and concepts at the PSA for later installation in GEMASOLAR, iv) Design, test and validate (in collaboration with Tecniker) of new low-cost radiometer for incident solar flux over 1000 kW/m^2; v) Test components to be used in molten-salt systems: valves, pumps, pipes, sensors, etc., vi) Accelerated ageing and durability testing of materials subjected to high incident solar flux and to heating/cooling thermal cycles.

Achievements in 2008-2009: As the project began in August 2009, there are no achievements worthy of mention yet.

3.3.4 SolHyCo (SOLar HYbrid power and COgeneration plants)

Participants: DLR (D, coordinator), Turbec (I), CIEMAT (E), CEA (F), Ormat (IL), Abengoa (E), FTF (D), Sonatrach (ALG), GEA (POL), Vitalux (BRA), e IIE (MEX)
Contact: Peter Heller (peter.heller@dlr.de); Thorsten Denk (thorsten.denk@psa.es)
Budget: European Commission under the 6th Framework Programme (Contract nº 019830).
Total project 3 M€; CIEMAT Participation: 0.5 M€.
Duration: January 1, 2006 to June 30, 2010

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

Purpose: The main purpose of SolHyCo is to develop a very high-efficiency solar-hybrid microturbine for electricity generation from both heat operating with concentrated solar radiation and biofuels, making it a completely renewable system. Other purposes of the project are studies on the introduction of this technology in the markets in Sunbelt countries, in particular, Algeria, Brazil and Mexico.

At the Plataforma Solar, solar testing in the CESA-1 tower was planned in two stages. The first was carried out in 2008 and 2009 on the 60-m level with a 250-kW turbine from the Israeli company, Ormat, which was already operated very successfully in the Solgate Project. This turbine was fed by three pressurized air receivers (one tube and two volumetric) with a total thermal power of 1 MW. The difference with Solgate was substitution of kerosene by a 100% biological diesel fuel (biodiesel).

In the second stage in 2010, a 100-kW_e Italian/Swedish Turbec turbine will be installed in the same place. For this turbine, a new type of pressurized-air receiver based on the tube concept, but with high-technology "multilayer" tubes will be used. These tubes have three layers, the outer one is of very-high-temperature steel, the middle one is copper for better heat distribution around the pipe circumference, and the inner one is very thin steel for mechanically stability of the copper layer.

Achievements in 2008-2009: Testing began in March 2008 still using kerosene to find out how the system behaved with its new components. After only four tests and improving some details, the system was prepared for the main goal, operation with biodiesel. Then on May 2, 2008, along with Ormat personnel, a gas turbine operated with concentrated solar energy and biofuel was operated for the first time. It was a resounding success, as in that first test design operating conditions were almost reached. The turbine operated for two and a quarter hours with solar radiation and two and a half hours with biodiesel. The highest receiver outlet air temperature was 758ºC, with generator power of 187 kW_e, and 96.6% of the rated turbine speed (54000 rpm). The most important power data are shown in Figure 3.19.

After that success, two new devices were installed to improve the air mass flow rate, crucial to receiver and turbine efficiency. These were a pair of flow meters for direct measurement of the turbine gas intake volume and a "tracer

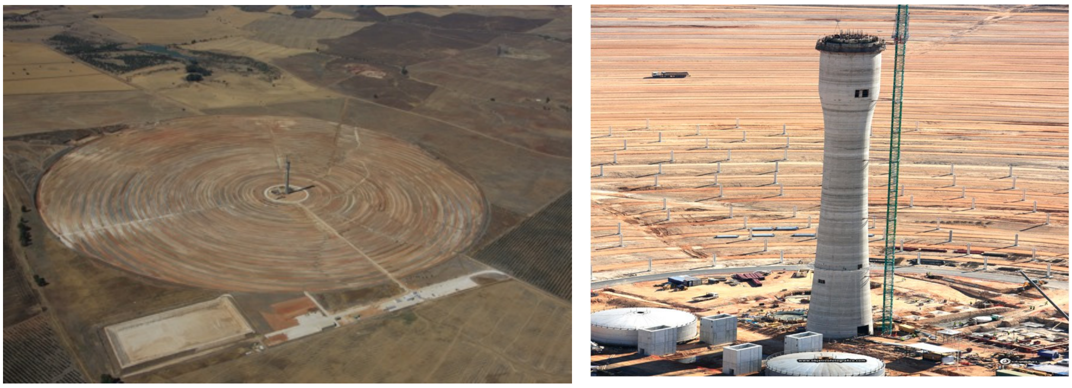


Figure 3.18 Current state of construction of the GEMASOLAR Plant

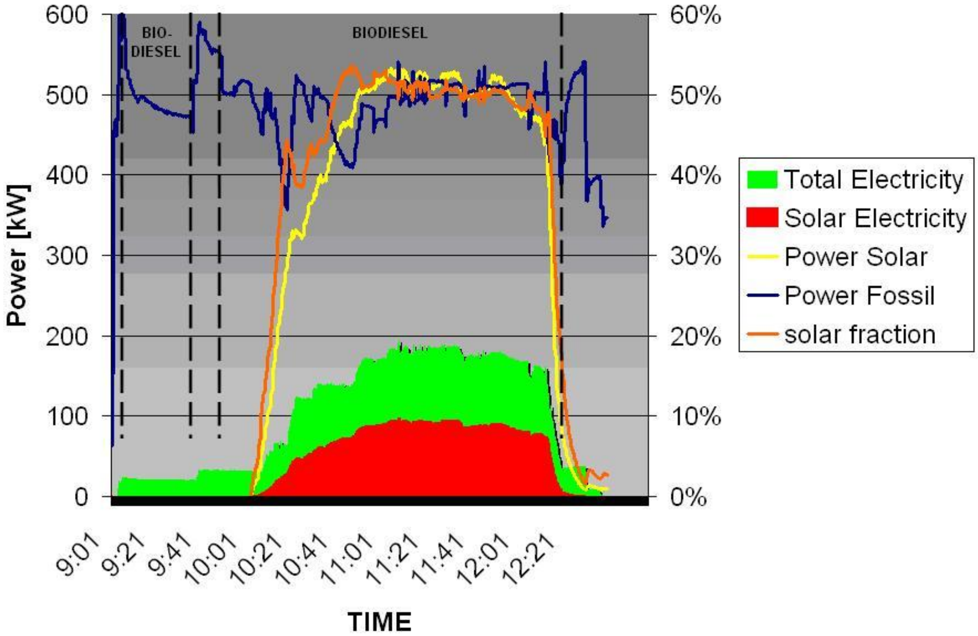


Figure 3.19 Power data from the first biodiesel test

gas" unit which finds the air flow rate by means of a gas marker. The flow meters can only be used at low powers, but as they are highly reliable, they were very useful for calibrating the "tracer gas" system. Eleven low-power tests were done in the summer of 2008. The "tracer gas" system caused some problems, but finally was calibrated and is now operating reliably.

Finally, on August 7, 2008, the flow meters were deactivated and high-power tests were begun again. Unfortunately, there were many problems with the turbine, so at the end of the time allotted for testing in mid-September, all of the nominal conditions had still not been reached. Testing was restarted in March 2009, with 6 tests in just one week. In the best of them, on March 13, 2009, extraordinary data were achieved. The outlet air temperature stayed at 840ºC for over an hour and reached a peak of 843ºC with an electrical power of 217 kW. However, it was not possible to reach 100% turbine speed. The cause is not entirely clear, but there is a possibility that installation of the flow-meter tube installation caused a slight pressure drop leading to poorer turbine performance.

Figure 3.20 Sistema SolHyco in operation, focal zone

In April 2009, the whole system was completely dismounted and the turbine was returned to Israel, after seven years in very successful operation with highly concentrated solar energy.

A total of 30 tests were done under the SolHyCo Work Package 3, with 77 hours of turbine operation, 60 of them with biodiesel and 58 with solar radiation. Biodiesel operation could hardly be distinguished from operation with kerosene, except in the different startup procedure. The improvement in air mass flow measurement produced the expected results, mainly because of the limitations the flow meters imposed on the system.

Work Package 5 components, including the 100-kW commercial Turbec turbine, and the advanced tube receiver were mounted starting in summer of 2009. Installation was completed in autumn 2009 and some off-sun turbine tests were done, but due to problems with combustion control caused by the additional mass of the receiver, in 2009, solar testing had still not begun. This testing is scheduled for completion in the first half of 2010.

Publications: [3.15]

3.3.5 CENIT-CONSOLIDA: Study of the state of the art and need for R&D in solar concentrating systems (Activity 2)

Participants: ABENGOA SOLAR NT, CIEMAT-PSA, IDESA, Prodintec termofluids and CTTC.
Contacts: Paula Llorente (Paula.llorente@solar.abengoa.es); Félix M. Téllez (felix.tellez@ciemat.es)
Budget: CDTI-ABENGOA-SNT: 75 k€
Duration: January 2008 to December 2009.

Background: This project is Activity 2 of the CENIT Consolida strategic industrial research project called "Solar R&D Consortium", coordinated by Abengoa Solar NT and approved at the fourth CENIT program, under the 2010 Ingenio Initiative.

A diversity of independent studies and the International Energy Agency itself confirm that solar thermal power plants are the most economical way to generate electricity from solar energy on a large scale. This diagnosis, however, places the direct cost of capital from 2.5 to 3.5 times higher than a conventional thermal power plant, and the cost of the electricity they generate 2 to 4 times more. Nevertheless, the margin for cost reduction is enormous and the goal of reducing the LEC to less than 8 c€/kWh is feasible within the next 15 years. The uncertainty existing in costs associated with many of the technologies due to the absence of current references in manufacturing and commercial installation, and their potential progress insofar as improved performance and durability makes a comparative analsyis based on technological survey and the corresponding feasibility studies necessary to set the priorities for R&D goals and content.

Purpose: This activity has two basic goals:

- Survey of technology options, current state of maturity, and associated risks.
- Identify the critical points in developing those technologies, their sensitivity and impact on the technologies becoming sufficiently competitive and penetrating in the future framework.

Achievements in 2008-2009:

- Parametric analysis of the optimum dimensions of parabolic-trough collectors (PTC)
- Storage management
- Influence of the working temperature and the type of heat transfer fluid used (gas, molten salt, silicone, direct steam generation, etc.) on the thermal efficiency of the solar thermal power plant.

3.3.6 CENIT-CONSOLIDA: R+D for improving key CRS technology components (Activity 3)

Participants: ABENGOA SOLAR NT, CIEMAT-PSA, IDESA, Prodintec termofluids and CTTC.
Contacts: Lucia Serrano (lucia.serrano@solar.abengoa.es); Jesús Fernández-Reche (jesus.fernandez@psa.es)
Budget: CENIT + ABENGOA-SNT: 200 k€
Duration: January 2008 to December 2011.

Background: Activity 3 of the CENIT Consolida strategic industrial research project, "Solar R&D Consortium" coordinated by Abengoa Solar NT and approved in the fourth call of the CENIT program under the Ingenio 2010 Initiative.

Tower technology projects to date for superheated steam, mainly SOLAR ONE, have shown this technology's need for technological development before it can enter the market. The presence in the same receiver of a fluid in two different phases and with very different thermodynamic properties makes evaporation and superheating of the water difficult to control, causing strong stress and deformation in the receivers tested up to now. Separation of evaporation phenomena and superheating simplifies control, making the combined process easier to operate. ABENGOA SOLAR NT, in collaboration with other companies and a research center, is evaluating a power tower solar receiver prototype for superheated steam that considerably improves system performance and cost under Consolida Activity 3.

Purpose: CIEMAT support consists mainly of i) consulting and selection of measurement instruments to be used in the superheated steam receiver, ii) drafting the test plan and iii) process control protocols, as well as iv) simulation of the magnitudes to be measured and other important process variables.

Achievements in 2008-2009: In 2008 and 2009, CIEMAT's work under CONSOLIDA Activity 3 consisted of recommending the measurement instruments to be used in the superheated steam receiver and simulation of the measurements found with them (incident flux map).

The project is now comparing the simulation with real plant data.

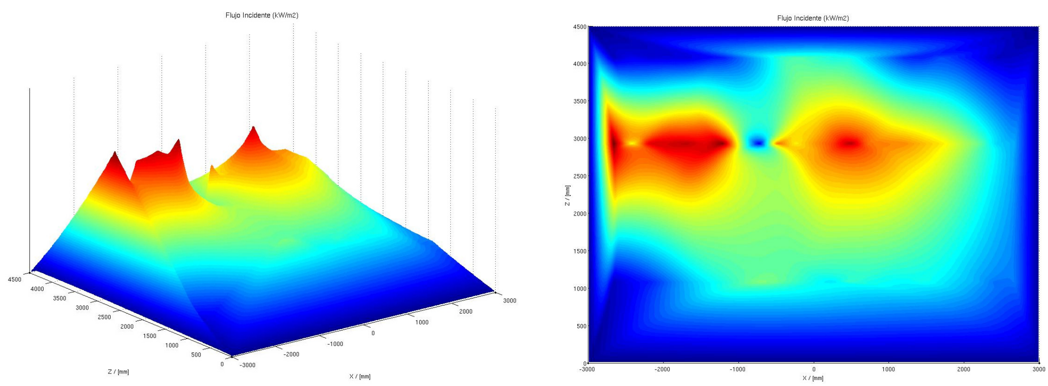


Figure 3.21 Incident flux and projection of this flux on the receiver aperture plane in the CONSOLIDA Project

3.3.7 Activities in the Radiometry Laboratory

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

Background: The Plataforma Solar de Almería (PSA) Radiometry Laboratory was born of the need to verify measurements of solar irradiance (“flux” in solar concentration jargon) and surface temperature of materials (IR detection), radiometric magnitudes of great importance to solar concentration.

Several systems are used at the PSA for measuring high solar irradiance on large surfaces. The basic component in these systems is the radiometer, and measurement of the incident concentrated solar radiation power in the aperture of the solar receivers depends on their proper use. Measurement of this magnitude is fundamental for determining the efficiency of the receiver prototypes evaluated at the PSA and for defining the design of future central receiver solar plants.

During the MEPSOCON Project (Measurement of Concentrated Solar Power in central receiver power plants, Ref. DPI2003-03788) A calibration procedure for high solar irradiance radiometers was defined and put into practice. Until that time there had been no procedure for calibration of these sensors. A systematic error in the measurement of high solar irradiance was found and corrected. Calibration of high solar irradiance radiometers continues to be a normal practice in this radiometry laboratory, which provides this service to national and international companies, such as Solucar, CENIM, DLR and CIEMAT.

Achievements 2008-2009: In 2008-9, functioning of radiometers operating in the PS10 and PS20 towers was analyzed and their calibration was verified.

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

Figure 3.22 Calibration of an IR detector in the laboratory

The Radiometry Laboratory has three black bodies which are used as references for calibrating IR sensors for measuring temperature with guaranteed traceability in the 0-1700ºC range. The MIKRON M330 black body is a cylindrical cavity and can provide any temperature between 300 and 1700ºC accurate to ± 0.25% and resolution of 1ºC. Its emissivity is 0.99 in a 25-mm-diameter aperture. The MIKRON M305 black body is a spherical cavity and can provide any temperature between 100 and 1000ºC with a precision of ± 0.25% and a resolution of 1ºC. Its emissivity is 0.995 in a 25-mm-diameter aperture. The MIKRON M340 black body is a flat cavity and can provide any temperature between 0

Figure 3.23 Radiometry Laboratory.

and 150ºC accurate to ± 0.2ºC and a resolution of 0.1ºC. Its emissivity is 0.99 in a 51-mm-diameter aperture. These black bodies have a PID control incorporated and the temperature is checked by a high-precision platinum thermocouple.

Some of the testing at the PSA requires measurement of high temperatures (>1000ºC) on the surface of materials. In some cases the use of quartz windows is even required to be able to work in the inert atmosphere necessary to impede oxidation of the test materials. The quartz allows most of the solar radiation to pass through it but impedes much of the infrared spectrum emitted by the hot surface from going back out. Thermocouples have commonly been used up to now even though it is widely known that contact measurements are not correct for surface temperatures. Therefore infrared detectors must be used (non-contact measurement) that allow the radiation emitted by the hot surface to be distinguished from the solar radiation reflected by that surface.

The most promising lines of research propose the use of infrared sensors that work in shortwave spectral ranges containing the atmospheric absorption bands for H_2O and CO_2 and use passband filters to be able to detect the radiation on the hot surface through a quartz window without distortion by the reflected solar radiation (Figure 3.24). During the last two years, an IR camera with pass band filters in the zones of atmospheric solar absorption of

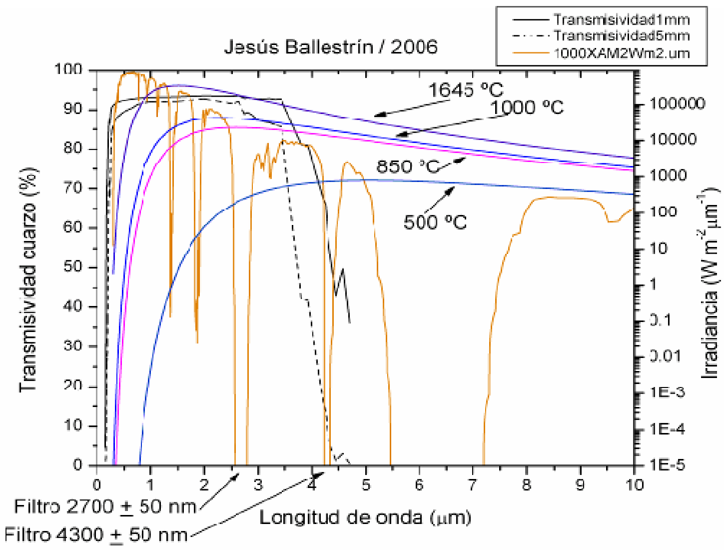


Figure 3.24 The problem of surface temperature measurement in the solar context

1900, 2700 and 4300 nm was defined, designed and validated.

In collaboration with the PSA meteorological station, studies for characterization of solar spectral irradiance have been begun.

Publications: [3.16]-[3.18]

3.3.8 Activities in Accelerated Ageing and Durability of Materials

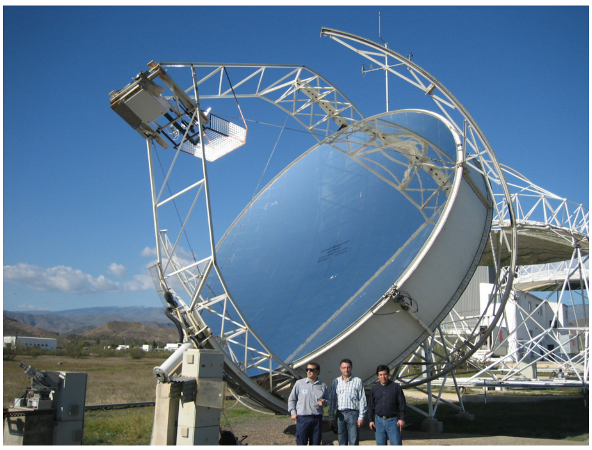
Participants: CIEMAT-PSA (E).
Contacts: Jesús Fernández-Reche (jesus.fernandez@psa.es), Mónica Álvarez de Lara (monica.alvarezdelara@ciemat.es)
Funding: ERDF, SOLNOVA Project (Plan-E) and own funding.
Duration: 2009-...

Background: One of the unknown factors that remains to be solved in power tower systems is the durability of the materials and components subjected to high-flux incident solar radiation and daily heating/cooling cycles at temperatures up to 1000ºC, mainly solar receivers. The AVANSOL project has begun to study the durability of absorber materials, and as a consequence of this project, the Plataforma Solar de Almería has started up a line of strategic research in durability of materials subjected to high solar flux and high temperatures. Fruit of this is the laboratory described below.

Purpose: i) Develop test methodologies for accelerated ageing and inference of durability of materials subjected to high solar flux and high temperatures, ii) reduce the uncertainty associated with component durability in solar power tower plants, iii) analysis and selection of materials adequate for the different tube or volumetric tower receiver technologies and for the different cooling fluids: steam, molten salt, air, etc.

Achievements in 2008-2009: The accelerated ageing laboratory consists of:

- A proper laboratory equipped with the instrumentation necessary for thermal cycling and materials analysis (kilns and high-temperature furnaces, weather chambers, etc.)
- 4 parabolic dishes in which test platforms have been installed to subject materials or scaled receiver prototypes to high solar concentration and perform accelerated temperature cycling.



