Plataforma
Solar de
Almería

# Annual Report
# 2001

MINISTERIO
DE CIENCIA
Y TECNOLOGÍA

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

# Table of Contents

# Introduction

This Annual Report for the year 2001 begins a new series in this type of document for the Plataforma Solar de Almería. For the first time it includes activities carried out at our facilities since the withdrawal of the German Aerospace Agency (DLR) in December 1998 from the joint operation and management of the PSA. Since January, 1999, the Plataforma Solar has been managed entirely by the CIEMAT, although it continues to enjoy the considerable fruitful collaboration of DLR in a new framework of relations based on specific R&D projects of mutual interest.

This new orientation, beginning in 1999 and 2000, and its results, permit us to write this report of 2001's activities optimistically, having now consolidated the new organizational structure and cleared up logical unknowns that at one time may have existed concerning the future of a facility that may be considered unique in the world. The publication of the Plan for the Promotion of Renewable Energies[1] in Spain in December 1999, the boost received from the European Commission's 5th Framework Program R&D projects and the assistance received from the European Regional Development Fund (ERDF) and PROFIT programs, not to mention the decisive internal support from the CIEMAT Executive Committee, have meant that we now enjoy an undoubtedly better situation than at the beginning of this new stage. Fruit of it are the significant R&D results in the different solar concentrating technologies described in this Report and the creation of new installations, that will be enlarged during the next two years as new projects in the fields of solar thermal storage for trough collectors, solar desalination with a new field of CPC collectors or high solar flux materials treatments in the new vertical-axis furnace are begun.

The imminent approval of a premium for electricity generated by solar thermal power plants, which recognizes their environmental benefit and that other renewable energies are already enjoying, will mean without a doubt in the immediate future a new challenge for the PSA and the team that comprises it, since it will have to confront new R&D requirements associated with industrial demand. This activity must be combined with better integration into the Spanish R&D system under the new policies being reinforced since the creation in 2000 of the Ministry of Science and Technology.

I would not like to end this introduction without acknowledging the professionalism and dedication of the PSA team, without whom it could not function and achievement of the objectives set would be impossible. Special mention is due the previous director, Dr. Manuel Blanco Muriel, whose determination and fine work from 1999-2001contributed in large part to the consolidated future of this great scientific facility.

M. Romero

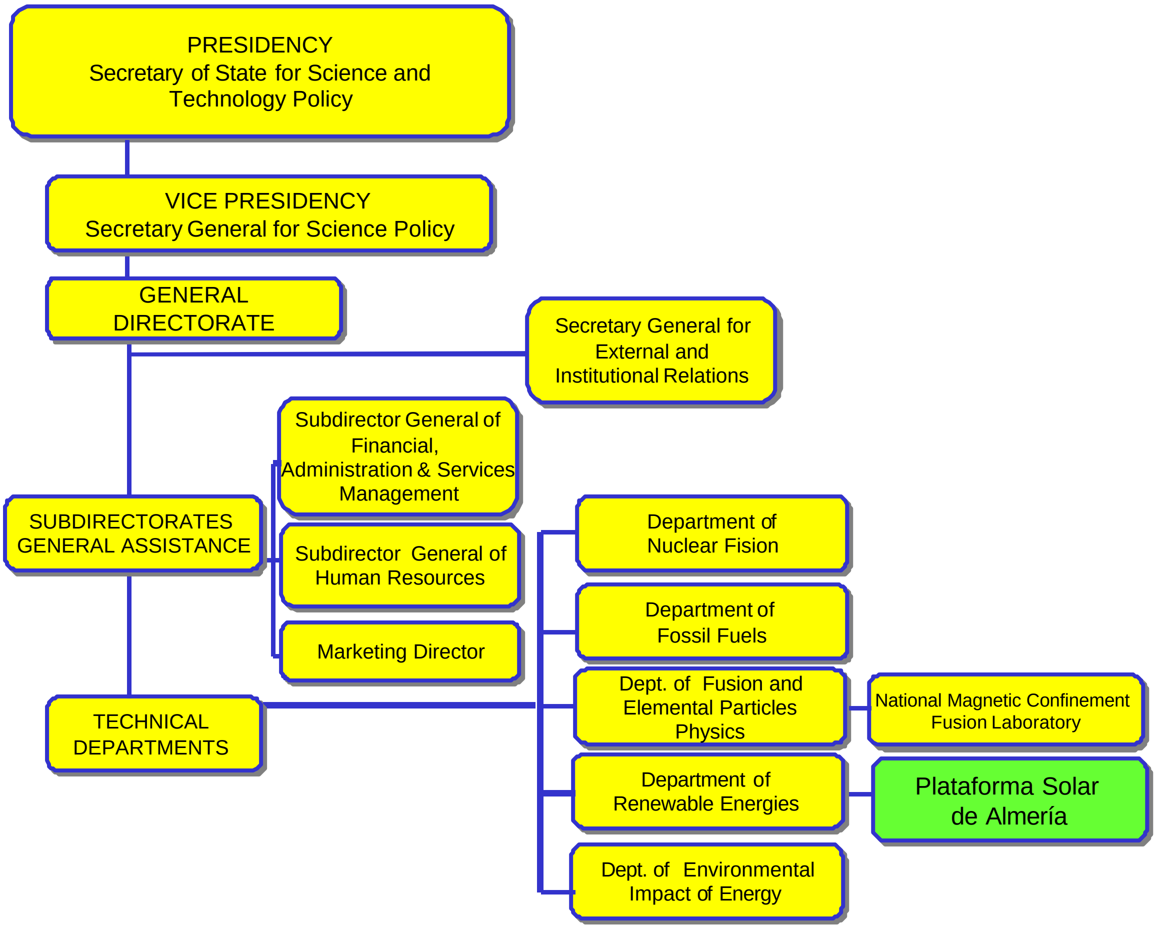
Manuel Romero Álvarez
Director Plataforma Solar de Almería