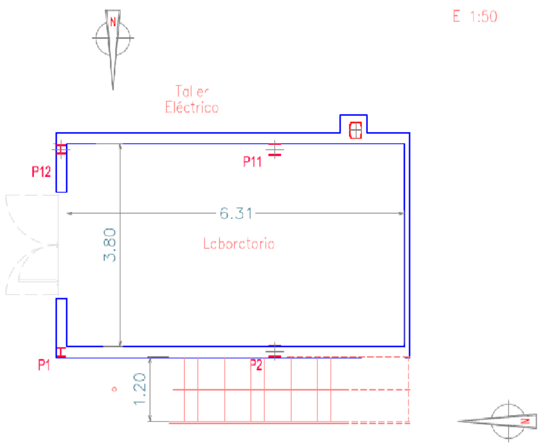


Figure 3.25 Thermal cycling in one of the parabolic dishes and floorplan of the materials and ageing laboratory (equipment to be completed in the first half of 2010).

In 2008, a series of preliminary thermal cycling tests were done on flat and cylindrical test pieces made of different materials.

Publications: [3.19]-[3.23]

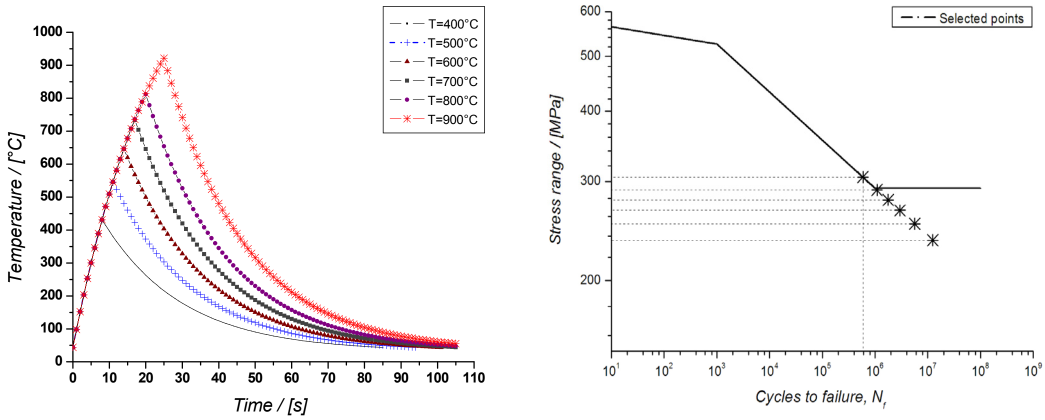


Figure 3.26 Thermal cycling of AISI 316TI and stress curve.

3.3.9 Other Activities of the High Concentration Group in 2008 and 2009

In addition to the R&D activities described in the paragraphs above, the Solar Concentrating Systems Unit's High Concentration Group carried out other activities similar to those in the Medium Concentration Group in 2008 and 2009:

- Improvement of heliostat optical characterization capabilities (modeling and instrumentation) by means of imaging and analysis of an image projected onto a white target on the tower.
- Testing/verification of auxiliary components for solar thermal power plants (such as valves, nitrate salt filters, auxiliary heating systems, etc.). The confidential nature of this type of work does not allow us to provide more specific information on the work done by the PSA in 2008 and 2009 with regard to these subjects.
- Diffusion of the central receiver technology by participating in conferences and courses on renewable energies. In this field, the most significant contribution of the High Concentration Group was our participation in the three courses on "Solar Concentrating Systems" given in Madrid in 2008 and 2009.
- Consulting for promoters and engineering firms and teams involved in central receiver technology in those areas in which the GACS has accumulated significant experience, such as measurement of high solar flux, diagnosis of heliostat incidents, selection of materials for solar receivers, thermal behavior of receivers and storage devices, design tools, simulation and estimation of annual electricity production, etc.
- Feasibility studies on central receiver CSP technology, including state of the art, the potential of innovations already available or implementable in the short term and production cost scenario analyses for regional systems (e.g., study done for Costa Rica).
- Ongoing technology review (commercial and pre-commercial projects, component development, applications, etc.) and strategic planning to di-

rect GACS activities attempting to push some concepts which we are convinced have high potential for being competitive in the short to mid term (such as pushing central receiver technology with unpressurized air as the heat transfer fluid).

- Finally, in view of the material and human resources available, we collaborated in and initiated project proposals for their partial financing 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

Production of fuels such as hydrogen and integration of solar concentrating technologies in industrial processes are the main goals of the H_2 Solar and Solarization of Industrial Processes Group. Given the low self-supply in our country and its high energy consumption, the initiatives directed at making use of renewable resources for diversifying the energy supply based on production of hydrogen or integration of the solar technology in very energy-intensive sectors could improve the wealth and welfare of our country.

The interest awakened by hydrogen as an energy vector in the transportation sector and the indubitable attractiveness that its clean production from solar energy presents makes the PSA give special attention to the adaptation of high-temperature solar concentrating technologies for their application to mass production of hydrogen. The following projects are now underway: SYNPET "Solar thermochemical application for production of syngas from heavy crude oil", a private initiative for demonstrating the technical feasibility of solar gasification by Eidgenössische Technische Hochschule ETH (Switzerland) and PDVSA (Venezuela), the HYDROSOL II Project "Solar hydrogen via water splitting in advanced monolithic reactors for future solar power plants"; EC FP6-2004-ENERGY, as the first pilot experiment in the world for the development of thermochemical cycles to obtain hydrogen from water, demonstrates the clear CIEMAT commitment to these technologies. Some national initiatives could also be mentioned, for example, the three stages of the Solter-H project "Generation of hydrogen from high-temperature solar thermal energy" (PROFIT) in cooperation with the Hynergreen company, the Community of Madrid PHISICO2 Project, and the CENIT Consolida strategic industrial research project "Solar R&D Consortium" CENIT-2008-1005.

Furthermore, since 2007, the CIEMAT is a member of a European initiative called the European Joint Technology Initiative (JTI), which is investing approximately 430 million Euros in 6 years in fuel cell and hydrogen research, technological development and demonstration projects

The application of solar concentrating technologies to high-temperature industrial and thermal processes is another field of enormous importance, which the PSA is channeling through its coordinated project, SOLARPRO, in cooperation with Spanish universities and research centers, the purpose of which is to demonstrate the technological feasibility of using solar thermal energy as an energy supply system in high-temperature industrial processes.

3.4.1 Hydrogen production

From the environmental point of view, combustion of fosil fuels is the major source of greenhouse gas emissions. This situation is not sustainable in the mid term and governments insist on the need to prepare a controlled transition toward a new clean, safe and reliable way of producing and consuming energy. One of the responses to this oncoming crisis is the use of hydrogen as an energy resource and its transformation into electricity by fuel cells.

Thus the term "hydrogen economy" responds to a vision of the future where clean, economical hydrogen would supply the majority of the energy needs of society. This proposal would reduce current dependence on fossil fuels, since hydrogen could be generated from other primary sources, such as renewable or nuclear energy. Air pollution and greenhouse gas emissions would also be decreased, since the only waste generated by a fuel cell is water.

Hydrogen is called on to be the perfect replacement (clean, unending, etc.) for fossil fuels, which in Spain make up 84% of primary energy consumed and for which it is 99.5% dependant on foreign supply. It is also an energy storage system, since waste energy can be used to produce it. Its production by reforming, gasification or oxidation of fossil fuels can only be considered a transition toward production processes that use mainly renewable energy sources.

Efficient, clean fuel cell technology is of maximum interest for a diversified energy future, since it allows the direct conversion of a fuel (hydrogen, and also hydrocarbons) into electricity. Thus, the use of fuel cells for generating electricity in buildings would enable efficient, clean conversion of traditional fuels (gas natural) or hydrogen. Electric cars powered by fuel cells demonstrate similar features to the traditional internal combustion, but with no polluting emissions. Portable devices (telephones, computers, etc.) that use fuel cells will have better features and more autonomy. Furthermore, greater integration of renewable energies will be possible by producing hydrogen and using fuel cells.

The CIEMAT has extendsive experience in work groups for scientific and technological development in sectors such as the production of H_2 and development of fuel cells. In the first case, the main goal of CIEMAT is research and development of efficient, competitive hydrogen production technologies that enable implantation of the hydrogen economy in the transportation and stationary consumption sectors in Spain from domestic energy resources.

The PSA is the basic instrument for development of renewable hydrogen production processes using the abundant solar resource available in our country and the excellent knowledge of concentrating solar technologies applicable to reactors operating at temperatures above 1,000ºC. There are two fields of activity:

- Development of fossil fuel decarbonization processes and technologies and their revaluation by solar gasification, with special attention to low-quality carbonaceous materials.
- Pre-commercial demonstration of the technical and economic feasibility of water dissociation for hydrogen production using thermochemical cycles with concentrated solar energy.

SYNPET
Solar gasification of oil coke project

Participants: Petróleos de Venezuela (PDVSA), Technological Institute of Zurich (ETH) and the CIEMAT.
Contact: Juan Carlos de Jesús, dejesusjc@pdvsa.com
PSA Contact: Alfonso Vidal, alfonso.vidal@ciemat.es
Funding: Project funded by the Partners, with PDVSA holding the majority share.
Budget: 6.950 k$. CIEMAT: 1.940 k$.
Duration: September 1, 2002 – February 28, 2010

Background: Solar gasification of carbonaceous materials is a route of great interest in the transition to the hydrogen economy. Specifically, gasification of oil coke is a complex process, but overall chemical conversion may be represented by a simplified net reaction.

$$CH_xO_y + (1-y)H_2O \rightarrow (\frac{x}{2} + 1 - y)H_2 + CO$$

where x and y are the H/C and O/C elemental molar ratios in oil coke respectively. The chemical product obtained is syngas, the quality of which depends on x and y.

In conventional gasification, the energy needed to heat the reagents and to supply heat for the reaction is supplied by burning a large amount of raw material. Internal combustion (autothermal reactors) causes pollution by gas products while in external combustion (allothermal reactors) performance is lower due to irreversibility associated with heat exchange. Therefore, the advantages of supplying solar energy for heat processes is multiplied by three: 1) the calorific value of the raw material is increased; 2) gases are not polluted by combustion subproducts; and 3) environmental pollution is avoided.

Purpose: The main purpose of the SYNPET Project is to demonstrate the technical feasibility of solar gasification of waste from processing extra-heavy oil from the Faja del Orinoco. Specifically, to develop the thermodynamic and kinetic parameters of the associated reactions, design a solar reactor with quartz window, and scale up to and evaluate a 500 kW facility located at the top of the CRS tower at the PSA.

Achievements in 2009: Plant construction was completed in 2009 and commissioned in July. Start-up underwent some delays because of the need to modify the configuration of the ceramic material in the front cone. This material was damaged (cracks, breakage, etc.) during irradiation tests made during the first weeks of commissioning. These first tests were done without the quartz window, and with irradiation flux of 1.5 MW/m^2.

Figure 3.27 shows a facility flow diagram and final arrangement of the equipment. The dosing system has a 40-L hopper able to dose powdered coke (50-200 µm) with a series of worm screws that ensure <5% precision. The dosing system (5-50 kg/h) supplies a 500-dm^3 vat where coke and water suspension is prepared. Finally, the pressurized suspension is forced into the SYNPET reactor by a positive displacement pump.

Inside the reactor the coke reacts at temperatures from 1100 to 1400ºC to produce a gas rich in H_2 and part of the material that has not reacted, coke, H_2O, inert material (ash, slag, etc.). The gas that leaves the reactor is cooled by a standard heat exchanger (TEMA BEU Type) designed to lower the temperature to 80ºC. A first estimation of the thermal load of the reactor outlet gas shows a maximum power of 200 KW supplied by the water in the cooling tower located at the foot of the CRS tower.

In continuation, a separator tank collects the solids and the steam that has not reacted. These solids are usually slag (inert material from the coke) and part of the carbon that has not reacted. Syngas production for this process has been estimated at 100 to 180 kg/h with an approximate composition of 40–60% H_2, 20–40% CO, <5% CO_2, <1% CH_4, <0.1% SH_2. This gas is burned in a torch at the end of the line.

Scale-up of the facility from the small 5-kW reactor tested in the PSI solar furnace (Zurich) with oil coke [3.26] has required a complete review of the feed concept, quartz window design and gas waste heat recovery. Construction and engineering solutions adopted by the PSA in each case are more like

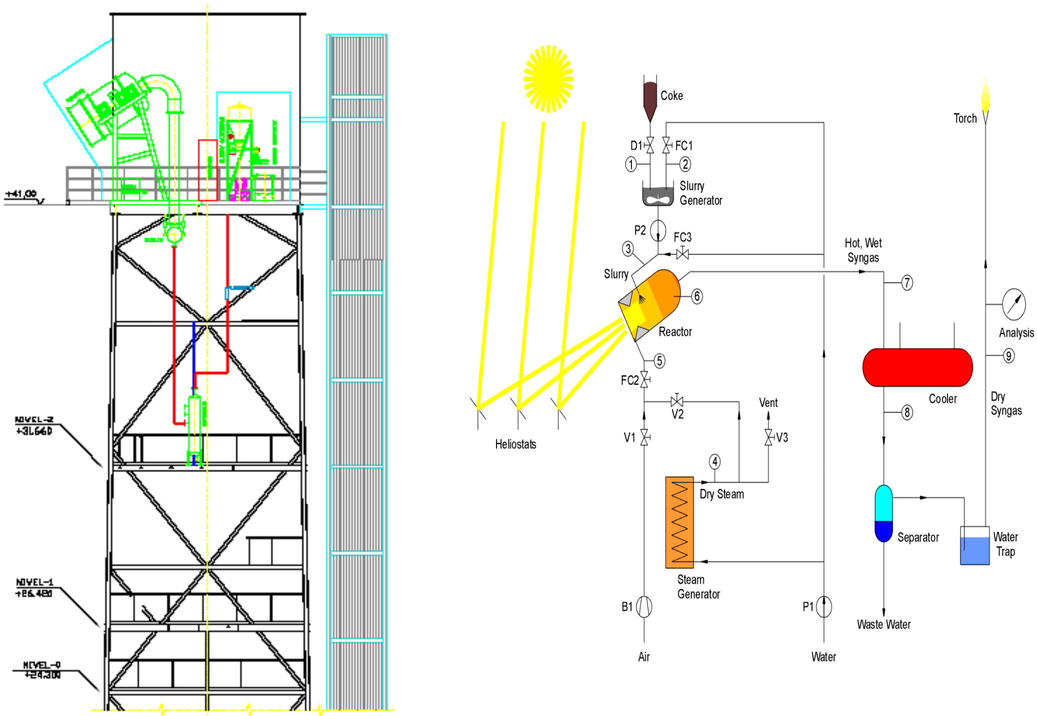


Figure 3.27 Flow diagram and arrangement of equipment in the tower

a real plant adapted to solar energy as the primary energy source.

Thus far, 2 processes have been patented in the U.S., gasification and the solar reactor [3.29]. In June 2009, the documents necessary to patent the quartz window used in this application were sent in.

Publications: [3.26]-[3.29]

Solter H Project
Generation of hydrogen from high-temperature solar thermal energy. PROFIT Project.

Participants: Hynergreen and CIEMAT.
Contact: Victoria Gallardo; victoria.gallardo@hynergreen.abengoa.com
PSA Contact: Alfonso Vidal, alfonso.vidal@ciemat.es

Budget: Cooperation Project funded by the MEC (Spanish Ministry of Education and Science) PROFIT program. Total budget: 987 k€. CIEMAT Budget not including personnel: 286 k€.

Duration: January 1, 2004 – March 31, 2009

Background: The most confidence is deposited in thermochemical cycles as a mid-to-long-range solution for mass production of clean H_2 for solar energy.

Thermochemical cycles have the great advantage of allowing dissociation of the water molecule into several stages, generating H_2/O_2 in different stages. As an example, a thermochemical cycle based on the use of Ni-Mn ferrites, which is the subject of study in the SOLTERH Project, is summarized below:

$$Ni_{0.5}Mn_{0.5}Fe_2O_4 \rightarrow Ni_{0.5}Mn_{0.5}Fe_2O_{4-\delta} + \delta/_{2}\,O_2$$

$$Ni_{0.5}Mn_{0.5}Fe_2O_{4-\delta} + H_2O \rightarrow Ni_{0.5}Mn_{0.5}Fe_2O_4 + \delta H_2$$

The use of mixed oxides (ferrites) has some important advantages, as it is a simple cycle that considerably lowers the material regeneration temperature. Hydrogen generation is based on artificially creating defects in the oxide structure.

Purpose: The main purpose of the SolterH Project is to demonstrate the usefulness of the binomial renewable energies-hydrogen vector, specifically, with solar thermal energy, for producing clean, renewable hydrogen from the unlimited solar resource. The final goal of the SOLTERH Project is to design, develop and evaluate a system able to produce hydrogen from high-temperature solar thermal energy, which would consist of testing a 5-kW solar reactor at the Plataforma Solar.

Achievements in 2009: In 2009, testing was done in the PSA Solar Furnace using Ni ferrites supplied by Sigma-Aldrich. The first tests were directed at determining the amounts of O_2 and H_2 obtained from each stage based on our laboratory experience.

The stages may be summarized along general lines as:

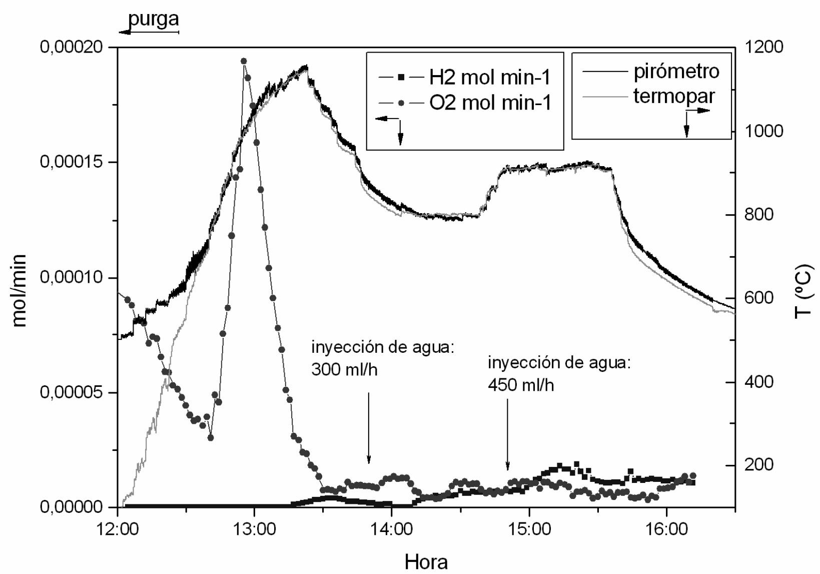


Figure 3.28 Evolution of O_2 and H_2 inthe first thermochemical cycle with $NiFe_2O_4$.

$$MO_{oxidada} \rightarrow MO_{reducida} + O_2 \qquad 1400^{o}\ C$$
$$MO_{reducida} + H_2O \rightarrow MO_{oxididada} + H_2 \qquad 900\ ^{o}C$$

This operation has been performed for several cycles to confirm the repeatability of the cycle and durability of the material after cycling. Figure 3.28 shows the molar flows of oxygen and hydrogen during the experiment, and the temperature on the surface of the ferrite bed.

The numerical integration of the molar flow-time curves gave the total amounts of oxygen and hydrogen produced, as shown in Table 3.1.

Table 3.1 Results of two cycles with $NiFe_2O_4$

Etapa	T max (ºC)	O_2 mmol g^{-1}	H_2 mmol g^{-1}	H_2/O_2	Performance hydrolysis (%)
Activation 1	1190	0.0105	-	0.1	5
Hydrolysis 1	1150	-	0.001		
Activation 2	1200	0.0028	-	5.7	285
Hydrolysis 2	1075	-	0.016		
Total		0.0133	0.017	1.3	65

The H_2/O_2 molar ratio reflects the chemical performance of the hydrolysis stage, keeping in mind that the stechiometric H_2/O_2 ratio for dissociation of the water molecule is 2. Furthermore, this ratio is an indicator of system cyclability, since a ratio closer to stechiometric would indicate more re-oxidation of the ferrite reduced and, therefore, more recovery of the original material.

The results of this first cycle, from the viewpoint of hydrogen production and the H_2/O_2 ratio are far from those found in the laboratory. However, in the second cycle, the contrary occurs. Although oxygen production in the second activation drops with respect to the first, hydrogen production increases noticeably in the second cycle over the first.

Similar results were found in laboratory cyclability studies with a $NiFe_2O_4$ sample, and may be explained by the second hydrolysis oxidizing part of the ferrite which had been reduced in the first cycle but not reoxidized. Laboratory tests combined with different physico-chemical characterization techniques for the study of this behavior are currently underway.

Publication: [3.32]

PHISICO2 PROJECT
Clean Hydrogen production: CO_2-Emission-Free Alternatives

Participants:	King Juan Carlos University, CSIC, INTA, REPSOL, HYNERGREEN and CIEMAT.
Contact:	David Serrano; david.serrano@urjc.es
CIEMAT Contact:	Alberto Quejido; alberto.quejido@ciemat.es
Budget:	Cooperation Project funded by the IV PRICIT- Madrid Regional Science and Technology Plan. Total Budget: 1,000 k€. CIEMAT budget not including personnel: 240 k€.
Duration:	January 1, 2006 – December 31, 2009

Background: This project is basically motivated by the need to coordinate the research efforts and capabilities of a series of research groups located in Madrid (URJC, CSIC, CIEMAT, and INTA) related to the study and development

Table 3.2 Amounts of O_2 and H_2 per gram of calcinated ferrites at different temperatures, found during the stage of activation and hydrolysis, respectively, during 2 consecutive thermochemical cycles

T CALCINATION	-		700		900		1100		1300	
Ciclo	1º	2º	1º	2º	1º	2º	1º	2º	1º	2º
mmol O_2/g	0.47	0.49	0.62	0.58	0.71	0.54	0.70	0.49	0.63	0.57
mmol H_2/g	0.62	0.54	0.52	0.42	0.49	0.50	0.55	0.54	0.65	0.55
H_2 / O_2	1.32	1.10	0.84	0.51	0.69	0.93	0.79	1.1	1.03	0.96

of different clean hydrogen production processes, that is, CO_2-emission-free, using renewable energies as the primary energy source for its generation. Two companies in the energy sector (REPSOL YPF and HYNERGREEN) have shown their interest in participating actively in the project and following up on the results. CIEMAT participation in this project is through several of its research groups, the PSA Division Hydrogen Group, the Chemistry Division, and the Fusion Laboratory's Materials Unit.

Hydrogen production processes included in this project are the following: photoelectrolysis of water, thermochemical cycles and decarbonization of natural gas. This project attempts to evaluate their mid-to-long-term technical and economic feasibility and their ability to lower CO_2 emissions from more conventional hydrogen production systems, such as gasification and steam reforming.

Purpose: The basic purpose of the project is to study different clean hydrogen production processes to advance in solving the technological and economic limitations it now presents, and which is essential to be able to carry out a future transition to a hydrogen economy. The alternatives in this project are characterized by avoiding the formation of CO_2 as a co-product of hydrogen and their use of renewable resources to provide the energy consumed in forming and releasing hydrogen.

1) Hydrogen production from water by photodecomposition
2) Hydrogen production from water by solar thermal processes based on thermochemical cycles
3) Hydrogen production based on natural gas by catalytic decarbonization
4) Comparative analysis of the different hydrogen production processes proposed

Achievements in 2009: During 2009, hydrogen production in thermochemical cycles with commercial ferrites calcinated at different temperatures was studied. From this evaluation it was concluded that commercial Ni ferrite is the one that provides the best results insofar as H_2 production and hydrolysis reaction performance, so it was decided to study this system in more detail.

The study was completed by carrying out the hydrolysis stages and completing a second cycle, including the results found with a sample calcinated at 1300ºC (Table 3.2). These results show that the amount of oxygen given off during the activation stage increases with calcination temperature to a maximum of 900 to 1100ºC. With the sample calcinated at 1300ºC, this tendency rises, which could be due to part of this sample having begun to activate during the calcination stage. In view of these results, the amount of hydrogen obtained in the hydrolysis reaction could be expected to follow the same trend. However, these values are not in keeping with any apparent relationship with the temperature of calcination, and it is the original uncalcinated Ni ferrite which has the highest hydrogen production and is the most efficient in the hydrolysis reaction, as shown by the H_2/O_2 molar ratio.

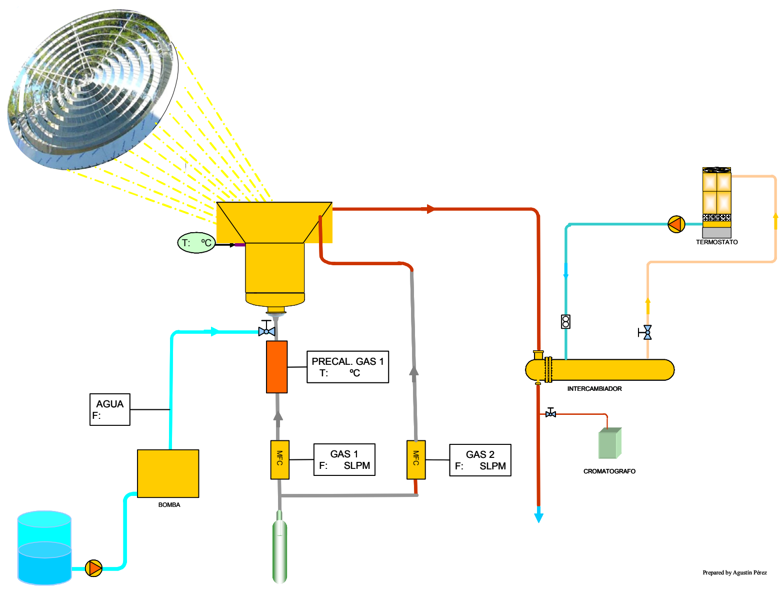


Figure 3.29 Diagram of the PHYSICO Project setup

At the same time this year, the solar fluidized bed reactor was design along with the GIQA-URJC Group. For this the GIQA-URJC Group performed laboratory fluidization experiments with the ferrite selected for the first solar tests ($NiFe_2O_4$ Sigma Aldrich). To do this, different particle sizes and temperatures were used until fluidization was achieved with a particle size between 125 and 250 μm as the smallest size possible at 900ºC. Keeping in mind the fluidization conditions found in the laboratory, the reactor dimensions were scaled up to match them to the solar concentrating system installed in CIEMAT-Madrid.

The solar reactor basically consists of a steel cylinder with a ceramic inner coating, with a cone at the top ending in a quartz window that allows the concentrated solar radiation to go through, the focal plane which is at the top of the fluidized bed, so the ferrite particles absorb this radiation directly. The inert gas enters at 700ºC to facilitate fluidization and make it possible to reach the reactor temperature necessary for thermal reduction of the ferrite.

The concentration device has a 6-m^2 reflective surface that makes it possible to reach a solar concentration of 500X, having measured 2 kW energy in a 20-cm diameter. The reactor system is complete with mass flux controllers for the gas supply (N_2), a water injection pump for hydrolysis, a ceramic heating element to preheat the gas, a water condensation system and a gas chromatograph (μ-GC).

Publication: [3.32]-[3.38]

PROYECTO HYDROSOL-II
Solar Hydrogen via Water Splitting in Advanced Monolithic Reactors for Future Solar Power Plants.

Participants:	APTL (GR), DLR (D), CIEMAT (E), STC (DK), Johnson Matthey (RU).
Contact:	Christos Agrafiotis; chrisagr@cperi.certh.gr
PSA Contact:	Antonio López; antonio.lopez@psa.es
Budget:	Cooperative Project funded by the EC 6th Framework Programme. Total Budget: 4.230 k€. CIEMAT budget: 647 k€.
Duration:	December 1, 2005 – September 30, 2009

Figure 3.30 Left Detail of the aperture of the 2 HYDROSOL-II Project reactors in operation. Right. View of the SSPS heliostat field from one of the HYDROSOL-II Project reactor apertures.

Background: Solar hydrogen production by the thermochemical route confronts the enormous challenge of achieving scaleup of the solar concentrating technologies and reactors able to operate at powers of several MW. At the present time, there are developments, many of them tested jointly by DLR and CIEMAT, at the PSA facilities, which enable operation with volumetric receivers at temperatures above 1000ºC. The reason for the Hydrosol-II Project is the confidence of being able to transfer the cumulative materials and system development experience with catalytic matrices using SiC with monolithic channels that were successfully validated durng the SOLAIR Project. Impregnation of these ceramic matrices with mixed ferrites would make their use possible for hydrogen production. The possibility of using this monolithic reactor with ferrites fixed to a substrate facilitates the separation of oxygen and hydrogen in alternating charge/discharge stages.

Purpose: The second stage of this project (Hydrosol-II) began in November 2005 and its purpose is to evaluate a 100-kW reactor at the Plataforma Solar de Almería using mixed Zn ferrites impregnated on ceramic SiC matrices. The novelty of this design is the use of a discontinuous charge/discharge operating mode. The endothermal stage is carried out with solar illumination in such a way that the focus of high solar radiation flux generated by the heliostat field moves alternately from some matrices to others to allow the following H_2 discharge stage to take place.

Achievements in 2009: In 2009, work at the PSA concentrated on evaluation testing of the installed monoliths.

The first tests were done in 2008 with monoliths not coated with oxides so that the influence of such factors as preheat air flow, focusing and defocusing of heliostats, the temperature reached in the reactor and effectiveness of temperature control with regard to the requirements of the water splitting/regeneration cycle. These first thermal cycles demonstrated the operational reliability of all of the necessary peripheral systems installed (such as the PLC, electric panel, wiring, desk support, thermocouples, pressure sensors, data acquisition system and process control system) and led to the first basic recommendations concerning operating strategy, especially the way to accomplish fast changes in temperature.

The first series of hydrogen production tests in 2009 demonstrated the feasibility of hydrogen production in the experimental reactor for two consecutive cycles. The monoliths used in the thermal tests were replaced by monoliths coated with zinc ferrite. At the beginning of the experiment the two reactors were heated up to operating conditions at 800ºC and in continuation, two cycles were performed (heating to 1200ºC and cooling to 800ºC) in both modules. Figure 3.31 shows results found during testing with both modules. The concentration measured would correspond to 30% steam conversión.

Several test campaigns were performed in 2009 with different types of monolith coatings, observing that the material shows the same activity as in the cycles shown in Figure 3.31. This testing demonstrated the operating capacity of the HYDROSOL II reactor for semi-continuous hydrogen production in a power tower with a heliostats field.

Publication: [3.39]-[3.41]

ORESOL PROJECT
Oxygen from Lunar Regolite with Solar Concentrating Energy

Participants: CIEMAT – PSA
PSA Contact: Thorsten Denk; thorsten.denk.psa.es
Funding: ERA-STAR Regions DeMoLOP Project (ERA – Space Technologies Applications & Research for the Regions and Medium-Sized Countries - CA-515793-ERA-STAR REGIONS), EC 6th Framework Programme. Total budget: 100 k€.
Duration: December 1, 2008 – December 30, 2009

Background: The US National Space Agency (NASA) is planning to again focus manned space exploration on the moon as the precursor of possible trips to Mars in the next two decades. The most important resource that will be required there is oxygen, for human consumption and for rocket fuel. If in situ oxygen could be achieved on the moon, a very substantial and costly part of the load that has to be transported from the earth would be saved.

Lunar regolite (powder) is rich in oxygen (up to 45% of its mass), but the chemical bonds are very strong, which means that for it to be extracted, very high temperatures over 1000ºC are necessary. As a consequence of prior studies, reduction of the lunar regolite component called ilmenite to water with hydrogen, followed by electrolysis to obtain oxygen and recover the hydrogen, is considered the most favorable chemical reaction.

$$FeTiO_3 + H_2 \rightarrow TiO_2 + H_2O + Fe$$
$$2\,H_2O \rightarrow 2\,H_2 + O_2$$

An attractive way to supply the energy necessary is using concentrating solar radiation systems, which provide high energy flux densities and would make it feasible to reach the temperatures necessary to carry out the process.

Purpose: The DeMoLOP Project is intended to study how to obtain oxygen from lunar regolite using concentrating solar energy, developing a complete demonstration system consisting of:

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

The contribution of the ORESOL project concentrates on execution of Point 2), development, construction, testing and characterization of a device able to

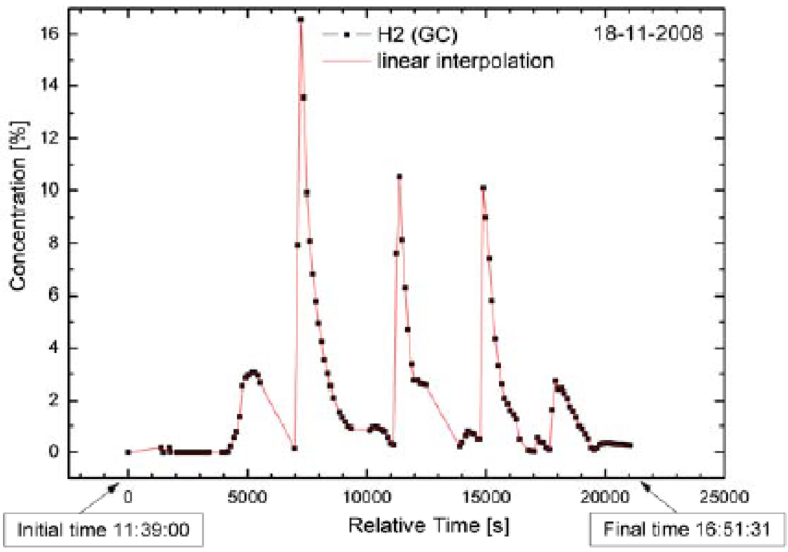


Figure 3.31 Hydrogen concentration detected by GC

carry out the chemical reaction with concentrating solar radiation to gain oxygen from a "lunar soil stimulant" made by NASA.

Achievements in 2008: The two main achievements in the Oresol Project in 2008 are complete process development and the solar reactor design.

The simplified basic Oresol process diagram is shown in Figure 3.32. Radiation from the sun is concentrated by the solar concentrator (1). The reactor is located in the focus (2). This reactor is fed by lunar regolite and hydrogen. The products are regolite slag and gas composed mostly of the excess feed hydrogen and the rest is steam, the desired solar thermal reactor product. Due to the low useful reagent (ilmenite) content in regolite, a large amount of solids will inevitably have to be processed with their associated energy consumption to heat them. Therefore, to simplify post-processing of the slag, a (partial) waste-heat recovery system is recommendable. (3) While solid waste is being ejected (8), the volatile components are sent to the water treatment system (4). In this step, excess hydrogen is separated from the water obtained, and, if necessary, the water is purified and stored. While the hydrogen reenters the process, the water goes to the electrolyzer (5). This equipment, which is the largest consumer of electrical energy in the process, dissociates the water into hydrogen and oxygen. While this hydrogen is also recycled, oxygen is the desired final product of the process (9). The diagram is completed by grounding (12), a heat rejection system (11), a regolite gate system (7) and slag (8), other regolite pretreatment systems (7) and various subsystems, especially for pumping and storing hydrogen.

The Oresol project is only the first step toward a lunar oxygen production plant, and therefore, the process has been greatly simplified. Research is concentrating first on the key step in the process, which is the solar reactor (2). The Solar Furnace of the Plataforma Solar de Almería is being used as the solar concentrator (1). A low-expansion fluidized bed in continuous operation was chosen as the Oresol reactor concept vertically concentrated solar radiation and direct absorption through a quartz window. The reactor is designed for operation with pure hydrogen to produce up to 700 g water per hour, consuming approximately 120 kg of regolite during this time. The most important tasks pending for 2010 are completion of reactor installation and testing.

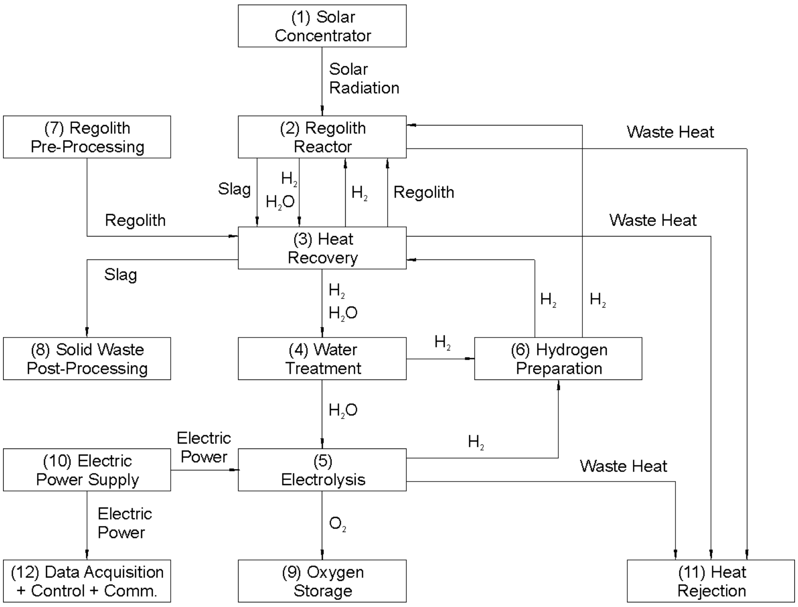


Figure 3.32 Oresol simplified basic process diagram

3.4.2 SOLARPRO II PROJECT
Development of preindustrial prototypes for solar generation of high-temperature process heat: Testing and characterization of application to production processes and waste elimination

Participants: CIEMAT, Univ. Seville, Instituto de Tecnología Cerámica, Polytechnic Univ. Cataluña, Centro Nacional de Investigaciones Metalúrgicas -CSIC

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Budget: SOLARPRO I: Project funded by the Ministry of Science and Technology under the National RD&I Plan (2003-2006). Total budget: 370.60 €. CIEMAT Budget: 176.60 €.
SOLARPRO II: Project funded by the Ministry of Science and Technology under the National RD&I Plan (2004-2007). Total budget: 35.04 €. CIEMAT Budget: 7.26 €.

Duración: SOLARPRO I: November 2003 – November 2006
SOLARPRO II: October 2006 – September 2007

Background: Solar thermal energy is the renewable energy which, because of its characteristics, must take on a relevant role in industry, as it can provide, directly or by transfer to a fluid or to an absorbent material, the thermal energy necessary for many industrial processes, and can supply process heat at different temperatures.

The industrial processes that usually require the highest energy input are those produced at high temperatures. For future implantation of the concentrating solar thermal technology in high-temperature industial processes, research and demonstration must focus on each particular process and its technological feasibility, and adjusting the design and production parameters.

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

- *Industrial production processes*: Since it is intended to take advantage of the capacity for generating high temperatures typical of concentrating solar systems, it was proposed to study the feasibility of the application of solar thermal energy to different processes of industrial interest in which a high energy input is necessary, and which have associated, if fossil fuels are used, high emissions of acidifying compounds, such as powder metallurgy processes, processes typical of the ceramic industry and a diversity of materials treatments.
- *Waste Treatment Processes*: Applying the same principle, it is intended to combine two effects beneficial to the environment, use of a renewable energy source and destruction of hard-to-eliminate waste.

Achievements: Three different, innovative prototype chambers or reactors were designed and built in parallel under SolarPRO I based on different technologies, in addition to different prototypes and test devices for specific applications. At the same time, we developed our own data acquisition and control programs, enlarged and improved facilities, put into operation and characterized the different reactors, and tested each of the different processes studied in “SolarPRO”. In SolarPRO II, these reactors were successfully improved, nearing the preindustrial goals of the project. At the present time, work on this project is continuing, developing second generations of these prototypes, and even prototypes of new designs, with successful results.

The different stages of the SolarPRO project have:

- Demonstrated the technological feasibility of using solar thermal energy as a sytem for supplying energy to different high-temperature industrial processes
- Developed three different innovative protype reactors, based on different technologies for generation of high-temperature solar process heat.
- Improved three innovative prototypes developed in the first stage of the

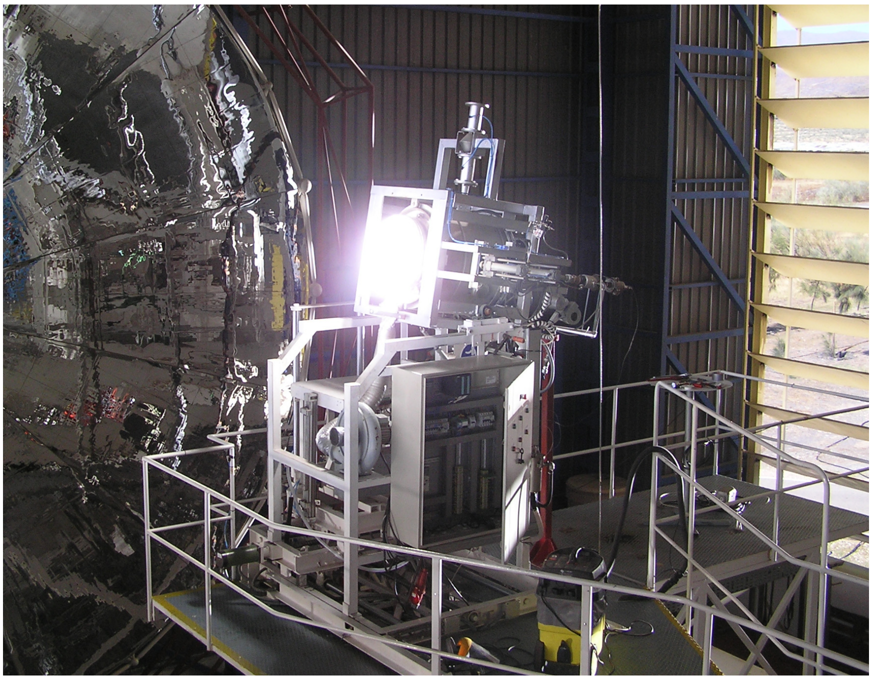

Figure 3.33 SOLARPRO Project solar reactor prototype in operation in the PSA Solar Furnace.

project, based on different technologies, with different temperatures and working conditions supplied by concentrated solar energy. The improvements made have advanced our knowledge of the prototypes and technology, so new improved pre-industrial scale prototypes can now be designed based on earlier ones.
- Identified possible new processes that could be powered by solar energy
- Acquired sufficient experience and knowledge to undertake a new stage in the pre-industrial scale project.