[1] Plan de Fomento de las Energías Renovables en España

# General Presentation

## Objectives of the PSA as a Large Solar Facility

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




**The PSA in the CIEMAT Organization Chart**

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[2] Centro de Investigaciones Energéticas Medioambientales y Tecnológicas

**Aerial View of the Plataforma Solar de Almería**

The objectives that inspire its research activity are the following:

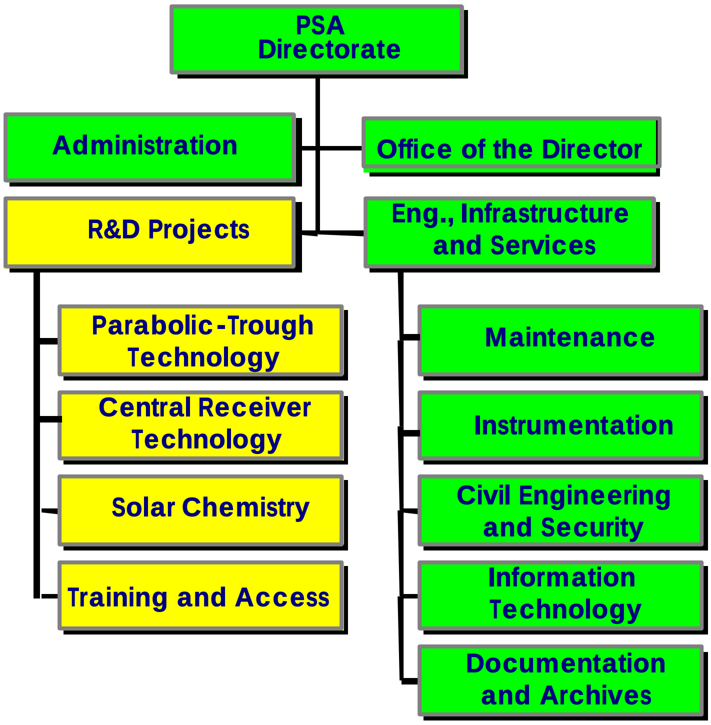
- Contribute to the establishment of a sustainable, clean, world energy supply.
- Contribute to conservation of European energy resources, climate and environment.
- Promote market introduction of solar thermal technologies and derived solar chemical processes.
- Contribute to development of a competitive European solar thermal export industry.
- Reinforce cooperation between the business sector and scientific institutions in the field of research, development, demonstration and marketing of the solar thermal technologies.
- Boost cost-reducing technological innovation, thus contributing to increased market acceptance of the solar thermal technologies.
- Promote North-South technological cooperation, especially in the Mediterranean Area.
- Assist industry in identifying market opportunities related to the solar thermal technologies.

## Organization and Functional Structure

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

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

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



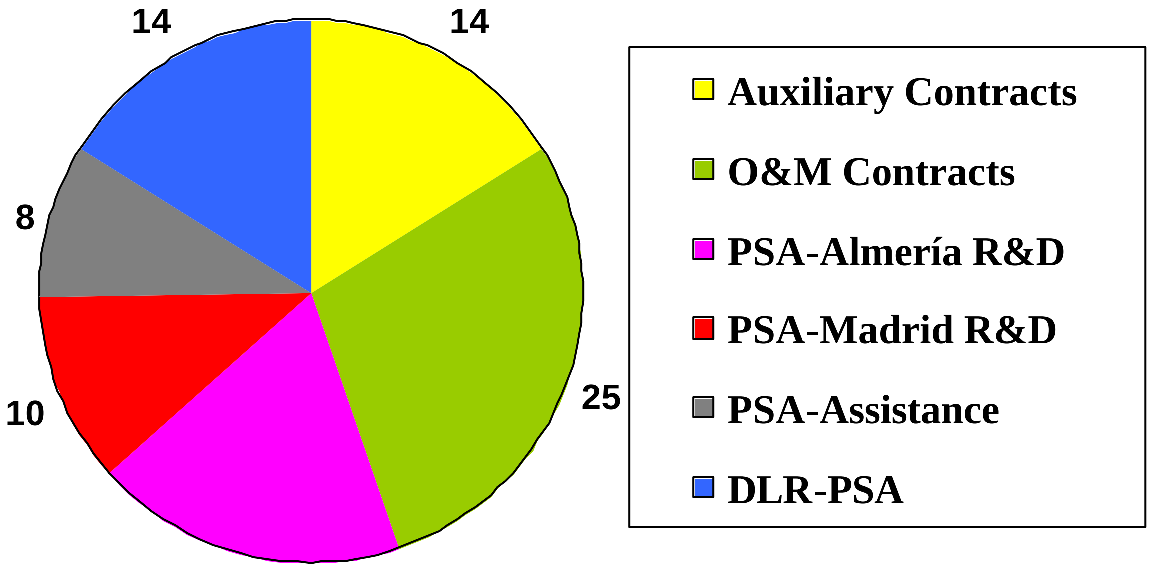

**PSA Organization Chart 2001. Directorate Technical and Administrative Service Offices are Indicated in Green.**

## Human and Economic Resources

The scientific and technical commitments of the PSA and their associated workload are undertaken by a team of 87 persons who, as of December 2001, made up the permanent staff that lends its services to the Plataforma Solar. Moreover, in addition to this permanent staff, there is a considerable influx of trainees and visiting researchers who are handled through the Training and Access Project described later.