Furthermore, collaboration agreements are being signed with various institutions for the development of new processes and prototypes for materials processes and treatments using concentrated solar energy related to this project.

- Specific Collaboration Agreement between the Centro de Investigaciones Energéticas Medioambientales y Tecnológicas, (CIEMAT), and the Centro Nacional de Investigaciones Metalúrgicas, (CENIM), entitled, "Thermal treatment of metals by concentrated solar energy and Characterization of solar concentrators." (2006-2008).
- Specific Collaboration Agreement between the Centro de Investigaciones Energéticas Medioambientales y Tecnológicas, (CIEMAT), and the Polytechnic Univ. of Madrid entitled, "Feasibility study of the use of concentrated solar radication for the fabrication of aluminum foams" (2005-2009)

Publications: [3.42]-[3.51]

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4 Environmental Applications of Solar Energy

Head: Julián Blanco Gálvez

Contributions: Sixto Malato Rodríguez
Pilar Fernández Ibáñez
Manuel Ignacio Maldonado Rubio
Isabel Oller Alberola
Benigno Sánchez Cabrero
Raquel Portela Rodríguez
María Dolores hernández
Silvia Suarez Gil
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 water and air 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) <u>Solar wastewater detoxification and solar water disinfection</u> (Head Researcher: Dr. Sixto Malato). The activities in this line of research include, among others:
   - Development and optimization of preindustrial solar photocatalytic detoxification technology for the efficient treatment of persistent organic pollutants from the chemical industry and intensive use of pesticides in agriculture dissolved in water.
   - Development of the basic technology for the disinfection of water for human consumption in rural locations in developing countries by photochemical processes based on sunlight.
   - Development of processes that combine the above for safe and efficient reuse of all types of water currently discharged into the environment.

- Development of processes that combine the above for safe and efficient reuse of all types of water currently discharged into the environment.
- 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 of air (Head Researcher: Dr. Benigno Sánchez), with the following associated lines of research:

- Treatment of volatile organic compounds (VOCs) and/or bioaerosols by solar radiation and/or lamps with different wavelengths and luminous intensities.
- Air treatment in interiors. "Sick building syndrome."
- Treatment of foul odors in interiors and exteriors.

C) Desalination of seawater (Head Researcher: Dr. Julián Blanco), with the following lines of research defined:

- Development of technological Systems enabling incorporation of solar energy as a primary energy source in desalination of seawater and brackish water.
- Development of hybrid solar-gas systems for seawater desalination
- Installation of a double effect absorption pump in multi-effect distillation systems (MED) combined with advanced control strategies
- Application of low-temperature stationary collectors in solar desalination
- Development of solar membrane distillation technologies
- Reuse of brine in desalination
- Optimization of thermal storage systems for continuous operation of solar desalination systems.
- Integration of inverse osmosis systems in solar thermal processes

As in previous years, the growth of our research activity has been constant in all areas of the unit, as shown by the increase in the number of projects underway, the associated budget (income) and the number of staff members. And speaking of staff, they have been characterized by their enthusiasm for the timeliness of these subjects, which open up a multitude of opportunities. Some of the more senior researchers in the unit have left us in these two years causing many of the "junior" researchers to support a heavier load and increased responsibilities.

As of December 31, 2009, there were 24researchers in the unit, as follows: 5 permanent researchers, 6 contracted researchers, 1 Ramón y Cajal fellow, 1 Juan de la Cierva fellow, 9 Ph.D. fellows and 2 lab technicians. The Solar Detoxification of Air Group is located In Madrid, while the other two groups are at the PSA. The average yearly income in the Unit in 2008 and 2009 was about 600,000€.

A very important factor closely related to the Unit has been the startup in 2008 of SolarPACES Task VI "Solar Energy & Water Processes and Applications". The operating agent of this task is currently the head of the Unit, enhancing and giving greater projection to the activities and projects developed at the PSA in water processes and technologies, the main core of Activities A and C above.

Publications: [4.1]

4.2 Water Detoxification and Disinfection Group

In 2008-2009, work continued in the activities already begun in 2007, in four European Projects (European Commission 6th Framework Programme), plus another three National R&D Program projects and also The National Plan for Access to Large Scientific Installations which due to its scientific and economic importance may be considered equivalent to several national projects. It is worth mentioning that of these projects, TRAGUA is a MEC Excellence project in the 2010 *Programa Ingenio* (CONSOLIDER). Details on each of these projects are given on the following pages. During these two years our group received over 20 guest researchers from other research centers and universities in Spain, Portugal, Germany, Argentina, Ireland, Greece, South Africa, Mexico, Italy, Switzerland and Venezuela. Furthermore, four Ph.D. theses were co-directed (Dr. Isabel Oller, Dr. Cosima Sichel, Dr. Leonidas A. Pérez and Dr. María M. Ballesteros, mentioned in the references in this section).

The importance given by the group to publishing project results in impact journals is demonstrated by the 45 articles published in two years, in addition to other articles in popular professional magazines. Several of them are review articles and so especially relevant (see references in this introduction). Furthermore, our scientific activity has also been recognized in 7 Ph.D. theses underway, 4 books, 1 chapter of a book and 40 communications (20 of them oral or invited, the most relevant also mentioned in this introduction) at 12 international congresses. It should also be mentioned that we edited two special issues of the journals *Catalysis Today* and *Photochemical Photobiological Sciences*.

Publications: [4.2]-[4.16]

4.2.1 FOTOBIOX

Development of a combined oxidation (solar photocatalysis and biological oxidation) system for treatment of water effluents polluted by non-biodegradable pesticides.

http://www.psa.es/webesp/projects/fotobiox/index.html

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

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

Funding: National RD&I Plan, MEC. CIEMAT Budget: 80 K€ + 1 FPI Ph.D. Research Grant.

Duration: October 2006 – September 2009

Background: Design of combined for solar photochemical and biological reactors for water treatment.

Purpose: The goals were:

1) Study photocatalytic detoxification of pesticide mixtures using experimental design and modeling techniques.

2) Study pollutant degradation routes, influence of intermediates formed during detoxification, and increase biodegradability of the water treated.
3) Study the toxicity of other pollutants present in waste water along with the pesticides and their influence on photodegradation.
4) Design a specific biological treatment system based on microorganisms adapted to the chemical nature of the pollutants pretreated by photocatalysis.
5) Design and build a combined photocatalysis-biological pilot plant
6) Evaluate system operability and economics.

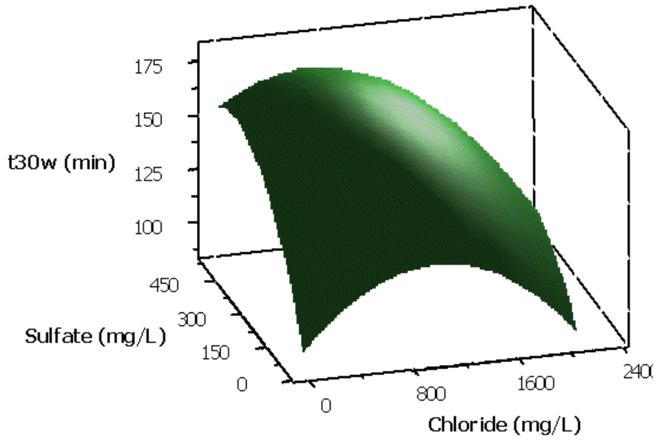

Figure 4.1. Effect of concentration of chlorides and sulfates on illumination time in the solar photoreactor necessary to completely degrade active pesticide ingredients.

Achievements in 2008-2009: In 2008 and 2009, the goals met were mainly in tasks related to goals 1 and 4-6. The modeling techniques for experiments and experimental design were used to evaluate the influence of the ionic strength of water and the type of salt (Figure 4.1) Cl^- increases consumption of H_2O_2 by formation of $Cl^{\bullet}$ and $Cl_2^{\bullet -}$, which may contribute to degradation if $[Cl^-]>$ 1000 mg/L, reducing the treatment time. The presence of SO_4^{2-} does not significantly affect consumption of H_2O_2 in the range studied, although it does increase treatment time slightly. The presence of SO_4^{2-} and Cl^- in the interval of concentrations studied (the usual in waste water) does not significantly modify photo-Fenton treatment time.

One of the purposes of this project is to determine the optimum solar photocatalysis treatment time for the pesticide in which toxicity is reduced and biodegradability has increased sufficiently to allow follow-up with conventional biological treatment (WTP). The reason for treating a pesticide mixture is not only to achieve more realistic waste water, but also so the original COD is high enough to properly evaluate the follow-up aerobic biological treatment. So it is essential to monitor toxicity and biodegradability of the pesticide mixture during the photocatalytic treatment. Figure 4.2 shows the mineralization of the pesticide mixture based on an original DOC of 500 mg/L and the COD (COD_0= 1500 mg/L) as a function of consumed H_2O_2. At the beginning of photo-Fenton, the decrease in COD is much sharper than the DOC, then smoothes out and they become very similar when all of the pesticides have been completely eliminated (at about 20 mM of H_2O_2) and their mineralization is more acute (decrease in DOC). This figure also shows how variation in AOS (average oxidation state) during photo-Fenton rises significantly at the beginning of the treatment, and when all of the pesticides in the mixture have been eliminated, it reaches its maximum (AOS=1.5). From this time forward, the

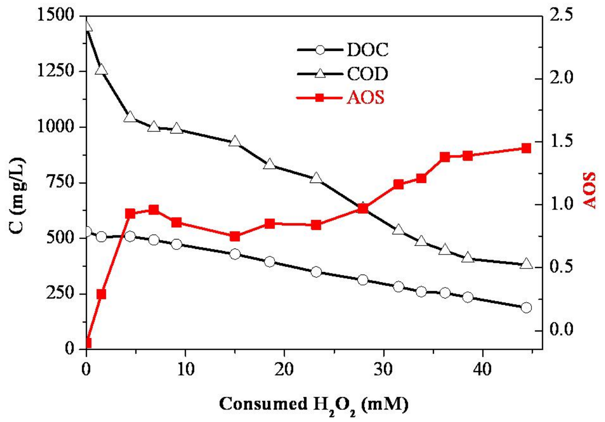

Figure 4.2. DOC, COD and AOS during photo-Fenton treatment of the pesticide mixture

AOS changes very slowly, which is a sign that it has reached a very advanced oxidation state and a possible increase in biodegradability of the mixture.

From the viewpoint of toxicity, photo-Fenton treatment of the pesticide mixture should be kept going for at least a few more minutes after their complete degradation, which is when toxicity begins to decrease. From here on, it would be necessary to test the biodegradability with activated sludge (Zahn-Wellens) to delimit the DOC interval in which the water could be discharged into a biological treatment. The Zahn-Wellens biodegradability test was therefore performed and no biodegradability was found in those samples with a DOC over 420 mg/L. However, all of the samples with a DOC under or equal to 400 mg/L were biodegradable. It may therefore be concluded that the time during the photo-Fenton photocatalytic treatment for combining the toxicological and biodegradability analyses, when biodegradability has improved sufficiently to be discharged into a biological treatment by activated sludge, has been found. This time corresponds to the complete, or almost complete, elimination (a few mg/L) of all the pesticides, ≥20% DOC and ≥60% COD.

These results must be compared to other concentrations of pesticides and other toxicity and biodegradability evaluation techniques, such as respirometry. To do this, other experiments were done. The one with the highest concentration is summarized in Figure 4.3. The original TOC in the mixture was

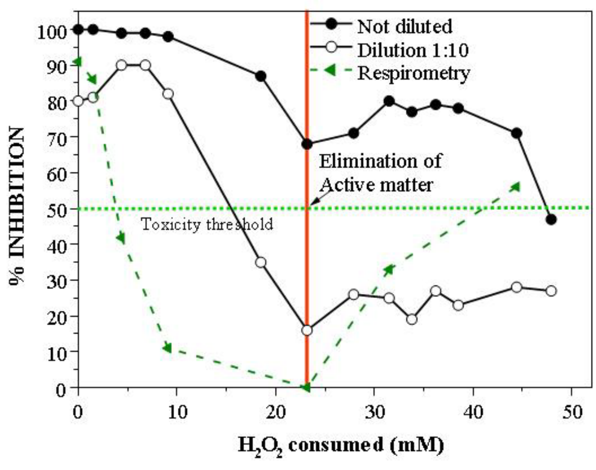

Figure 4.3. Toxicity (expressed as % of inhibition) evaluated using *Vibrio fischeri* and activated sludge in samples partly treated by photo-Fenton.

also 500 mg/L. The samples with important concentrations of active ingredients (pesticides) are toxic. These results, found in experiments with an original TOC of 500 mg/L, promise successful treatment of water in a commercial bioreactor. So results were therefore validated in a a 1060-L commercial reactor system consisting of a photoreactor with a 150-m^2 CPC field connected to a fixed-bed (immobilized) biological reactor (IBR) (2 x 1230 L) colonized by activated sludge from a municipal wastewater treatment plant (MWTP), also with a mixture of commercial pesticides (Vydate®, Metomur®, Couraze®, Ditimur-40® y Scala®) at 500 mg/L TOC (Figure 4.4). Photo-Fenton has been demonstrated to enhance biodegradability of biorecalcitrant pollutants, but only after optimizing treatment time and H_2O_2 dose.

Publications: [4.17]-[4.37]

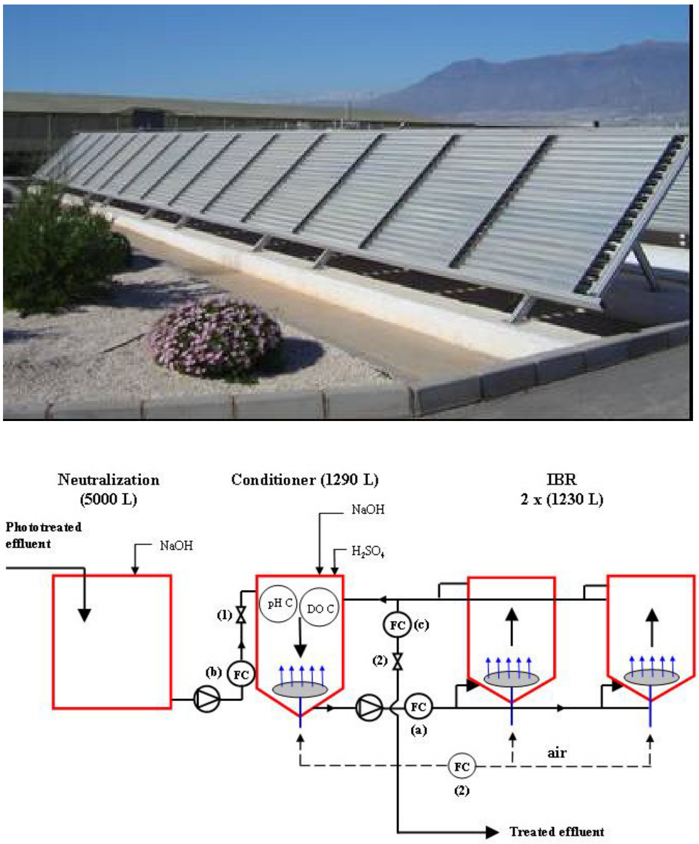

Figure 4.4. (Top) View of one of the rows of the CPC field and (Bottom) bioreactor flow diagram

4.2.2 PhotoNanoTech

Photozyme nanoparticle applications for water purification, textile finishing, photodynamic biomineralization and biomaterials coating

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

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

Funding: EC, 6th FP. Nano-biotechnologies: Using nature as model for new nanotechnology-based processes; 1,720 k€. CIEMAT Budget: 350 K€.
Duration: April 2007-March 2010

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

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

Achievements in 2008 and 2009: All the first experiments were done with photozymes synthesized in the laboratory of the coordinator (University of Sofia) and these consisted of testing up to 40 different photozymes, some based on Rose Bengal, Dextran-Rose Bengal and Chitosan Eosin (Figure 4.5), others based on polymers Poly(styrene-co-vinyl sulfonate) with fluoresceine, Poly(Styrene sulfonate-co-Vinyl benzene chloride -co- 4- amino phthalocyanine), Poly(Styrene sulfonate-co-Vinyl benzene chloride -co- vinylcarbazole) with fluoresceine, or the same polymers fixed on iron minerals, such as goethite, lepidocrocite, magnetite, limonite and hematite. Results, in which the photozyme was sufficiently reactive to the solar irradiation with significant degradation of some model pollutants (phenol, atrazine, pyrimethanil, etc.) were promising only in some cases. They do show that it is necessary to go into greater depth in the development of the photozymes to reach the efficiencies found with other catalysts already known, such as TiO_2, or with photo-Fenton.

In general, photozymes are able to degrade pollutants such as those shown in Figure 4.6, but at a much slower reaction rate. In some cases it was even found that the photozymes themselves are slowly degraded, since a rise in TOC in water was observed. This is not at all desirable as not only do the photozymes become less efficient, but the water is enriched by an undesirable organic compound. It was also observed that in those cases where photozymes successfully degrade the pollutant, the TOC in water was not significantly diminished. This means that the photozyme is unable to mineralize the products generated from the original compound. This is also a serious drawback for application of photozymes to water treatment. Therefore, the project is still underway at the Univ. of Sofia where they are attempting to synthesize new photozymes that adapt better to application for water treatment.

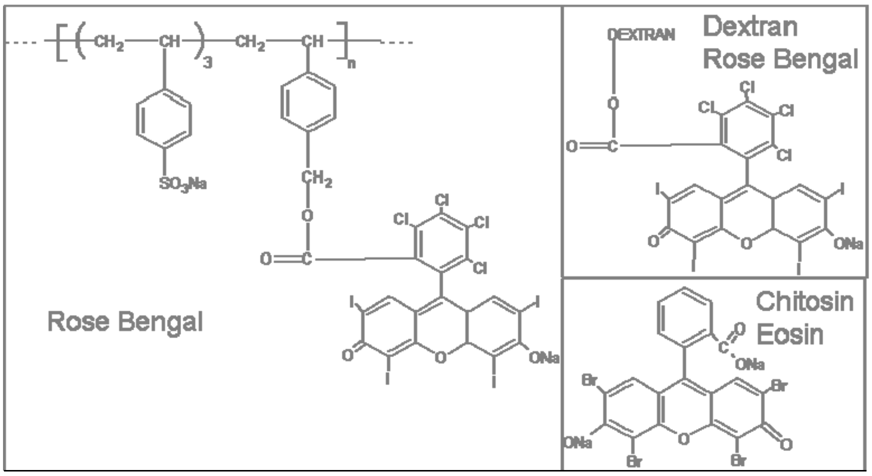

Figure 4.5. Some photozymes based on dyes tested at the PSA in the PhotoNanoTech Project.

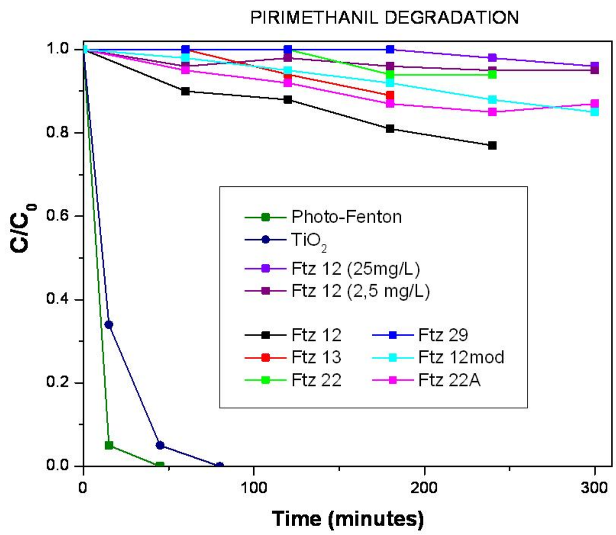

Figure 4.6. Comparison of some of the photozymes tested and the most conventional TiO_2 and photo-Fenton processes applied to degradation of pyrimethanil.

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

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

Motivation: Granulated aerobic biomass, combination of advanced oxidation processes and biological treatment and integration of membrane processes are all considered high-potential innovations for development of industrial process wastewater treatment. These technologies 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 2008 and 2009: During these two years, we worked on optimizing the combined photo-Fenton/biological treatment of a diversity of industrial waste waters. One of them, from the Austep Company (synthesis of nalidixic acid), contains a significant amount of biodegradable compounds, of which nalidixic acid was the target to be eliminated in the combined treatment because it is not biodegradable. Another type of water was from washing shredded plastic pesticide bottles. A combination of solar treatment and fixed-bed biomass reactor was used to do this. In the first case, the combined photo-Fenton biological treatment mineralized 95% of the COD (COD_0= 775 mg/L), of which the nalidixic acid and 33% of the COD were eliminated by photo-Fenton and 62% by the biological treatment. However, keeping in mind that the waste water contains basically biodegradable compounds, the biotreatment/photo-Fenton combination was even more successful, eliminating 97% of COD, and much more efficient in each of the basic treatment parameters (21 min vs 350 min with photo-Fenton, 12 mM H_2O_2 consumption vs. 65 mM and 4 days biotreatment compared to 6 days). Furthermore, suitability of the process has been irrefutably demonstrated by HPLC-TOF-MS analysis. Figure 4.7 shows analysis of wastewater containing nalidixic acid (NXA) before and after treatment. Most of the organic content has been eliminated by the biological treatment, but pollutants are only completely eliminated after solar photo-Fenton.

In the case of the water from washing shredded pesticide containers, the biological/photo-Fenton combination is not feasible because of the high toxicity and low biodegradability of the waste water. Therefore, only a photo-Fenton pretreatment is possible to reduce that toxicity down to a suitable biodegradability level before proceeding to biological treatment. This water is especially difficult since it contains such diverse pesticides as imidacloprid, dimethoate, pyrimethanil, tiacloprid, carbofuran Metalaxil, Spinosina-a, Bupirimate, Phenamiphos, Azoxistrobin, Malathion and Tebufenozide (all determined by HPLC-TOF-MS). However, the treatment is effective to very low concentrations (total elimination or at most 0.1 mg/L only in cases of pyrimethanil and tiacloprid) in the effluent. Figure 4.8 shows the result of the combined treatment, which took two days to complete.

Publications: [4.38]-[4.52]

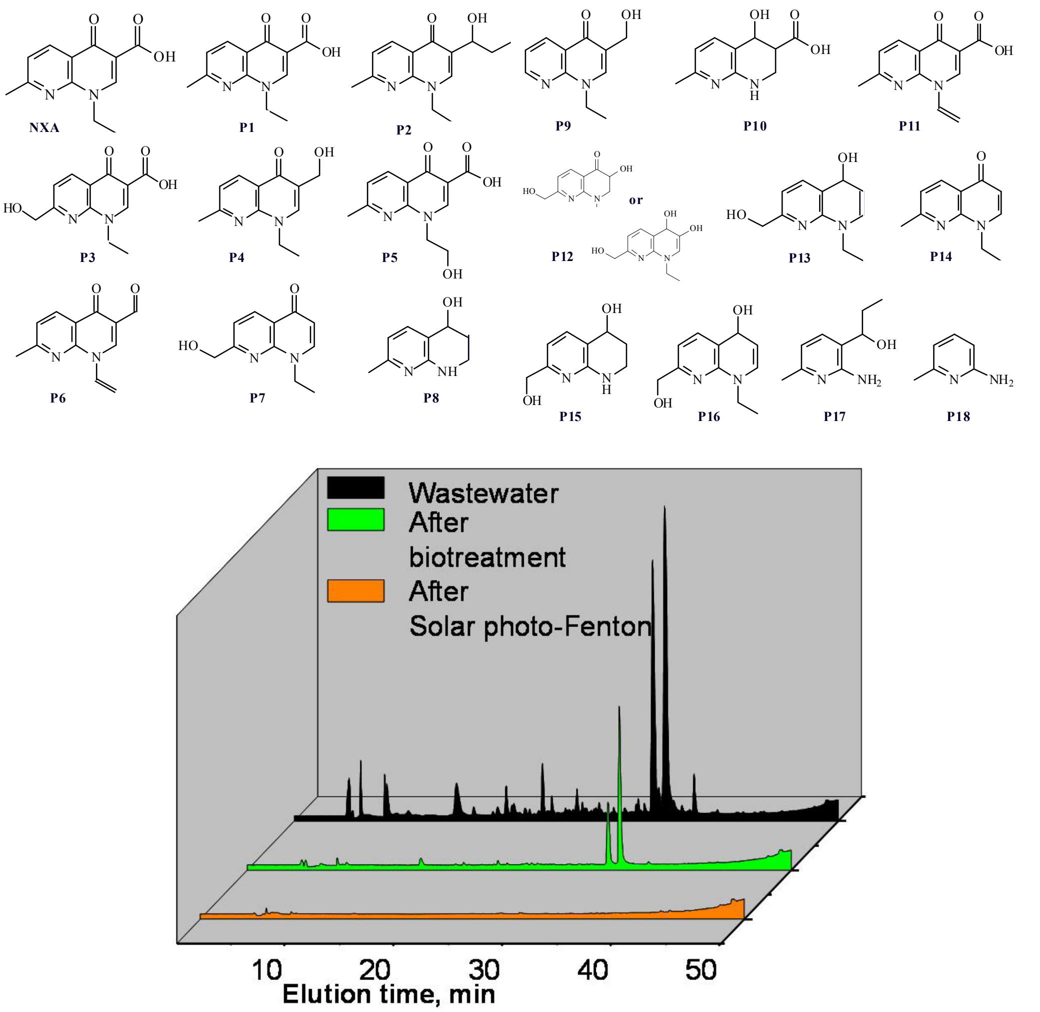

Figure 4.7. Qualitative composition of pharmaceutical waste water (top) and (HPLC-TOF-MS) analytical results after treatment (bottom).

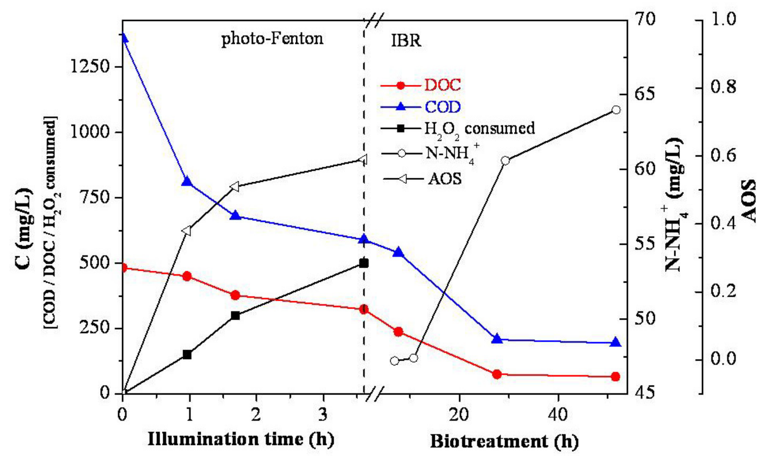

Figure 4.8. Mineralization of DOC and COD, hydrogen peroxide consumption, average oxidation state and ammonium in the combined photo-Fenton/biological system.

4.2.4 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), UL (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 2008-2009:In 2008 and 2009, the possibilities of developing different photoreactors for solar disinfection of different pathogens susceptible to SODIS treatment were studied for treatment of over 25 liters of water. As a result of this work, two new systems have been constructed and evaluated.

The first system is a 2.5-L-batch system. It consists of a contaminated water tank (feed tank), a CPC solar collector system with a 2.5-L Pyrex glass tube, a treated water collection tank (storage tank), two automatic open/close valves and a control system that measures and calculates the solar UV radiation dose received during the exposure time. When the water contained in the solar collector receives a dose above a certain value ("lethal dose"), the control system opens the outlet valve in the treated water storage tank and then the valve that fills the contaminated-water tube. Thus 50 liters of water contaminated with bacteria can be treated on a completely sunny day at the Plataforma Solar de Almería (Figure 4.9). The UVA solar radiation estimation can be done by measuring 380-nm wavelength radiation.

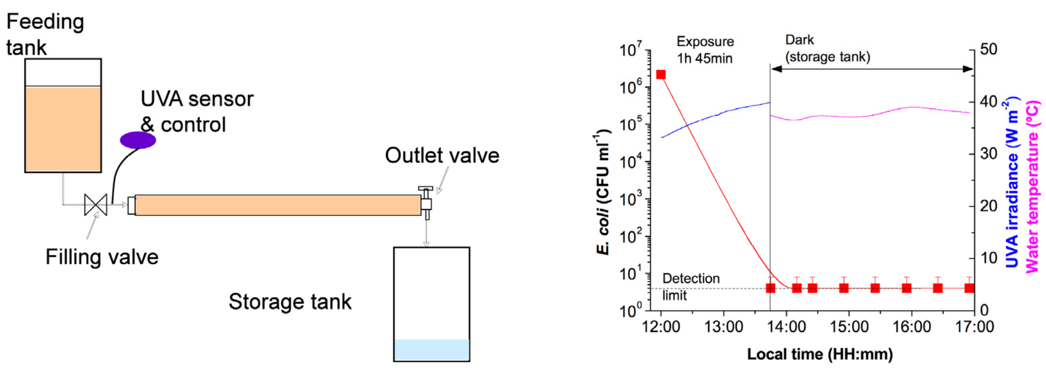

Figure 4.9. General diagram of SODIS disinfection batch system design (left). Graphic of disinfection of water contaminated with 10^6 UFC/mL of *Escherichia coli* (right).

The second SODIS system developed consists of a 25-litre methacrylate bottle located in the focus of a CPC built for a 20-cm diameter. This reactor allows water contaminated with bacteria (*Escherichia coli*, 10^6 UFC/mL) on a sunny day. On cloudy days, at least seven hours of exposure to sun are required (Figure 4.10). This system was used to analyze solar disinfection of water contaminated by *Criptosporidium parvum* oocysts.

Publications: [4.53]-[4.73]

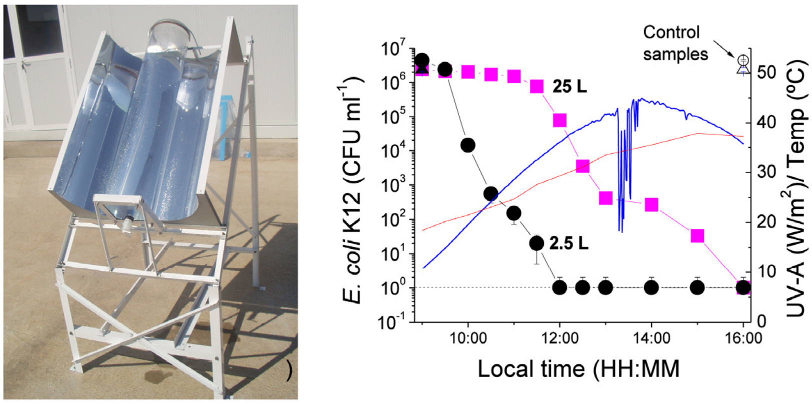

Figure 4.10. 25-liter SODIS-CPC reactor (left). Graphic of disinfection of natural well water contaminated by 10^6 UFC/mL de *Escherichia coli* with a 2.5-L batch system (dots) and 25-L system (squares) (right).

4.2.5 FITOSOL

Elimination of phytopathogens in water by photo-catalysis: application to disinfection and reuse of recirculating nutrient solutions in hydroponic cultivation

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

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

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

Budget: National RD&I Plan, MEC. CIEMAT Budget: 117 K€ + 1 Ph.D. research fellowship FPI.

Duration: October 2006 – September 2009

Background: The purpose of this project is the destruction of phytopathogenic microorganisms by photocatalytic treatment with solar radiation (using a non-soluble semiconductor such as titanium dioxide or photo-Fenton), avoiding the use of conventional chemical disinfectants (toxic and nonbiodegradable) that make the nutrient solution undesirably toxic. The effectiveness of the photocatalytic treatment will be evaluated using models present in horticulture crops of Southeast Spain: *Pythium aphanidermatum*, which causes root and hypocotyl necrosis, leading to withering of *Cucurbitaceae*, *Phytophthora parasitica*, sp. *radicis-cucumerinum*, a fungus not having zoosporangium which causes significant crop losses, and *Olpidium bornovanus*, the vector of MNSV in melon and watermelon.

Goals:

- Laboratory study of elimination of model plant pathogens in recirculating feed water of soilless crops by solar photocatalysis with TiO_2 (in suspension and immobilized) and with photo-Fenton).
- Design and construction of a pilot solar rector for disinfection of water containing the abovementioned plant pathogens for application to reuse of water used in hydroponic crops.
- Evaluation of photocatalytic water treatment of plant pathogens using model pathogens of the different types commonly found in soilless crops.

- Demonstration of the feasibility of photocatalysis for disinfection of real polluted irrigation water from hydroponic crops.

Achievements in 2008 y 2009: Work was related to lab-scale photocatalytic disinfection of phytopathogens and design, construction and evaluation of an experimental pilot system. Engineering parameters were calculated and the following system was designed according to the results found in 2007, when a series of lab-scale experiments were carried out, and our previous experience in developing reactors for water disinfection.

Finally, the prototype design is shown in Figure 4.11 and a photo of the as-built prototype in Figure 4.12. This treatment system can disinfect 60 liters of polluted water per batch and design operating flow rate is 30 liters per minute. The basic specifications of the system are given in Table 4.1.

Photocatalytic disinfection with TiO_2 at 50 and 100 mg/L catalyst has been observed to improve substantially with this new prototype compared to previous results with other photoreactors

Table 4.1. Main specifications of the prototype developed for the project.

FITOSOL prototype specifications	
Total volume treated	**60 l (batch)**
Flow rate	**30 l·min^{-1}**
Linear speed	**0.31 m·s^{-1}**
Recirculation	**150 W_e Centrifuge pump**
Solar CPC collection area	**4.5 m^2**
# Modules / # tubes	**2 CPC / 20 tubes**
Total tube length / illuminated	**1500 mm / 1400 mm**
Transmissivity tube (section)	**90% in UVA (280 nm)**
CPC mirrors	**CF=1**, high-reflectivity anodized Al.
Illuminated volume (V_{irr}./V_{tot})	**45 L** – 75% of total volume

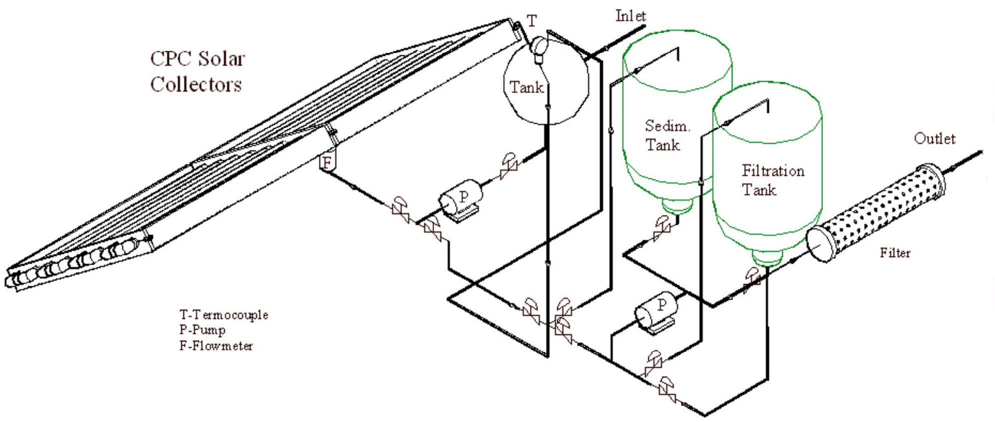

Figure 4.11. General diagram of the photoreactor prototype for disinfection with advanced oxidation processes driven by solar radiation.

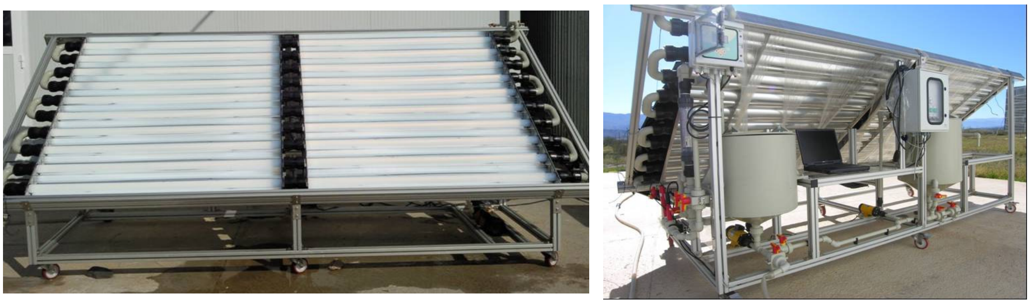

Figure 4.12. Front and back views of the FITOSOL prototype.

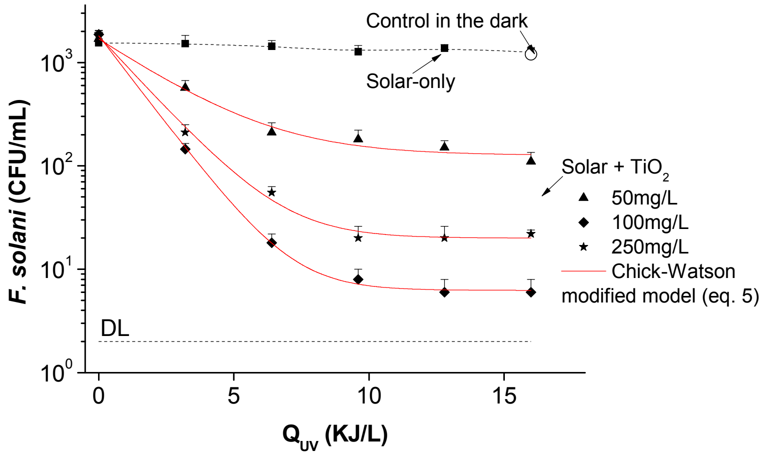

Figure 4.13. Viability of *F. solani* in distilled water compared to solar energy density received (QUV) during solar photocatalytic experiments with TiO_2 at 10, 50, 100, 250 and 500 mg/L in the CPC photoreactor.

A study was done of the fungicidal effect of low concentrations of hydrogen peroxide in the presence of solar radiation. Results show significant synergy between the hydrogen peroxide and solar radiation which completely inactivates the *Fusarium* spores, even in natural well water (Figure 4.14).

Publications: [4.74]-[4.85]

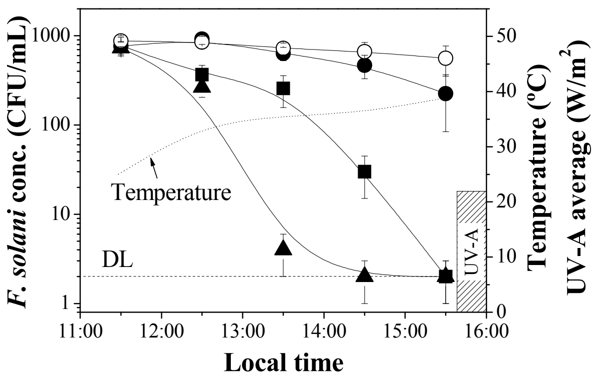

Figure 4.14. Exposure of *F. solani* to solar radiation in bottle reactors with concentrations of H_2O_2 of 5 mg/L (-●–), 10 mg/L (–■–) and 50 mg/L (–▲–) in well water. The control did not have H_2O_2 (–○–).

4.2.6 Plan for National Access to the PSA.

Participants: Univ. Santiago de Compostela; Univ. Extremadura; Univ. Zaragoza; Univ. Barcelona; Polytechnic Univ. Valencia; IIQAB-CSIC; IDAEA-CSIC.
Contact: Dr. Manuel I. Maldonado. mignacio.maldonado@psa.es
Budget: Plan Nacional de I+D+i, MEC.
Duration: 2008 – 2009

Background: Since one of the CIEMAT guidelines is to promote knowledge of renewable energies in the Spanish public, it has made the facilities and advisory services of the PSA technical-scientific personnel at the disposition of the scientific community through the Access to Spanish Large Scientific Installations Program (Project GIC-05-17).

Purpose: The basic purpose is to provide access to the largest number of researchers possible, whether Ph.D. research students and researchers in training or senior researchers in National plan projects. The Water Detoxification and Disinfection Group also intends for this program to increase the level of collaboration with Spanish research groups, identifying new partners for future projects, making use of ideas contributed by visitors and motivated to maintain and improve the installations.

Achievements in 2008-2009: The researchers selected by the external selection panel from different Spanish research groups have achieved the following results:

Univ. Santiago de Compostela, Lab. Parasitology; School of Pharmacy. Researchers: Hipólito Gómez Couso, Elvira Ares Mazás and María Fontán.

This Group demonstrated inactivation of *C. parvum* oocysts in water by natural solar radiation at the Plataforma Solar de Almería facilities. They also demonstrated that *C. Parvum* can be inactivated in turbid water, although less efficiently than in more transparent water. Another aspect of this work marked as a goal was to check the effectiveness of the SODIS technique on the viability of *Cryptosporidium parvum* oocysts using:

- Pilot-scale stationary CPC photoreactors (25 liters).
- Immobilized catalysts as a photocatalytic improvement.