Of the 87 persons that work daily at the PSA, an important part come from auxiliary services, operation and maintenance contracts (39 persons). The auxiliary contracts are for three cleaning persons, six administrative personnel and five security guards. The O&M contracts are for eight facility operators, four operation watchers and 13 persons for mechanical, electrical and electronic maintenance. The rest of the personnel are composed of the 34 persons on the CIEMAT-PSA staff and the 14 who make up the DLR permanent PSA delegation that result from the current commitments of the Spanish-German Agreement.

Focusing on R&D personnel, the PSA has a still small staff of 26 persons of whom 16 are in Almería and 10, while integrated in PSA R&D projects, work at the CIEMAT in Madrid. Another 12 DLR delegation staff members also work in R&D totaling 38 persons devoted to R&D at the PSA. This is without doubt one of the first improvements to be made and it is the firm desire of CIEMAT that in the coming years the ratio of personnel devoted to R&D be continually increased.

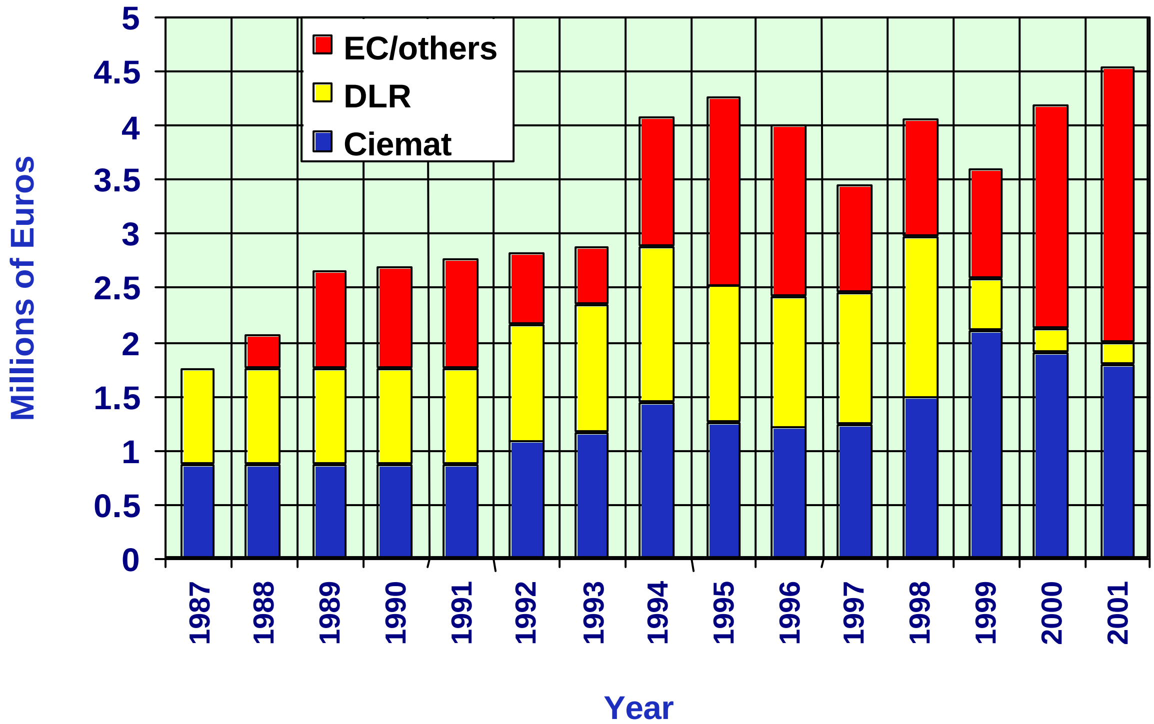



**Distribution of PSA permanent personnel as of December 2001.**

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

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

The PSA budget in 2001 reached 4.5 million Euros (not including Madrid R&D personnel costs). Of this 60% is from external revenue.




**Evolution of PSA budgeted expenses and distribution of source of financing**

## Scope of Collaboration

As mentioned above, since 1987, the PSA has maintained the Agreement for Spanish-German cooperation, commonly known as the CHA, with the DLR. Annex I of this Agreement was terminated in December 1998, and was replaced by a new Annex that regulates the new R&D-project-based relations with DLR. The new CHA expired in December 2001 and has been extended by mutual agreement for another year until December 2002. In 2002, the CHA will be subject to revision and updated in order to include the future interests of both institutions that wish to continue working together in the same framework of cooperation and friendship.

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

Under the Training and Access Project, as one of the large scientific installations in the EC IHP (Improving Human Potential) program, the PSA maintains relations with over 60 research teams and universities from different European countries. There is also an agreement for joint management of grants with the University of Almería, as well as educational agreements with the Ecôle Nationale des Ponts et Chaussées of Paris and the ETH (Polytechnical University of Zurich). An agreement is also being forged with the CNRS Solar Materials Laboratory in Odeillo (France) and intense participation in the European EUROCARE Network for Solar Energy and Advanced Combustion Projects is ongoing.

In parabolic-trough technology, the scope of collaboration continues to be quite broad, since the PSA has contractual relations with a wide range of domestic and international institutions. Collaboration continued in the year 2001 with the University of Seville, research centers (DLR, ZSW and the Fraunhofer Institute for Solar Energy Systems of Germany), the National Institute of Chemistry of the University of Ljubljana in Slovenia, the National Testing and Research Institute of Sweden; the Dutch TNO, the Greek CRES and the Swiss Solartechnik Prüf und Forschungsstelle), electric utilities (the Spanish ENDESA and IBERDROLA), industry (Spanish INABENSA and German FLABEG Solar International) and engineering firms (the German FICHTNER and SBP and Spanish INITEC).