The most relevant results were:

It was demonstrated that it is possible to inactivate *Criptosporidium parvum* oocysts from 90% to 20% overall viability in 25 liters of transparent polluted water in the solar reactor used in eight hours of solar exposure (0 NTU). The effectiveness of inactivation decreases as turbidity increases: at 30 NTU overall viability drops to 40%.

However, no differences are observed between disinfection results found in the photocatalytic system in absence or presence of the catalyst.

Univ. Extremadura. Dept. Chemical Engineering and Physical Chemistry. Researchers: Guadalupe Fernández and Eva María Rodríguez.

The goals set were to study application of different Advanced Oxidation Processes based on the use of sunlight in degradation of Bisphenol A (BPA) in aqueous solution. The systems to be tested were the following: Fe^{3+}, Ferric-carboxylate, H_2O_2, photo-Fenton, TiO_2, Fe_2O_3, FeO and $KMnO_4$/Mn(II) (all of them in presence of sunlight), as well as several different combinations of the various processes.

The effectiveness of the systems was compared by analyzing evolution of the BPA concentration, the Total Organic Carbon (TOC) concentration and toxicity of the samples, depending, as a function of the radiation dose.

It was demonstrated that under the experimental conditions applied in this work, at pH3, the Fenton and photo-Fenton processes were the most effective in degrading BPA and its reaction intermediates. At that pH, most of the mineralization took place by photo-Fenton and TiO_2/Fe(III). At pH6.5, the fastest degradation was of BPA was applying Fe(III)oxalic acid, and the TiO_2/UV process (regardless of the presence of α-Fe_2O_3) was the most effective in terms of the oxidation of degradation intermediates, while α-Fe_2O_3 had a positive defect in terms of mineralization. There was an obvious relationship between reduction of TOC and toxicity, whereby toxicity fell from 70% to 30% when 20% mineralization was reached. Nevertheless, an increase in toxicity is observed at the beginning of the Fenton and photo-Fenton treatment, due to the accumulation of degradation phenolic intermediates as determined by GC-MS and the Folin-Ciocalteau method.

Univ. Zaragoza. Dept. Chemical Engineering and Environmental Technologies / Water Quality and Treatment Group. Researcher: Rosa Mosteo.

The goals that framed this Project were to apply the technology available at the Plataforma Solar de Almería in a pilot-scale photoreactor plant for degradation of organic matter present in winery wastewater.

Photolysis and heterogeneous photocatalysis (TiO_2) were carried out on winery wastewater, with effluents from wine and grape juice, in a CPC reactor. The influence of the TiO_2 concentration was evaluated. The results reveal that photolysis in itself produces very little mineralization of the organic content in this type of water. The experiments performed with 200 mg L^{-1} of TiO_2 lowered TOC by 8% in winery wastewater. If the concentration of the catalyst is increased by 200 mg L^{-1} to 500 mg L^{-1}, no significant drop in TOC is achieved, with a drop of 10% after 400 minutes of illumination, the same as for a concentration of 200 mg L^{-1}. It may be deduced that titanium dioxide with solar illumination is not very efficient, even when the catalyst concentration is increased, for lowering the TOC present in this type of water.

Figure 4.15 presents the application of the photo-Fenton method to winery wastewater. The experiments were made with a first addition of Fe2+ = 55 mg L-1 at pH 3. The original concentration of peroxide was 12 mM, kept constant by successive additions throughout the experiment. It may be observed that after 500 minutes of illumination and with hydrogen peroxide of 151 mM mineralization was 54% of the original. These results are not particularly exceptional as the reaction took a long time and consumed a large amount of H_2O_2.

One possible explanation could be the fast disappearance of iron in the reaction medium due to the formation of complexation iron with some compounds present in this type of water. This fast disappearance of iron in the reaction medium may be seen in Figure 4.15, especially in the first 100 minutes of the reaction.

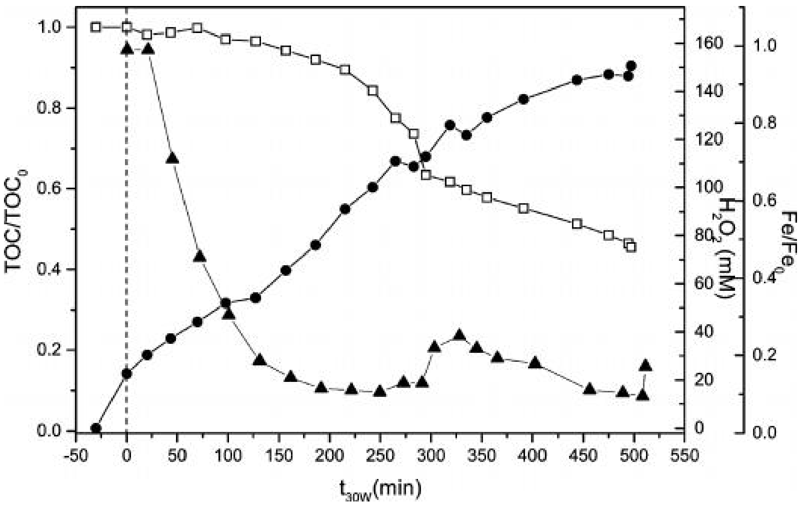

Figure 4.15. Photo-Fenton treatment of winery wastewater from wine using CPC reactors. Evolution of the TOC (□), hydrogen peroxide (●) and iron (▲) during the reaction. Experiment conditions: $[Fe^{2+}]_0$ = 55 mg/L, $[H_2O_2]$ = 12 mM; inicial pH = 3.

CSIC. Research and Development Center (CID). Dept. of Industrial Chemistry. Chemical and Environmental Research Institute (IIQAB). Researcher: Jelena Radjenovic.

The technical feasibility and performance of photocatalytic degradation of the anti-inflammatory pharmaceutical acetaminophen (ACTP) and ß-blocker atenolol (ATL) were studied in a Compound Parabolic Collector (CPC) pilot plant under solar radiation. Heterogeneous photocatalysis with titanium dioxide (TiO_2) and heterogeneous photocatalysis by photo-Fenton were studied with two different types of matrix, distilled water and synthetic effluents from a municipal wastewater treatment plant. The initial pharmaceutical concentrations were 10 mg L^{-1}, while the concentrations of the catalysts employed were 200 mg L^{-1} of TiO_2 and 5 mg L^{-1} of iron. Total disappearance of original compounds and moderate mineralization of all the compounds were observed. The main degradation intermediates of atenolol were structurally elucidated by tandem mass spectrometry (MS2) using a quadropole/time-of-flight (QqTOF) mass spectrometer connected to a ultra-performance liquid chro-

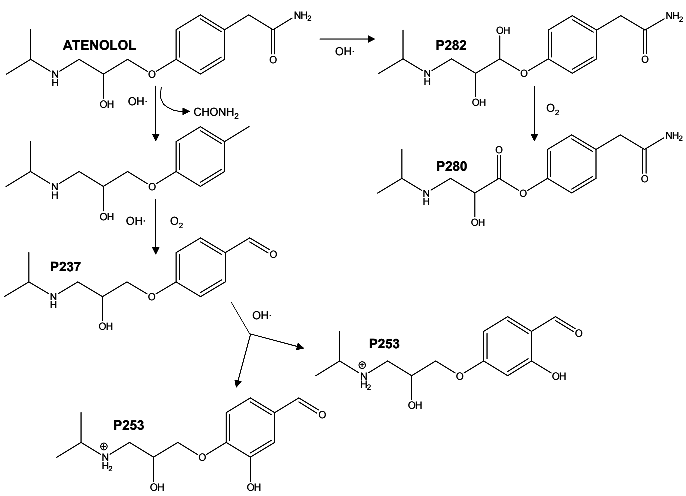

Figure 4.16. Solar TiO_2 and photo-Fenton photocatalytic degradation route proposed for ATL in aqueous solution.

matograph (UPLC). Six transformation products were characterized, formed by the consecutive attack of the hydroxyl radical ($^{\bullet}OH$). The degradation route of atenolol by TiO_2 and photo-Fenton was described for the first time (Figure 4.16).

Polytechnic Univ. of Valencia at Alcoy. Dept. of Textile and Paper Engineering. Researchers: Juan Soler and Lucas Santos-Juanes.

The best Photo-Fenton treatment time for water containing a mixture of commercial pesticides (Ultracid®, Sevnol®, Laition®, Metasistox®) to obtain acceptable loss of toxicity and a considerable increase in biodegradability was determined. These experiments were done at lab and pilot-plant scale. However, real water can contain species that may interfere with the treatment. Interference by anions and cations has already been studied in the lab an in pilot plant. Organic tensoactive agents and solvents may be of special interest because they could increase treatment time required to achieve the desired final conditions. The first experiments at lab scale show the presence of these organic compounds diminishes the pesticide degradation rate. It is therefore of interest to apply the photo-Fenton treatment in presence of these substances and study the effect of different parameters, such as disappearance of the active ingredients, evolution of organic carbon, hydrogen peroxide consumption, presence of dissolved iron, etc., during treatment in a pilot plant with sufficient sample volume for the necessary analyses.

The main results found that the presence of tensoactive agents (Triethoxylated isodecyl alcohol) causes strong inhibition of the reaction due probably to a competitive reaction between pesticides and the aliphatic molecule in the tensoactive agent for hydroxyl radicals. Mineralization in the sample was also inhibited. In this case, the presence of aliphatic molecules, difficult to attack with a photo-Fenton process, could explain this point. To confirm elimination of tensoactive agents with the photo-Fenton treatment, the surface tension of the samples was measured, and even though it increased, final values were far from those for distilled water.

The average oxidation state (AOS) increased during the process. This variation in AOS in treated water is translated into increased biodegradability of the sample, as the BOD_5/COD ratio, which increased with longer treatment times, shows. The same tendencies were found with electrolytic respirometry measurements.

The role of the solvents was also studied. For this study, acetophenone, which is the solvent commonly employed in commercial pesticides and which is soluble in water and not very volatile. The results followed the same trend as those found with the tensoactive agents: there was an inhibitory effect, probably to competitive reactions with the hydroxyl radical generated. However, in this case, the effect was not as pronounced as for the tensoactive agents. For biocompatibility of the samples, there was also a clear increase in the BOD_5/COD ratio, showing that it would be possible to apply a later biological treatment.

Both the triethoxylated isodecyl alcohol and the acetophenone were shown to have a negative effect on the solar photocatalytic treatment of water polluted by the mixture of four pesticides. However, a significant increase in biodegradability was observed in both cases after elimination of the active ingredients, although longer irradiation times were required.

Univ. Barcelona. Dept. Chemical Engineering. Researcher: María del Mar Micó.

The purpose of experimentation at the Plataforma Solar is to confirm the effectiveness of the solar photo-Fenton process as a first step in developing pilot-scale water treatment equipment for field testing. It is also intended to optimize the use of reagents for this process and determine the maximum concentrations of pesticides and salinity that can be worked with. A study was carried out for this using Fosetyl-Al and Imidacloprid as model pollutants.

In the first run, three combinations of pesticides were tested, hydrogen peroxide and Fe^{2+}, which had previously been defined as optimal after experimental design (Table 4.2).

Table 4.2. Fosetyl-Al test parameters

[Fosetyl] (mg L^{-1})	[H_2O_2] (mg L^{-1})	[Fe (II)] (mg L^{-1})	TOC_0 (mg L^{-1})	TOC_f (mg L^{-1})
15	30	15	3,4	1,5
25	50	20	5,5	0,7
30	100	25	11,7	5,0

Reactions took place in the SOLEX device, loaded with 35 L of solution, in which the pH was adjusted to about 2.8. Temperature was allowed to evolve freely. Total organic carbon (TOC), dissolved Fe(II), total iron, hydrogen peroxide and phosphates were monitored in all three experiments.

According to the TOC shown in the table, it may be seen how the most mineralization was found for intermediate amounts fosetyl and hydrogen peroxide. In fact, the short list includes an iron concentration with a ratio to peroxide ([Fe (II)]/[H_2O_2]) which is also intermediate.

Analyzing the progress of iron and phosphates during the reaction, some interesting phenomena are observed:

1) Dissolved Fe(II) disappeared almost completely in 5 minutes coinciding stoichiometrically with the first drop in hydrogen peroxide (Fenton reaction). To the contrary, there is no such coincidence during the Fenton test carried out in parallel with the intermediate concentrations.
2) A drop in total iron filtered was observed which could be due to the formation of precipitates of iron III with phosphate released during oxidation of phosphonate in the fosetyl.
3) The phosphate concentration gradually increased up to nearly what would be observed if all of the phosphonate ions became phosphates. This could mean an indirect way of finding out the evolution of the pesticide during the reaction.

A mixture of pesticides was also tested to see the influence that different species could have on competition for hydroxyl radicals. A mixture with the characteristics described in the table below was tested (Table 4.3):

Table 4.3. Test parameters for the mixture of 3 pesticides

[Fosetyl] (mg L^{-1})	[Imidacloprid](mg L^{-1})	[Methomyl] (mg L^{-1})	[H_2O_2] (mg L^{-1})	[Fe (II)] (mg L^{-1})	TOC_0 (mg L^{-1})	TOC_f (mg L^{-1})
20	20	20	200	20	94.0	91.0

Even though no data are available on the evolution of fosetyl-AL, an abnormal drop in the elimination of pollutants is observed that could be monitored by HPLC (imidacloprid and methomyl). The results show almost complete elimination of imidacloprid compared to degradation of only 70% of methomyl. Furthermore, the existence of a "delay" is demonstrated in which the reaction continues without affecting the concentrations of these two pesticides.

Finally, with the intention of making the experiment closer to treatment of a real effluent, reactions were tested in which the aqueous matrix, in addition to the reagents ([Fosetyl-Al]=25ppm, [H_2O_2]=50ppm and [Fe^{2+}]=20ppm), contained KNO_3, the most common salt in rural lixiviates. Nitrate was used at 0, 100, 250 and 500 ppm.

Evolution of total organic carbon is similar in all the experiments. Hydrogen peroxide is observed to be consumed faster at lower salt concentrations.

Since the TOC evolution of TOC is identical in all four cases, but not H_2O_2 consumption, salt may be causing some effect which makes the peroxide decompose more slowly but more efficiently.

CSIC, Centro de Investigación y Desarrollo (CID), Instituto de Diagnóstico Ambiental y Estudios del Agua (IDAEA). Researcher: Cristina Rebollo.

This study evaluated degradation of cocaine and methadone in distilled water and synthetic municipal wastewater effluent by natural solar radiation and two photocatalytic processes, TiO_2 and photo-Fenton in parabolic-trough collector a pilot plant. In general, degradation of methadone was faster than degradation of cocaine in all the photocatalytic treatments used, although both compounds were mineralized in similar treatment times. Degradation and mineralization were faster for both substances in distilled water than with the synthetic effluent. Methadone was completely degraded, but not mineralized with photolysis, while cocaine was, but very slowly. Degradation kinetics were calculated for the process and severe toxicity of the photoproducts generated. The intermediates generated during photocatalytic treatment are being studied by liquid chromatography-quadrupole time of flight mass spectrometry (LC-Q-TOF-MS).

Publications: [4.86]-[4.100]

4.2.7 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 2008-2009: 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 in 2008 and 2009: (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" (published by Springer); (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.

Furthermore, complying with the project goals, in 2008-2009 two conferences and a course were organized in Mediterranean countries. These summarized achievements under EU and national projects (not only those included in INNOVA-MED, but also other relevant research projects or coordinated actions) where European or Mediterranean partners in several disciplines relevant to wastewater treatment and reuse were involved. The first congress was in Agadir (Morocco) from April 29 to May 1, 2008, "Mediterranean Workshops on new Technologies of Recycling Non Conventional Water in Protected Cultivation", and contributions related to technologies developed for adequate reuse of waste water for irrigation, for desalination of brackish and sea water, for collecting rain water and development of greenhouses that minimize water consumption in agriculture. The second congress took place in Girona (Spain) on October 8-9, 2009, "Innovative processes and practices for wastewater treatment and reuse in the Mediterranean Region". This congress was structured in five sessions in which the guest speakers spoke on analysis of xenobiotic compounds in wastewater treatments, new water treatment technologies, advance practices for reuse of treated effluents, socio-economic and legal factors, and wastewater and water resource management. Finally, a course entitled, "Towards an integrated approach for wastewater treatment and reuse in the Mediterranean Region" was organized in Ismalia (Egypt) on December 15-17, 2008, in which subjects related to wastewater treatment and reuse in the Mediterranean region were discussed and several real cases studies form some of the countries participating in the project were presented.

Publications: [4.101]-[4.104]

4.3 Air Detoxification Group

4.3.1 DETOX-H_2S Development of new toxic and corrosive compound elimination Systems in air generated in wastewater treatment plants http://webgc.ciemat.es/portal.do?IDM=325&NM=4

Participants: CIEMAT, ICP-CSIC, ICV-CSIC and UNED (E); UENF (BRA); USACH (RCH) and University of Wisconsin (USA).
Contact: Dr. B. Sánchez; benigno.sanchez@ciemat.es
Budget: Madrid Regional Program (IV PRICIT), Total Budget 700 k€
Duration: January 2006 – December 2009

Background: Unpleasant odors generated by wastewater treatment plants are a serious obstacle for their acceptance. These emissions contain, among other foul-smelling compounds, H_2S, mercaptans and amines. However, the possible annoyance to the population is not the main problem associated with these air pollutants. It is much more important that such emissions can be found in concentrations toxic to plant workers and cause corrosion in equipment and construction materials. At present there are several commercial treatments available for treatment of these emissions, but they are either not very efficient or they are expensive. The purpose of this project is to develop an alternative system that improves treatment of foul emissions from wastewater treatment plants.

Purposes:

1) Development of a photocatalytic reactor activated either by solar radiation or by UVA lamps, able to operate continuously for the treatment of real emissions.
2) Design an adsorption treatment system that retains pollutants present in the gas streams under normal processing conditions.
3) Based on results from both systems, design and install a new mixed system combining adsorption and photocatalysis, to make best use of the synergies between them.

Achievements in 2008-2009: An adsorbent based on sepiolite and iron has been found to have an adsorption capacity several orders of magnitude higher than commercial adsorbents (Spanish patent applied for), which has been very satisfactorily evaluated under real plant conditions. Work on the photocatalytic treatment of H_2S has led to development of TiO_2 photocatalysts by sol-gel which is more porous and improves H_2S conversion previously found with other synthesized coatings. Furthermore, hybrid materials based on TiO_2 and sepiolite, combining their photocatalytic and adsorbent properties has been studied. With these materials, treatment capacity and durability was improved, as well as delay in appearance of SO_2. Optimization of this type of promising materials is a challenge for the future. Figure 4.17 shows some of the results of photocatalytic activity.

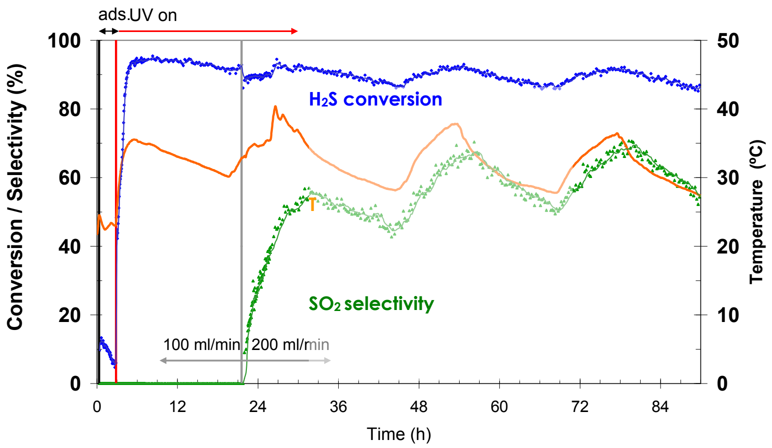

Figure 4.17. H_2S conversion, SO_2 selectivity and temperature during a flat reactor test using a hybrid TiO_2P25/SiMgOx material

An important part of the work done was devoted to the design, installation and operation of the hybrid annular photoreactor shown in Figure 4.18. The photoreactor is designed to operate with solar radiation and/or artificial for 24-hour continuous operation. It consists of a non-concentrating parabolic-trough collector (CPC) and an internal UVA lamp which is activated when necessary.

Preliminary tests done with PET monoliths coated with TiO_2 located in the interannular space resulted in highly efficient degradation of H_2S. To adjust

Figure 4.18. Hybrid photoreactor for continuous treatment of gas emissions

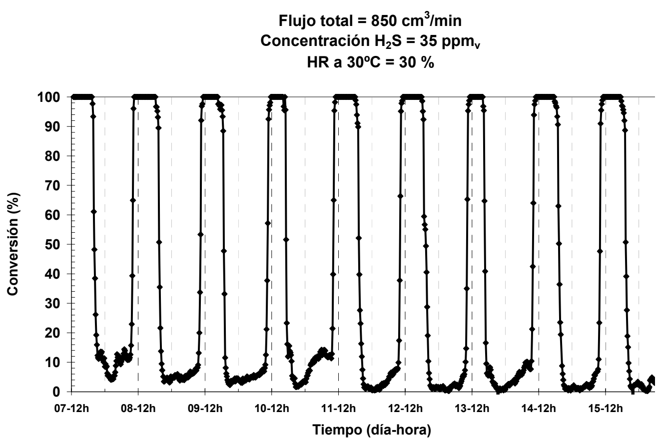

Figure 4.19. Conversion of H_2S in the hybrid photoreactor working with solar radiation and 10 star-shaped TiO_2modules deposited on glass by sol-gel. August 2009.

the reactor to many kinds of supported photocatalysts, a star-shaped polygonal structure was designed for modular distribution of simple photocatalysts in the reactor, both transparent, such as sol-gel-coated glass plates and opaque, for example hybrid adsorbent/photocatalyst material plates (Spanish patent applied for). Figure 4.19 shows the conversion with this system during a solar test lasting several days in which glass plates coated with porous TiO_2 were used.

H_2S is completely eliminated during the hours of sunlight, while efficiency falls during the night. The use of internal lamps solves this problem.

Publications: [4.105]-[4.110]

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

Participants: CIEMAT, ICP-CSIC, LBNL, UENF, USACH, UNED
Contact: Benigno Sánchez; benigno.sanchez@ciemat.es
Budget: Ministry of Science and Innovation: 94 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 2008-2009: In 2009, the first year of the project, an intense literature search on characterization and treatment of VOCs in interiors was made. Identification and quantification of these compounds was done by ATD (Automated Thermal Desorber) GC-mass spectrometry equipment. To do this the experimental equipment had to be prepared and analytical methods developed for measuring the samples. The sampling variables affecting the analysis have been determined, and also the sampling time and the kind of adsorbent. An experimental system for evaluating the photocatalyst efficiency of supported photocatalysts. Figure 4.20 shows some of the results with a photocatalyst based on TiO_2 thin films. The figure compares reference samples of indoor air from a laboratory and samples that have gone through the photocatalytic reactor. Over 60% of the samples were degraded with a conversion ratio over 60%. The results demonstrate the efficiency of photocatalysis for eliminating ppb-level VOCs.

Publications: [4.105]

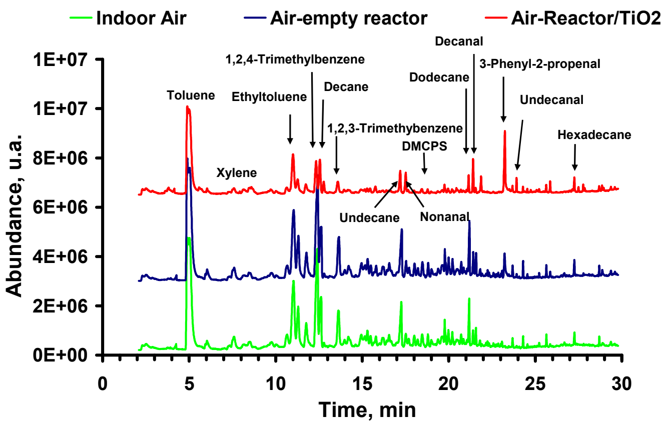

Figure 4.20. Chromatograms of indoor air samples taken in: i) laboratory air, ii) air gone through reactor without photocatalyst, iii) air gone through reactor with photocatalyst and UV lamps.

4.3.3 NANOTITAN
New photocatalysts for solar applications based on one-dimensional TiO_2 nanostructures found by functionalization of titanate

Participants: CIEMAT_PSA
Contact: Benigno Sánchez; benigno.sanchez@ciemat.es
Budget: Ministry of Science and innovation: 76 k€
Duration: January 2009 – December 2011

Background: The recent discovery of a simple method of synthesis that makes it possible to prepare TiO_2 nanotubes under very mild conditions (Figure 4.21) has opened a new potential way to prepare high-efficiency photocatalysts which in the last 5 years has acquired enormous relevance.

There are several reasons for the growing interest of the scientific community in these nanostructures. For one, TiO_2 nanotubes have a large specific area (up to 400 m^2/g) and narrow pore-size distribution, which facilitates diffusion of reagents. Furthermore, the proximity of the structural relationship between titanates and TiO_2 makes reversible transformations from nanotubes, nanofibers and nanoparticles possible using very mild methods, making the whole photoactive assembly very versatile on a nanometric scale. Finally, a loaded laminar titanate structure allows the ion exchange to contribute flexibility to the synthesis which TiO_2 lacks. Titanates, given their capacity for ion exchange, could be used as intermediates to widen the spectral response of TiO_2, incorporating cations capable of absorption in the visible band.

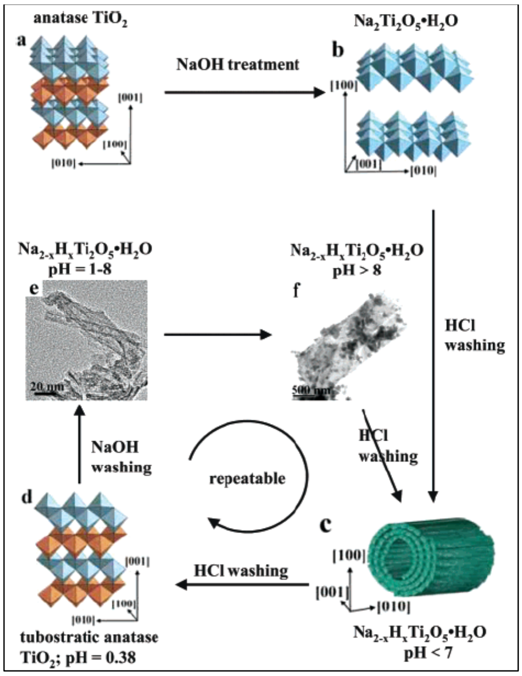

Figure 4.21. Diagram of nanotube formation from treatment of TiO_2 with NaOH and later transformations induced by washing under different conditions (Tsai et al., Chem. Mater. 18, 2006, 367).

Purpose:

1) Attain maximal control over the synthesis process in order to optimize the method of obtaining one-dimensional TiO_2 nanostructures
2) Develop a synthesis methodology for depositing TiO_2 nanotubes and nanofibers as thin films on the best substrates for use as photocatalysts in continuous operation.
3) Make use of the titanate nanotube capacity for cation exchange to synthesize nanostructured photocatalysts with visible-band activity.
4) Synthesize titanate nanotubes that incorporate organic cation sensitizers as a way to make use of the possible synergies between semiconductors and photoactive molecules.

Achievements in 2008-2009: In 2009, the first year of the project, the literature on TiO_2 nanotube synthesis was studied in depth. Although there a a considerable number of publications in the literature related to hydrothermal synthesis of these nanostructures, different results and contradictory conclusions are generally found on the effect of the various parameters on the synthesis process. There also discrepancies on the stages and on the possible nanotubes formation mechanism. Therefore, it is considered essential in this first stage of the project to make a synthesis method optimization study on the influence of different process parameters on the morphology and physicochemical characteristics of the materials analyzed by transmission electron microscopy (TEM), x-ray diffraction (XRD) and N_2 adsorption isotherms. The effect of the TiO_2 precursor stage, temperature and duration of the hydrothermal treatment and procedure for washing afterwards, a stage which been shown to be crucial to nanotube formation have been taken into consideration (Figure 4.21). This study will allow us to select the best conditions for synthesis to use during the following stages of the project.

Publications: [4.112]

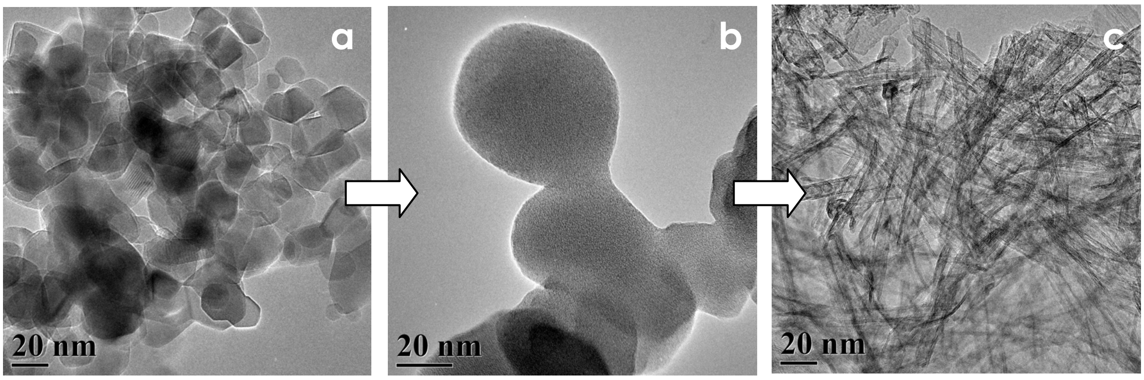

Figure 4.22. TEM images showing the material in different stages of synthesis: (a) Degussa P25 TiO_2 precursor; (b) after hydrothermal treatment in NaOH 10N and (c) after washing with HCl 0.2N.

4.3.4 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 generates 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. Easily manipulable shapes were developed from a porous adsorbent material coated with a TiO_2 thin film. Coating TiO_2 thin films on previously shaped porous materials is not an easy task, so a priority goal of the project is optimizing the method of incorporating TiO_2. A key part of this project is the use of sunlight as the source of illumination of the photocatalytic system. The use of solar photoreactors, which increase the percentage of $\lambda < 380$ nm solar radiation available to activate the TiO_2, is another alternative of great interest to the project. So the influence of the reactor configuration on COV degradation using a compound parabolic collector (CPC) enabling more efficient use of diffuse radiation is going to be analyzed. Compounds such as trichloroethylene, toluene, and formaldehyde will be used as model molecules for analyzing the photocatalytic system efficiency.

Achievements in 2008-2009: During this period we have studied hybrid systems based on magnesium and titanium oxide. The materials were structured in a plate-like shape which makes the photoactive material simple and convenient to manipulate. Different material configurations were studied, incorporating the photoactive material in the adsorbent or depositing a semiconductor film on the porous support. This study optimized synthesis conditions and the calcination time and temperature and its influence on the textural and crystalline properties of the material. The photocatalytic properties of these materials for degrading trichloroethylene (TCE) as the model molecule were evaluated and the formation of partial oxidation products, which can be even more polluting than the original compound, was analyzed. The most innovative results found are shown in the diagram in Figure 4.23. The synergetic effect between TiO_2 and silicate is shown on the left. Close contact between the semiconductor, where the photocatalytic reaction begins, and the adsorbent favors migration of partial oxidation products such as $COCl_2$, increasing mineralization of TCE. However, when the TiO_2 layer is too thick, migration of these compounds is inhibited and formation of undesirable reaction subproducts increases.

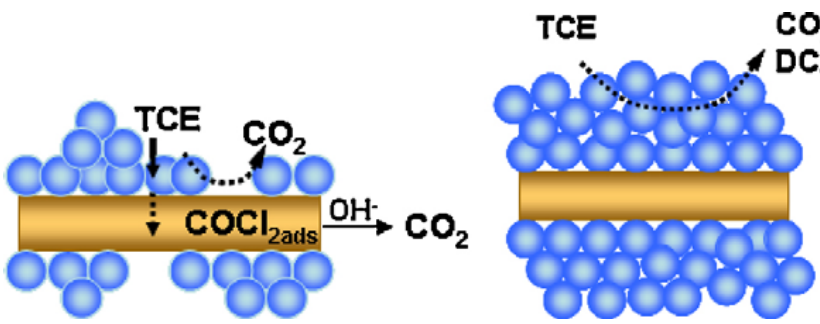

Figure 4.23. General diagram of TCE degradation, varying the distance between the adsorbent and the photocatalyst: ( )TiO_2 particles, ( ) adsorbent, SiMgOx. TCE: trichloroethylene; DCAC: diacetyl chloride.

The use of solar radiation in compound parabolic collectors (CPC) with this type of materials, has shown very satisfactory results. These systems have made it possible to achieve conversions of over 95% at high volumes of gas with significant concentrations of pollutants at the hours of maximum solar irradiation.

Publications: [4.113]-[4.115]

4.4 Solar Desalination Group

It is well known that water is absolutely indispensable to human beings and, when it is not available by the usual means (rivers, lakes or underground resources), the only additional resource is desalination of brackish or sea water, but at a very high energy cost.

As in all the technologies related to solar energy, research in solar desalination processes and technologies has boomed in the last few years. The reason for this is not only the usual geographic coincidence of high availability of the solar resource and water shortage. It is also because the visions and future projects for large areas of solar collectors producing energy in developing regions for later transfer to developed regions would not be feasible were it not for their relevant contribution to the development of those regions where water is usually even a more valued asset than energy.

For all of the above, the technological development of solar desalination going on at the Plataforma Solar de Almeria is not only aimed at developing and optimizing this technology, but also analyzing the possibilities of integration in solar thermal power plants. In this context, in 2009, the Unit of Environmental Applications of Solar Energy undertook the ambitious project of designing and beginning construction of a test bed called CSP+D (*Concentrated Solar Power & Desalination*) which is integrated in the solar desalination facilities, and enables study of configurations and specific technologies in which this integration makes technical and economic sense.

A good idea of the intensity of the activity at the PSA in this field is the list of projects recently developed or currently underway in the field of solar desalination, and which are summarized below.

4.4.1 OSMOSOL PROJECT
Desalination by solar thermal reverse osmosis
http://www.psa.es/projects/osmosol

Participants: Univ. of la Laguna (Coord.), CIEMAT-PSA, Univ. Rovira i Virgili - CREVER

Contact: Dr. J. Blanco, julian.blanco@psa.es (coordinator)
Dra. L. García, lourdesg@esi.us.es

Budget: Ministry of Education and Science (National Plan for Scientific Research Development and Technological Innovation, 2004-2007); 70 k€ (CIEMAT).

Duration: December 2005 – December 2008

Background: Desalination consumes a large amount of energy. State-of-the-art reverse osmosis with seawater consumes around 3.5 kWh/m^3. Keeping in mind the $2{\cdot}10^6$ m^3/day produced in Spain, the need to develop sustainable and economically feasible technologies is beyond doubt. Existing implementations of reverse osmosis plants with solar energy to date are based on photovoltaic or wind technology. The use of solar thermal energy in this process would make better use of the solar resource and impact less on the environment by eliminating the problems of waste involved in the use of batteries with solar photovoltaic energy.

Purpose: The main purpose of the OSMOSOL project is to develop an innovative technology based on the application of solar thermal energy to desalination by reverse osmosis which complies with the principles of environmental sustainability and economic feasibility at the same time. To do this, the ther-

Figure 4.24. Experimental evaluation of the CPC 1.5x collector prototype

mal energy collected and concentrated in a solar device will be used to drive a thermodynamic cycle based on an organic fluid (organic Rankine cycle) that vaporizes at a relatively low temperature and which, connected to a turbo-compressor system, can transform thermal energy directly into the mechanical energy required by the osmosis process.

Achievements in 2008: In 2008, a large-area, low-cost stationary CPC solar collector prototype, which can be operated with an acceptable thermal performance in the 80-100ºC temperature range, was experimentally evaluated. This prototype, manufactured by the Portuguese company Ao Sol, has a total area of 5 m^2 and concentration ratio of 1.5x. This experimental evaluation determined its normal incidence efficiency curve.

Several latest-generation 1.15x-concentration CPC collectors were also installed in the PSA MED solar field in 2008. The purpose was to study the long-term performance of these collectors when continually subjected to operation at different temperatures between 50 and 90ºC. Very good permformance of the new materials and manufacturing processes was observed, and no corrosion or degradation problems were observed in any of the collector parts. All of these collectors were specially designed to drive ORC processes.

Finally, annual dynamic performance models were developed at the PSA for the design of solar fields of CPC collectors such as those evaluated in the OSMOSOL project. These models, implemented in Matlab, determined the solar fraction and compared the results found with other conventional methods such as F-CHART.

Publications: [4.116]

4.4.2 POWERSOL PROJECT
Generation of mechanical energy based on solar thermal engines
http://www.psa.es/projects/powersol

Participants: CIEMAT-PSA (Coord., E), Univ. de La Laguna (E), IDMEC (P), AOSOL (P), ETH (CH), ECOSYSTEM (E), INETI (P), ENIT (TN), PHOCHEM (EGY), LOTUS (EGY), AES (TN), LENREZA (DZ), Univ. de Seville (Coord., E)

Contact: Dr. J. Blanco, julian.blanco@psa.es
Dra. L. García, lourdesg@esi.us.es

Budget: FP6-2004-INCO-MPC-3. Topic: B.1.5 – Renewable Energy: Cost-effective renewable energies for Mediterranean specific

needs; 1.050 k€.
Duration: January 2007 – December 2009

Background: The absence of an electricity grid and/or drinking water shortage are limiting factors for socioeconomic development in many regions in the Mediterranean Region where solar resources are abundant. Therefore, the use of solar technologies offers an opportunity to provide these communities with basic needs while promoting their development. Solar thermal generation has been developed for generating electricity in the range of tens of MW (SEGS Plants, USA). However, many applications, such as irrigation, HVAC, rural electrification, etc., in remote areas only require a few dozen kW for their development. Furthermore, simple, robust systems which are easy to control and operate and do not require qualified labor are required in these areas.

Purpose: The main purpose of the POWERSOL project is to develop a mechanical energy generation technology based on solar thermal energy which is low-cost and environmentally-friendly and is optimized to supply the basic needs of rural communities or small populations, using ORCs.

Achievements in 2008-2009: In the second year of the project (2008), Organic Rankine Cycle simulation models were implemented for three maximum temperature ranges: 80-90ºC (Cycle 1); 150ºC (Cycle 2) and 250-300ºC (Cycle 3). For each of the three cycles work substances were selected and delimiting conditions were determined. The Cycle 1 was powered by an advanced flat plate collector. For Cycle 2 a stationary CPC solar collector was used and for Cycle 3, a Fresnel collector design was chosen.

In 2008, the design and detailed engineering of the Plataforma Solar de Almeria ORC test platform was begun. Although in principle it was conceived as an installation able to test all of the three cycles mentioned above, in the end, for technical reasons, it was decided to implement a system for evaluation of ORC cycles in a maximum temperature range between 150 and 300ºC. An agreement was made with the Swiss company Eneftech for the technological development of a 5-kW ORC plant. Among its innovations is the organic fluid (Solkatherm SES36) and the development of a new turbine specifically designed for use in this type of applications.

Figure 4.25. PSA organic Rankine cycle test bed

In 2009, a new prototype was manufactured and the PSA test loop was installed. This test loop is connected to the Acurex parabolic-trough solar collector field, which provides thermal oil in the range of 140 to 300ºC. This variable range will make it possible to characterize the ORC system under nominal conditions and outside of them.

Publications: [4.117][4.118][4.119]

4.4.3 MEDESOL PROJECT

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€

Duración: 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 per day

Achievements in 2008-2009: Throughout most of 2008, work on the project concentrated on commissioning and testing the membrane distillation plant (MEDESOL-1), which was designed and installed the year before. The experiments carried out during the first half of 2008 were directed at characterizing the plant and each of its components during real operation. Plant results were presented at several international congresses. In 2009, under the same project, we cooperated in the design of the demonstration plant which is planned to be installed in the desalination facility in Carboneras. At the same time, a cooperation agreement was signed with Keppel-Seghers, one of the companies marketing the Memstill Consortium prototype, to test one of their modules at the PSA facilities. Results would be used to provide additional knowledge and recommendations to the Medesol Project. Modifications required to the plant and mounting of the new facility were done in the second half of 2008 and were completed in December the same year, so experiments could begin the following year. Testing was done from February to June 2009. A favorable report on the combination of this technology with solar energy was presented to the company. It was considered that this cooperation and been fruitful for both parties and new cooperation was planned, this time with a multi-stage concept to begin early in 2010.