In the scope of domestic central receiver technology, the PSA collaborates in projects with INABENSA, GHERSA, AICIA, IBERESE and SERLED and universities such as the University of Sevilla, Almería and UNED[3]. In 2001, the EHN Company, because of its Montes del Cierzo Solar Plant initiative in Tudela, joined in this collaboration. Under the umbrella of the 5th Framework Program's Energy Program and the Spanish German Agreement, collaboration with the DLR has been intense in several projects with other European institutions and companies such as ORMAT (Israel), TUMA (Switzerland), Heron (Netherlands), FICHTNER (Germany), STC (Denmark), Forth-Cperi (Greece), Saint Gobain (France), Nexant (United Kingdom) and SIMTECH (Austria).

The number of institutions and companies with which the PSA collaborates in the scope of Solar Chemistry and especially in the use of solar photocatalysis for the detoxification and decontamination of both liquid and gaseous effluents is enormous. One relevant network in which the PSA is currently participating is the CYTED network for "Semiconductor oxides and materials related to optical environmental applications", through which the PSA collaborates with over 20 groups in Argentina, Brazil, Mexico, Chile, Colombia, Peru, Cuba, Venezuela and Spain. In the regional context in 2001, the PSA participated in the Andalusian Network for Measurement of Ultraviolet Radiation and Photoprotection,

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

coordinated by the University of Malaga with participation of the INTA[4]. In the European sphere, participation in the "Targeted Research Action on Waste Minimization and Recycling (TRAWMAR)" network has involved the PSA in around 30 different European BRITE-EURAM projects, approved under the EC 4th Framework program. Other national cooperative R&D projects are underway with the University of Almería, the ICP-CSIC (Madrid) the UA (Barcelona) and the ICMAB-CSIC (Barcelona). In Europe, collaboration with the University of Vienna, the Portuguese INETI and AOSOL company and the Paul Scherrer Institute of Switzerland is outstanding. The diversification of activities of the Solar Chemistry Project in the year 2002 predicts intense collaboration in other fields such as hydrogen production and solar desalination.

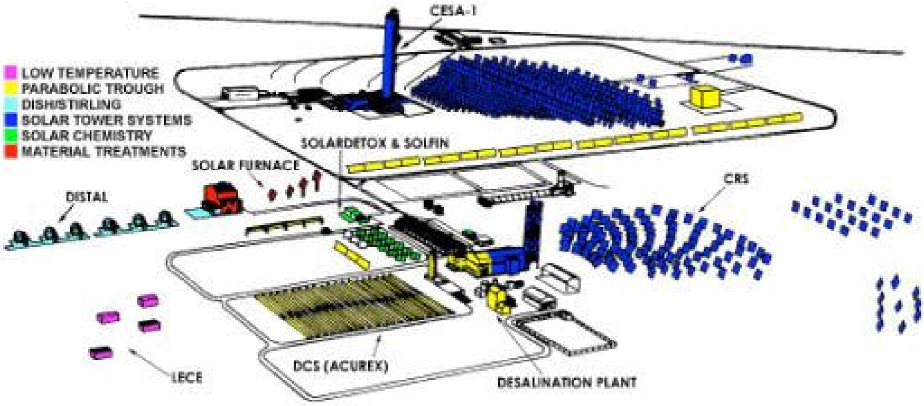
[4] Instituto Nacional de Técnica Aeroespacial

# Facilities and Infrastructure

## General Description of the PSA

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

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




**Location of the main PSA test facilities**

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

- CESA-1 and SSPS-CRS central receiver systems, 7 and 2.7-$MW_t$ respectively.
- SSPS-DCS 1.2-$MW_t$ parabolic-trough collector system, which has an associated thermal storage system and water desalination plant.
- The 1.3-$MW_t$ DISS test loop, which is an excellent experimental system for two-phase flow research and direct steam generation for electricity production.
- The HTF test loop, which has a complete oil circuit that allows evaluation of new components for parabolic trough collectors.
- A facility with 6 dish/Stirling systems called the DISTAL.
- A 60-$kW_t$ solar furnace for thermal materials treatments.
- A multiple facility for solar detoxification applications consisting of a parabolic-trough loop with two-axis tracking and three CPC photoreactors for different types of trials.
- The SOLFIN (Solar Fine Chemicals Synthesis) facility for synthesis of fine chemicals,
- The Laboratory for Energy Testing of Building Components[5] (LECE).
- A meteorological station.

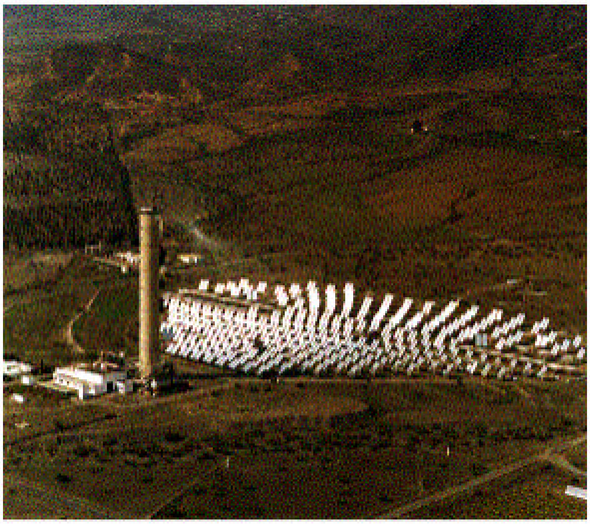
[5] El Laboratorio de Ensayo Energético de Componentes de la Edificación