Publications: [4.120]-[4.125]

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

Participants: Repsol YPF, Acciona Solar (CIEMAT-PSA as subcontractor), Ulma Agrícola, Ulma Packaging, Acciona Agua, Ulma Handling Systems, Fundación Cajamar, Agrobio, Biomiva, Grupo AN, Ingeteam
Contact: Dr. J. Blanco, julian.blanco@psa.es (CIEMAT Activities)
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 to 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 medium-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 2008-2009:

a) Mid-temperature parabolic trough collector. A type of small-sized, low-cost parabolic-trough collector has been identified that is suitable to mid-temperature thermal applications: the Polytrough 1200 prototype from the Australian company NEP-Solar, with a rated thermal efficiency of over 55% in the 120-220ºC range at 1000 W/m^2 direct normal radiation and a nominal rated production of 15.8 kW per module with a mean collector

Figure 4.26. Polytrough 1200 prototype to be installed at the PSA

temperature of 200ºC for polygeneration and multi-effect desalination at the PSA.

b) ORC: In 2008, a study was done on different cycles applicable to solar cogeneration (ORC, Kalina, etc.) for temperatures below 300ºC. An extensive review of the literature was done, distinguishing between theory and pilot-plant installations. In particular, within the small-scale cogeneration applications (< 1 MW_e) with ORC, commercial products available on the market for real implementation of a solar ORC have been identified. Finally, a mathematical model, implemented in EES (Engineering Equation Solver), for simulating Solar ORC, both at low temperature (stationary solar collectors) and mid-temperature (parabolic-trough solar collectors) was developed.

c) Solar thermal disinfection. Based on bibliographic and experimental studies on solar thermal inactivation (< 80 ºC), work on solar disinfection has been done at the Plataforma Solar de Almeria for the main purpose of achieving an effluent that meets the quality parameters for pathogenic organisms in the regulations for reuse of treated water (R.D. 1620/2007).

Given the potential of Advanced Oxidation Processes (AOPs) in water treatment (disinfection) for reuse and irrigation in agriculture, we analyzed the possibilities of their large-scale development so their application would be of interest. Based on PSA previous work on the strong susceptibility of *Fusarium* sp. to disinfection with suspensions of TiO_2 in 250-ml bottles and in a 14-L CPC solar reactor with distilled water and natural solar radiation, the process was studied on reactor scale with tens of liters to treat, not only contaminated distilled water, but also natural underground water and polluted wastewater treatment plant (WTP) effluent. The main process operating parameters, such as flow rate, dissolved oxygen and temperature, as well as design parameters and system design parameters, such as photoreactor solar collector area, total volume to be treated, residence time under illumination, and the ratio of illuminated to total volume were analyzed. To date, very few studies have contributed to disinfection of water with photocatalysis in a CPC solar reactor pilot plant, but none of them are on disinfection of water with phytopathogens for reuse in irrigation. The 60-L CPC solar photoreactor prototype used in this study was designed and built based on our experience, analyzing and adjusting parameters.

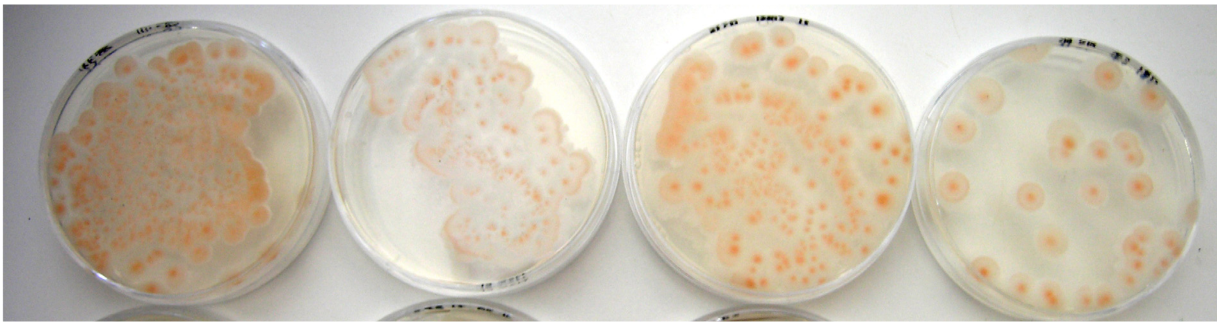

Figure 4.27. Decrease in number of *Fusarium solani* colonies in water on malt agar in Petri dishes after different solar treatment times with titanium dioxide: 0, 1, 3 and 5 hours (left to right).

The solar photocatalytic treatment's disinfection efficiency for a diversity of pathogens was demonstrated in distilled water and in well water.

4.4.5 PRODES PROJECT
Promotion of Renewable Energies through Desalination
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 general knowledge of the related technologies

Achievements in 2008-2009: With a view to developing a roadmap, databases of researchers, companies and professionals in the sector were developed. Selected researchers and professionals were contacted to input from their criteria and experience in the strategy to be defined. A draft of this roadmap was presented to the public in May 2009, in a specific strategic session of the European Desalination Congress in Baden Baden, in which over 100 specialists from all over the world will discuss the document. The survey has already begun.

Insofar as the educational aspect of the project, the basic contents of a course in desalination with renewable energies has been defined, a task which was led by the PSA. Part of the course is theory and part practical. The first consists of seven units, introduction, conventional desalination processes and technologies, review of renewable energies applicable to desalination, desalination technologies associated with renewable energies (solar thermal, photovoltaic solar, wind and others), design and operation of plants, environmental aspects and economic questions concerning desalination with renewable energies. The second includes calculations of the solar resource and wind, mass balance and energy in thermal desalination, design of solar fields to combine with different thermal desalination systems, design of a conventional reverse osmosis plant, as well as the photovoltaic solar field and wind farm to power it, and review of existing facilities. The educational material for the course has already been prepared for both theory and practice so it will be the same every time the course is given.

The course has been given in Italy (third-cycle students of the University of Palermo), in Greece (short version for sector professionals at a seminar organized by CRES) and twice in Spain. The first time, the PSA gave the course to the students of the third Master's Course in Solar Energy organized by CIESOL as an extension to Module VII on application of solar energy to water processes, which allowed them to cover the official course outline. The PSA also organized an international desalination course in Almería (October 19-21, 2009) which was attended by researchers and professionals from nine countries. It is worth mentioning that applications to attend exceeded the defined limit of 25. The course included theory and practice at the Plataforma Solar de Almeria.

Publications: [4.126]

Figure 4.28. Students at the International course on desalination with renewable energies during the practice session in the multi-effect distillation plant at the PSA (October 20, 2009).

4.4.6 CONSOLIDA PROJECT
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 2008-2009: CIEMAT-PSA has met its commitment to write reports on the state of the art of the multi-effect and membrane thermal distillation technologies. Studies were also done on the physical principles of both desalination systems, developing the theoretical mathematical formula for modeling each.

The PSA also cooperated in identifying the best solar thermal system for applicable to each desalination process, making reports including the theoretical mathematical formula for modeling each.

Publications: [4.127]

4.4.7 HISPAMED PROJECT
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 driven by solar energy.

Achievements in 2008-2009: Among the first tasks in this project is the design and construction of a simple distiller, comprised of two effects, one of them provided with a preheater and the other connected to the final plant condenser. In 2009, a mathematical model was developed and compared with the experimental results in the PSA MED plant. The literature on materials technology was also reviewed in order to choose the best for using in the first MED prototype plant.

4.4.8 Environmental Applications Workshop Solar technologies applied to environmental problems

Participants: CIEMAT-PSA y 3iA - UNSAM (Instituto de Investigación e Ingeniería Ambiental de la Universidad Nacional de San Martín, Argentina)

Contact: Julián Blanco (julian.blanco@psa.es)
Miguel Blesa (miblesa@cnea.gov.ar)

Budget: 20.400 €. Agencia Española de Cooperación Internacional para el Desarrollo (AECID)

Duration: January 2009 – December 2009

Background: The project basically proposed for the organization and presentation of the course on “Solar technologies applied to environmental problems, emphasizing water treatment”, at the National University of San Martín (Argentina), directed at postgraduate students, professionals, university instructors and students in their last year of degree programs associated with the subject matter in the areas of physics, chemistry, environment and related engineering.

Both institutions (PSA and the 3iA-UNSAM) have wide experience in the subject of the environment and in international cooperation, the main reason for the project being the promotion of joint activities in training specialized human resources and diffusion of the results that promote transfer and exploitation of water disinfection technologies to problems of water desalination, decontamination and disinfection in rural areas and poor areas through the use of solar energy. The 3iA-UNSAM is an institute devoted to research, education and knowledge transfer in environmental subjects.

Purpose: The general purpose of this project is to train human resources specialized in solar energy applications to environmental problems in a workshop on the abovementioned subject, exchange of researcher-instructors and diffusion of results, promoting the transfer and exploitation of solar technologies, particularly in rural and poor areas. The specific purposes of the project are for students who participate in the workshop to acquire:

1) A clear view of the possibilities and state of the art of solar technology applications to environmental problems, and water in particular.
2) A better understanding of the physical and chemical processes involved in the environmental improvement introduced through the use of solar energy.
3) A view of the social and economic impact produced by using solar technologies to solve environmental problems.
4) Motivation for performing entrepreneurial activities related to the subject of the course.

5) Educational and informative material resulting from the notes prepared by the course professors.

Achievements in 2008-2009:The course took place from September 28th to October 2, 2009 at the Miguelete Campus of the National Univeristy of San Martín. The course described the state of the art of use of solar energy for thermal processes. It reviewed the ways of generating electricity, direct use of solar energy to process water (desalination, decontamination and disinfection), in the context of the Argentina's reality (state of water resources and water management). The main responsibility for teaching was held by the Solar Chemistry Group of the Plataforma Solar de Almeria: Sixto Malato, Pilar Fernández, Diego Alarcón, Manuel Ignacio Maldonado and Isabel Oller. The course was also enriched with presentations by Argentine researchers: Alicia Fernández Cirelli described water management in Latin America; Víctor Pochat, the state of water resources in Argentina; Luis Saravi, activities of the *Instituto Nacional de Energías No Convencionales* (National Institute of Non-conventional Energies) (CONICET INENCO, and the National University of Salta); Hugo Grossi Gallegos, the characteristics of the solar resource in Argentina and Orlando Alfano, solar decontamination and disinfection studies at INTEC (CONICET- National University Litoral). The course was attended by around forty students, in general postgraduate students from different institutions around the country.

Afterwards, the two most outstanding students in the course were selected to be awarded a 2-week scientific-technical visit to the Plataforma Solar de Almeria. The winners were Martín Altamirano and Pablo Enrique Martínez, the students who had received the highest grade on the exam given at the end of the course. During their visit to the PSA these students had the opportunity to see the main projects and activities going on at the PSA in general and, more specifically, in the area of Environmental Applications of Solar Energy.

4.4.9 SOLARNOVA PROJECT (CSP+D Test bed) Integration of MED thermal desalination systems in solar thermal power plants

Contact: Julián Blanco (julian.blanco@psa.es)

Budget: Plan E

Background: A test bed is going to be developed to study possible connection strategies between a CSP plant and a seawater desalination plant (CSP+D) which makes use of the waste heat from the steam turbine. For this, the test bed should allow different possible configurations of MED desalination plant and Double Effect Hat Pump integration to be studied, individually or together, in a solar thermal power plant. This test bed will be installed associated with the MED plant and Heat Pump already existing at the Plataforma Solar de Almeria and its main purpose will be to be able to simulate different types of commercial turbines and configurations of interconnection of the systems above.

The system will be powered by thermal energy from the Acurex 3001 parabolic-trough collector field (Therminol 55 thermal oil, which allows a maximum temperature of 280-290ºC), using an auxiliary electrical system to provide the increase in temperature necessary to reach higher temperatures when required. The installation is also planned to serve as a test bed for low-power steam turbines (up to 500 kW_{th}).

Purpose: The main purpose is to study the possibility of using a part of the exhaust steam from the turbine of a Rankine cycle, by regeneration with steam from an intermediate extraction, for an MED desalination plant. The main underlying idea therefore, is to attempt to use the first cell of the MED plant as the condenser of the power cycle, reducing the cooling requirements of the Rankine cycle and using that thermal energy desalinate water (Figure 4.29).

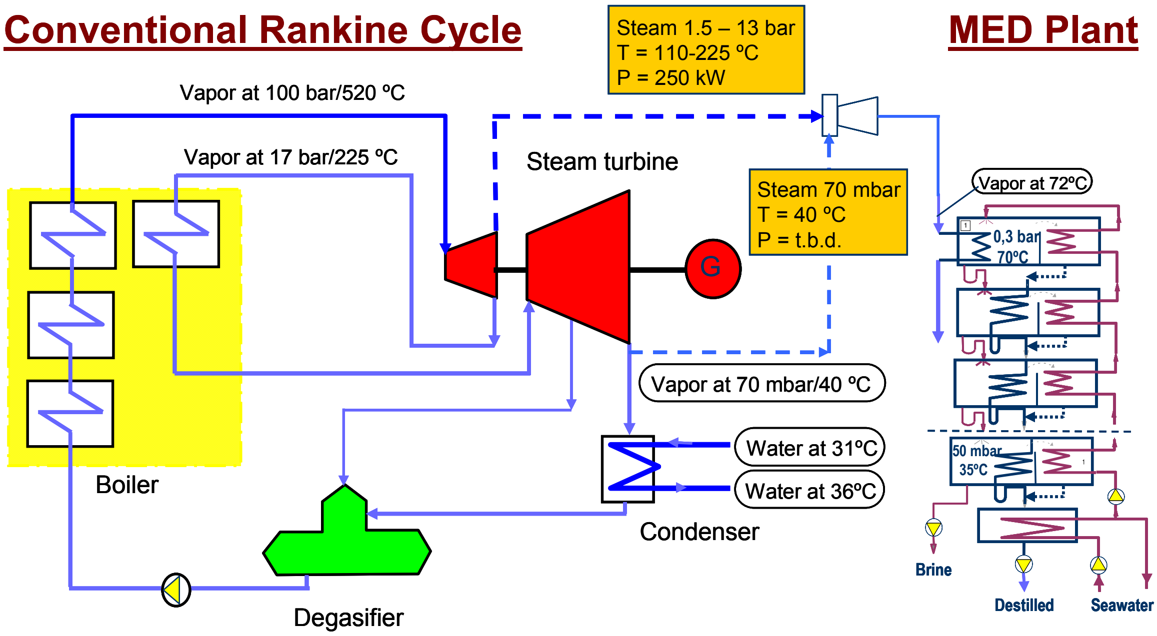

Figure 4.29. Conceptual diagram of the CSP+D test bed, for configuration of the MED plant without the heat pump.

The final system will allow simulation, on a scale up to 500 kW, of any possible turbine that might be used for simultaneous production of electricity and water from concentrating solar energy. Furthermore, the test bed will have different operating configurations to be able to integrate the Double Effect heat Pump, also already installed at the PSA, which works in a range suitable for the MED and reduces the overall energy consumption significantly over conventional MED systems, although at the cost of higher temperatures requires from the power supply. The entire system will be housed in a 2-story building.

Achievements in 2008-2009: In 2009, engineering necessary for the complete definition of the facility and tender award for its construction has been completed.

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5 Events

Diego Martínez Plaza

The new PSA parabolic-trough loop for new working fluids was inaugurated on January 17, 2008. This new "gas loop" project, which is particularly promoted by the CIEMAT General Directorate, is intended for exploration of the feasibility of using inert gases such as CO_2 or N_2 in a PTC system. Scientific direction of this project is in the hands of Dr. Carlo Rubbia, holder of the Nobel Prize in Physics.

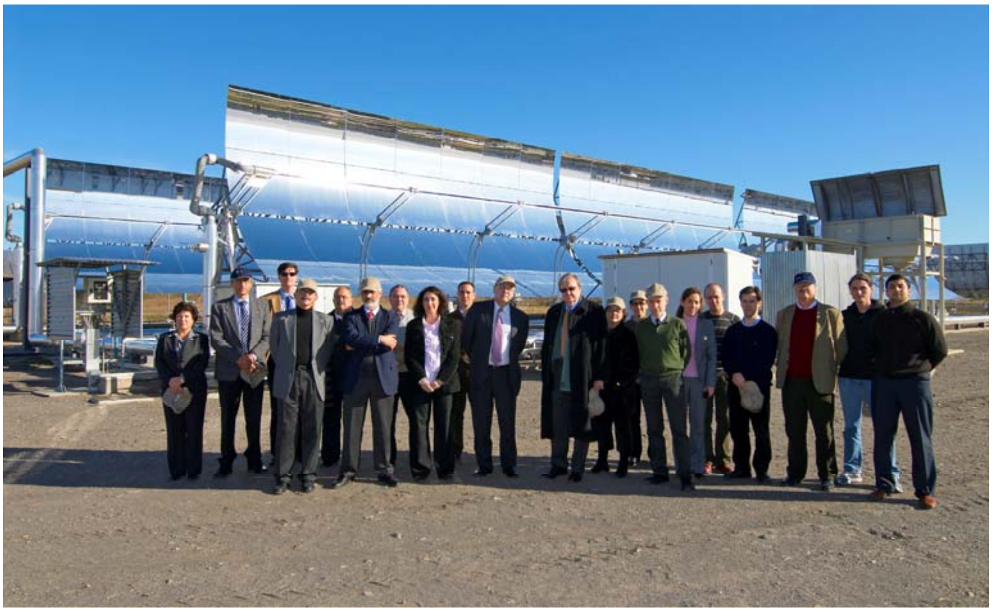

Figure 5.1. "Gas Loop" Project work group

Another test facility, the reactor for hydrogen production with power tower technology under the HYDROSOL-II Project, was inaugurated a few weeks later on March 31st. This important international project is partly funded by the European Commission 6th Framework Program.

Prof. Cayetano López represented the CIEMAT at the ceremony, which was attended by representatives from all of the participating institutions.

The workshop began with a seminar in which the technology developed and project plans and expected results were explained. Afterwards, participants visited the Hydrosol-II facility in the CRS where a project technician explained the test campaign scheduled and the equipment involved.

On March 23rd, the Minister of Science and Innovation, Ms. Cristina Garmendia visited the PSA. Apart from seeing our facilities, the Minister took advantage of the occasion to announce the extraordinary investment of 10 M€ in the PSA under the Spanish Government's "Plan E" (*Fondo Especial del Estado para la Dinamización de la Economía y el Empleo*).

In addition to the Minister and other celebrities who visited us that day were the Andalusian Regional Minister for Science, Innovation and Business, Mr. Francisco Vallejo Serrano and the Provincial Delegate from Almería, Ms.

Figure 5.2. Seminar on Hydrosol technology

Figure 5.3. Explanation of Hydrosol technology in the CRS Room

Figure 5.4. The Director General of CIEMAT, Juan Antonio Rubio, welcomes the Minister on her arrival at the PSA

Figure 5.5. Press conference in the DISS Control Room

Sonia Rodríguez. The Mayor of Tabernas, Mr. Antonio Úbeda, also accompanied us.

First they visited the PSA's experimental facilities, where the various head researchers explained the activities carried out at our Center to the Minister.

Afterwards, in the DISS Control Room, there was a press conference for members of the media present at the event. The Minister also participated in a "chat session" organized by the MICINN (Ministry of Science and Innovation) Press Secretary, in which she answered questions on the "Plan E" and the various initiatives undertaken by the MICINN.

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 oxidation state
AR......... Anti-reflective
ASME..... American Society of Mechanical Engineers
ASP .... Active Server Pages
ATD .... automated thermal desorber
ATD-GC-MS .... automated thermal desorption gas chromatography mass spectrometry
ATL........ atenolol
ATR .... Attenuated total reflection (Spectrometer accessory)

BLG .... Bulgaria
BOD....... biological oxygen demand
BRA .... Brazil
BSRN..... Baseline Surface Radiation Network

CA......... Coordinated action
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'

CNRST... National Center for Scientific and Technical Research (MA)

COD ...... chemical oxygen demand

CPC....... Compound parabolic concentrator

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)

CSIRO ... Commonwealth Scientific and Research Organization (AU)

CTAER ... Centro Tecnológico Avanzado de Energías Renovables

DAD ...... diode array detector

D .... Germany

DER ...... Renewable Energies Dept. (CIEMAT)

DISS ..... Direct Solar Steam

DK .... Denmark

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

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 (I)

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 program
FPI .... Ph.D. research fellowship
F........... France
FT-IR ..... Fourier transform infrared (Spectrometer)

GACS..... High Solar Concentration Group (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
HVAC..... Heating, ventilating, air conditioning

ICP-CSIC Instituto de Catálisis y Petroleoquímica -CSIC
ICROSS.. International Community for Relief of Starvation and Suffering
ICV-CSIC Instituto de Cerámica y Vidrio - CSIC
IDAE...... Instituto de Diversificación y Ahorro de Energía
IL.......... Israel
IMP........ Isolated Measurement Pods
INCO ..... Programme for RTD Cooperation with third countries and international organisations
INETI..... Instituto Nacional de Engenharia (P)
INTA....A Instituto Nacional de Técnica Aeroespacial (ES)
I .... Italy
IT.......... Information Technology

JTI......... Joint Technology Initiative (EU)

LEC .... Levelized energy cost
LECE...... Laboratory for Energy Testing of Building Components

MA .... Morocco
MCYT..... Spanish Ministry of Science and Technology

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
NASA	National Aeronautics and Space Agency (USA)
NEAL	New Energy Algeria
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.
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
RU	Russia
SCC	stress corrosion cracking
SEM	Scanning electron microscope
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

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

UAL .... Univ. Almería

UNED ..... National Univ. for Distance Education (ES)

UENF ..... Universidade Estadual do Norte Fluminense (BRA)

UL .... University of London

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 (DE)

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