# Central Receiver Facilities: CESA-1 y CRS

## 7-$MW_t$ CESA-I Facility

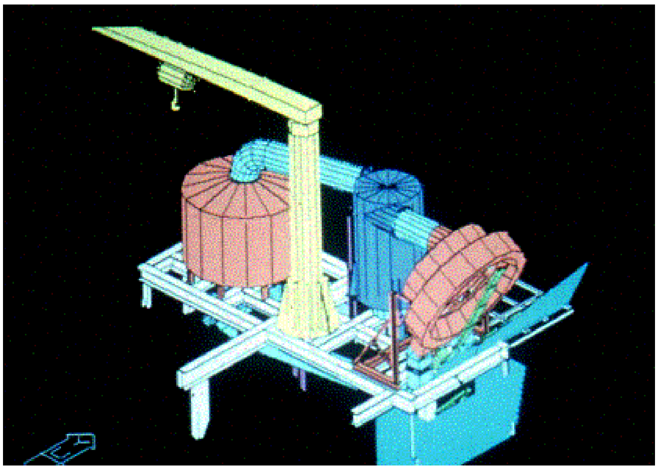
The CESA-I project, inaugurated in May 1983, was promoted by the Spanish Ministry of Industry and Energy to demonstrate the feasibility of central receiver solar plants and enable the development of the necessary technology. At present, the CESA-1 does not produce electricity, but is operated as a very flexible test facility for subsystems and components such as heliostats, solar receivers, thermal storage and control systems. It is also used for other applications that require high flux concentrations on relatively large surfaces, such as chemical processes for methane reforming, surface treatment of materials or astrophysical experiments.

The facility collects direct solar radiation by means of a field of 300 39.6-$m^2$-surface heliostats distributed in a 330-x-250-m north field into 16 rows. The heliostats have a nominal reflectivity of 92%, the solar tracking error on each axis is 1,2 mrad and the reflected beam image quality is 3mrad. North of the heliostat field there are two additional test zones for new heliostat prototypes, one located 380 m from the tower and the other 500 m away. The maximum thermal power delivered by the field onto the receiver aperture is 7 MW. At a typical design irradiance of 950 W/$m^2$, a peak flux of 3.3 MW/$m^2$ is obtained. 99% of the power is focused on a 4-m-diameter circle, 90% in a 2.8-m circle.

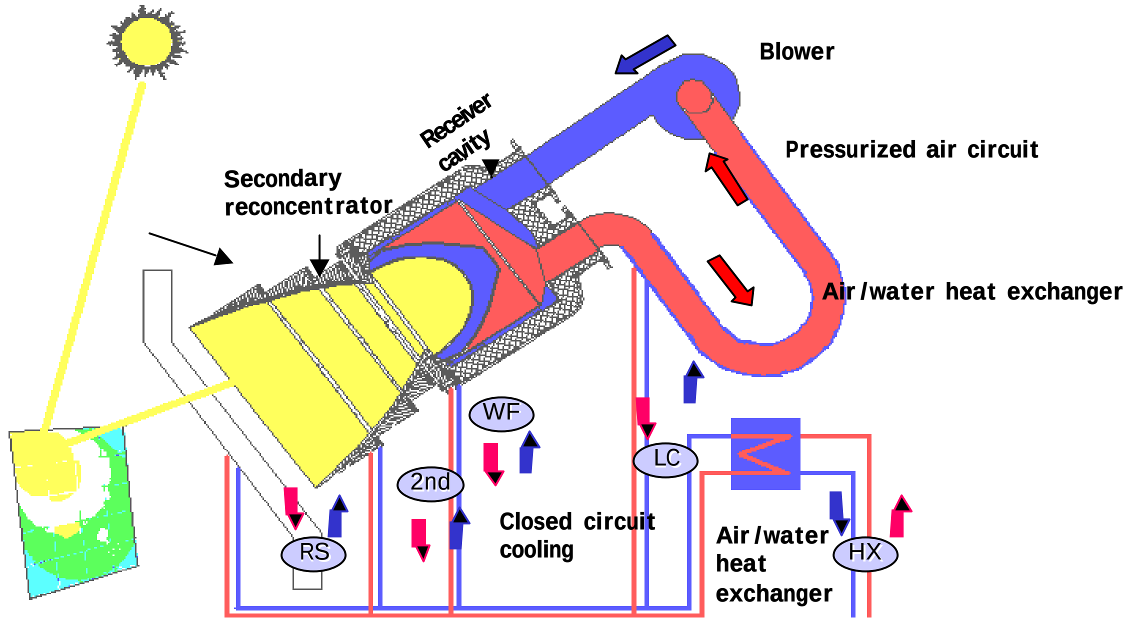


**Aerial view of the CESA-I facility**

The 80-m-high concrete tower, which has a 100-ton load capacity, has three test levels: A solar furnace for materials testing at 45 m, the REFOS test bed for pressurized volumetric receivers with calorimetry bench at 60 m and the 2.5-MW TSA facility for testing of atmospheric volumetric receivers at 80 m. The tower is complete with a 5-ton-capacity crane at the top and a freight elevator that can handle up to 1000-kg loads. Finally, for those tests that require electricity production, the facility has a 1.2-MW two-stage turbine in a Rankine cycle designed to operate at 520ºC 100-bar superheated steam.



**Artist's view of the TSA facility located in the CESA-I tower at the 80-m level. On the right the tilted solar receiver, in the center the crane and steam generator, and to the left the thermal storage system.**




**Presurized test loop for REFOS-type volumetric receivers located at the 60-m level in the CESA-I tower.**

The TSA and REFOS facilities are calorimetric test benches that enable measurement of solar receiver efficiency, in the first case up to 2.5 $MW_t$ and in the second up to 1 MW. The TSA consists of a receiver with a 3.4-m-aperture metal mesh absorber that heats air at atmospheric pressure up to 700ºC. The air circuit has two blowers and valves that allow hot and cold air to be sent to either a steam generator or thermal storage. The steam generator, which has a nominal capacity of 1.8 MW, receives the hot air and cools it to approximately 200ºC. The energy that is collected here produces 340ºC 45-bar steam of sufficient quality to feed a steam turbine. The 18-ton insulated cylindrical storage tank, which contains a bed of ceramic balls ($Al_2O_3$), has a capacity of 1000 kWh. The REFOS closed air circuit consists of a fan and two coaxial ducts that act as heat exchangers by circulating water from a connected cooling tank on the outside to cool air. The power absorbed by the receiver is transferred to the cooling water, which allows the solar power absorbed to be evaluated by a calorimetric method. A data acquisition system records 20-sec temperature, flow rate, pressure data, etc.

## The 2.7 $MW_t$ SSPS-CRS Facility

The SSPS-CRS plant was inaugurated as part of the International Energy Agency's SSPS project (Small Solar Power Systems) en September 1981. It was originally a demonstration electricity production plant and used a receiver cooled by liquid sodium that also acted as the thermal storage medium. At the present time, as with the CESA-I plant, it is a test facility devoted mainly to testing small solar receivers in the 200 to 350-kW thermal capacity range. The heliostat field is made up of 91 39.3-m² first generation units. A second field north of it has 20 52-m² and 65-m² heliostats that are controlled by radio and that can be used as support. The nominal average reflectivity of the field is 87%, the solar tracking error is 1.2 mrad per axis and the optical reflected beam quality is 3 mrad. Under typical conditions of 950 W/m², total thermal capacity of the field is 2.7 MW and peak flux obtained is 2.5 MW/m². 99% of the power is collected in a 2.5-m dia. circumference and 90% in a 1.8-m circumference.

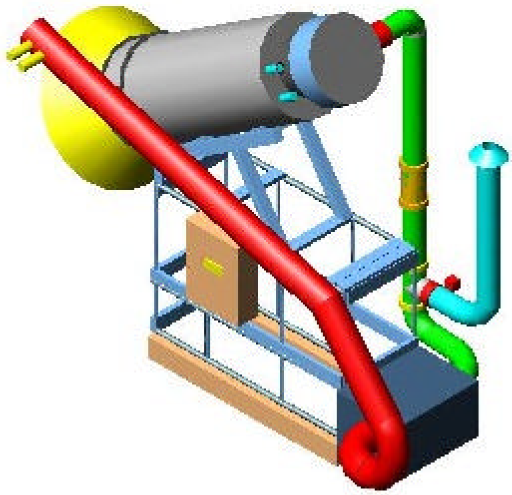
The 43-m metal tower has two test platforms. The first is a two-level open area at 32 and 26 m prepared for testing new receivers for chemical applications. The second is at the top, at 43 m, and houses an enclosed room with crane and calorimetric test bench for the evaluation of small atmospheric-pressure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

The tower infrastructure includes a 600-kg-capacity crane and 1000-kg-capacity rack elevator.

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

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

**A CRS field heliostat reflecting the tower.**



**Schematic diagram of the volumetric receiver test bench and air circuit in the CRS tower.**

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

## Linear-focusing concentrator facilities: DCS, DISS, EUROTROUGH and LS3

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

## The DISS test loop

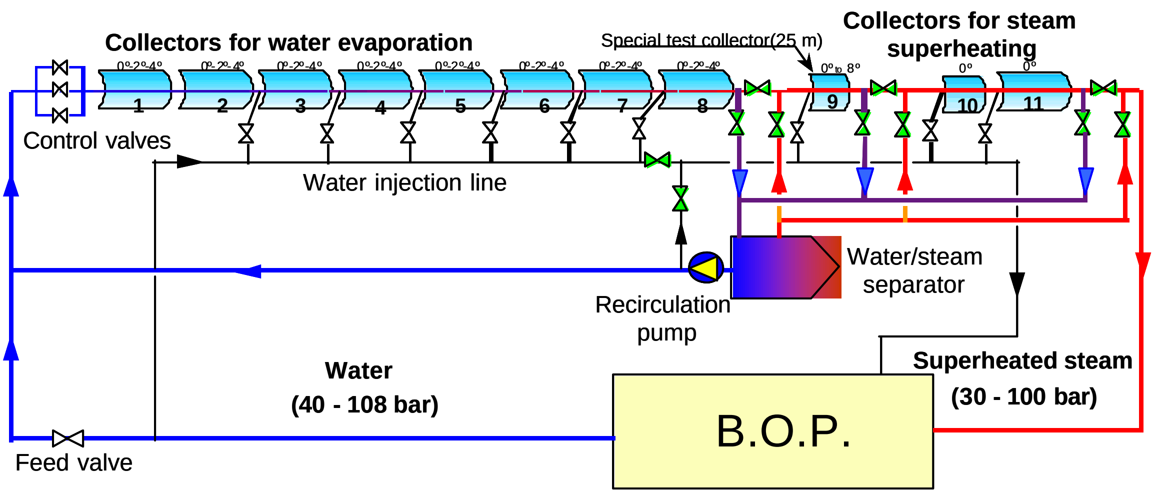
This facility was erected and put into operation in 1998 for experimenting with direct generation of high-pressure high-temperature (100 bar/400ºC) steam in the parabolic-trough collector absorber tubes. The DISS loop is the only facility in the world where two-phase flow (water/steam) processes in parabolic trough collectors can be studied under real solar conditions. It is very appropriate not only for the study and development of control schemes, but also for the study and optimization of operating procedures, that must be implemented in direct steam generation solar fields.

The DISS loop consists of two subsystems: the Solar Field of parabolic-trough collectors, and the Power Block. In the solar field, the feed water is preheated, evaporated and converted into superheated steam as it is circulated through the absorber tubes of a 550-m-long row of parabolic trough collectors having a total solar collecting surface of 2,750 m$^2$. The facility can produce 0.8 kg/s of 100-bar 370ºC steam.

The Power Block is where the superheated steam generated in the solar field is condensed, processed and reused again as feed water for the solar field (closed-circuit operation).

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

The figure below shows a simplified diagram of the DISS loop in which the solar field is shown as one row of 11 parabolic-trough collectors with north-south-oriented rotating axes. Nine collectors are composed of 4 reflective parabolic-trough modules, while two collectors (nos. 9 and 10) have only 2 modules. Each module is 12 m long by 5.7 m wide. The solar field consists of two parts, the evaporating section and the superheating section. At the end of the evaporating section there is a recirculation pump and a water/steam separator which augments the operative flexibility of the system.




**Simplified diagram of the PSA DISS loop.**

The Power Block consists of water/steam separators, condensers, chemical-dosing system, preheaters, degasifier and water pumps.

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

**View of the DISS solar field in operation**

## The LS-3 (HTF) test loop

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

The facility consists of a thermal oil circuit connected in a closed loop to a solar collector made up of four 12-m-long by 5.7-m-wide LS-3 parabolic-trough modules with a total collecting surface of 272.5 $m^2$. The thermal oil used in this facility (Syltherm 800) has a maximum working temperature of 400ºC, and a freezing point of –40ºC. The rotating axis of the solar collector is oriented east west, which increases the number of hours per year in which the angle of incidence of the solar radiation is less than 5º.

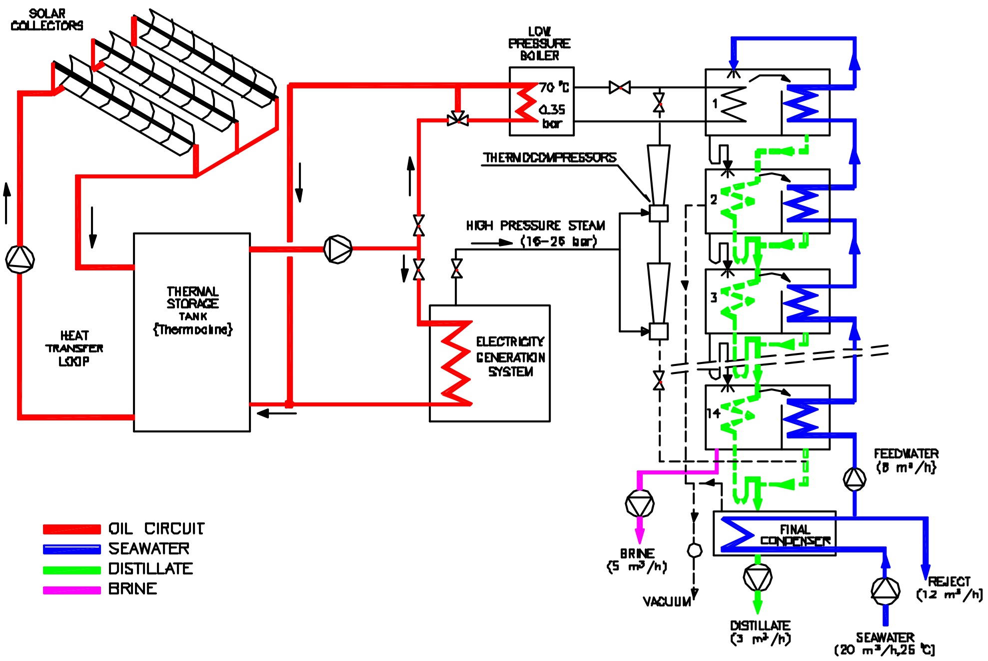
**General view of the LS-3 test loop**

The facility's oil circuit, which has a maximum working pressure of 16 bar, is made up of the following elements:

- 1-$m^3$-capacity oil expansion tank, with automatic nitrogen inertization system
- Oil circuit sump tank
- Mechanical draft oil cooler, with air speed control and 225-kW maximum cooling.
- Centrifugal oil pump, with a flow rate of 0 – 2,8 liters per second
- 40-kW, 3-x-380 V electrical oil heater.

## SSPS-DCS plant with solar desalination system

This 1.2 $MW_t$-capacity facility consists of four main subsystems, as shown in the diagram below:




**General diagram of the SSPS-DCS plant**

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

- A 5-$MWh_t$-capacity thermal storage system consisting of a 140-$m^3$ thermocline oil tank for charging/discharging temperatures of 295º/25ºC with automatic fire-extinguishing system, automatic venting valves and volatile-condensing system. It also has a water-cooled oil cooler for quick cooling during transient testing.

- A 500-kWe water/steam Rankine cycle electricity generating system consisting of a steam generator fed by the hot oil delivered by the solar field and/or storage tank; degasifier; steam turbine; electric generator and mechanical draft closed-loop cooling tower.

- The MED desalination plant, called the SOL-14, consists of a 14-stage multi-effect distillation plant, which is connected to the thermal storage system described above. For a nominal production of 3-m³/h distillate, plant consumption is 190 $kW_t$, with an efficiency factor (number of kg of distillate produced for every 2,300 kJ of energy consumed) over 9. The saline concentration of the distillate is around 50 ppm. The nominal temperature gradient between the first and last stages is 40ºC, with an operating temperature of 70ºC in the first stage.
- The vacuum system, which is made up of hydroejectors fed by 3-bar seawater, is used to evacuate the air from the unit at startup and to compensate for any small amounts of air and gas liberated from the feed water, as well as any slight losses that might be produced in the various connections.

| | |
|---|---|
| Capacity: | 3 m³/hour |
| Number of effects: | 14 |
| Feed water: | Seawater (35,000 ppm) |
| Product: | Distillate (≤50 ppm) |
| Recovery Factor: | 38% |
| Feedwater flow rate: | 8 m³/hora |
| Thermal consumption (FR): | 63 kWh/m³ (>9) |
| Electricity Consumption: | 3 kWh/m³ |
| Solar field capacity: | 1.2 MWp |
| Solar field performance: | 50% |
| Collector surface: | 2762 m² |
| Type of collectors: | ACUREX 3001 (CCP) |
| Storage: | 5 MWh (Therminol 55) |
| Maximum oil temperature: | 300ºC |

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

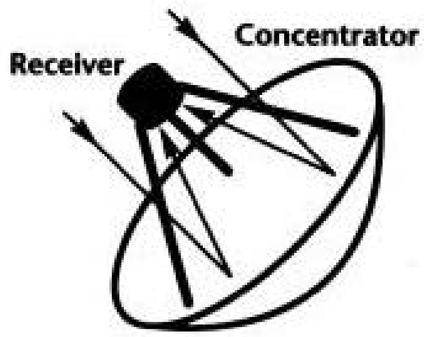
There is also a double-effect absorption heat pump, which represents the first real prototype of a device of its kind for this application. The connection of this device increases the performance ratio of the MED plant to 20 thanks to condenser heat loss recovery.

# Dish/Stirling Systems: DISTAL and EURODISH

## Principles

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

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




Functional diagram of a parabolic dish with Stirling motor at the focus.

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

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

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

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

## DISTAL I

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

The concentrator prototype was made using the stretched membrane technique, which maintains the parabolic shape with a small vacuum pump. It has 94% reflectivity and can concentrate the sunlight up to 12,000 times in its 12-cm-diameter focus. It has a focal distance of 4.5 meters and polar solar tracking.

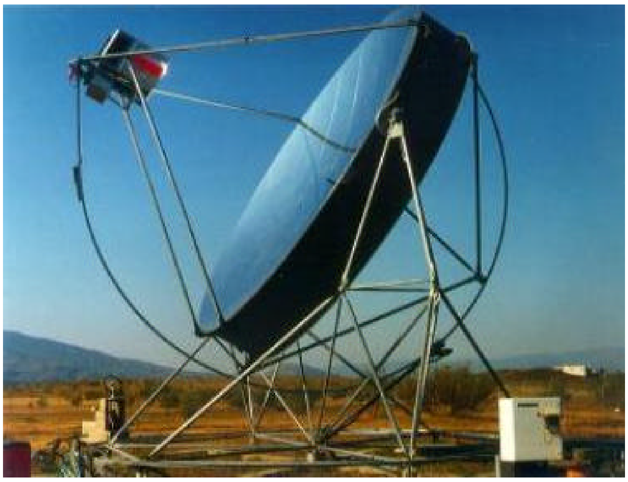
A DISTAL I dish in operation

Two DISTAL I units were disassembled in the year 2000 and replaced by third generation EURODish units.

## DISTAL II

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

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

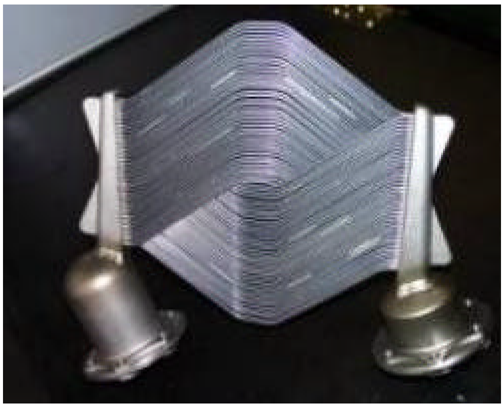


DISTAL II unit

## EURODish

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

- Reduce the price of components by using standard industrial elements.
- Develop a new dish manufacturing system discarding the stretched-membrane technology and applying a “composite”-material molding system.
- Improve the Stirling SOLO V161 motor, especially those components used in the receiver cavity.
- Develop a new optimized system assembly procedure that uses new specially developed tools.
- Remote control and monitoring over the WWW.
- Test pre-commercial units as reference systems.



**New Stirling motor receiver cavity absorber tubes.**

**Front and back views of the EURODishes.**

# The Solar Furnace

## GENERAL DESCRIPTION AND PRINCIPLES OF OPERATION

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

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

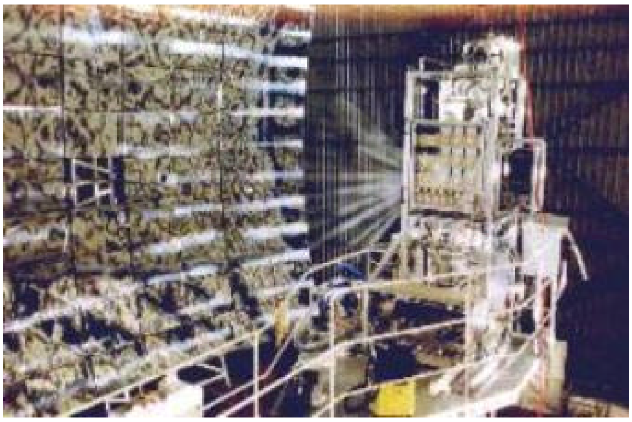
The flat collecting mirror, or heliostat, reflects the parallel horizontal solar beams on the parabolic dish, which in turn reflects them on its focus (the test area). The amount of incident light is regulated by the attenuator located between the concentrator and the heliostat. Under the focus there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

## HELIOSTATS

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

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

## CONCENTRATOR



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

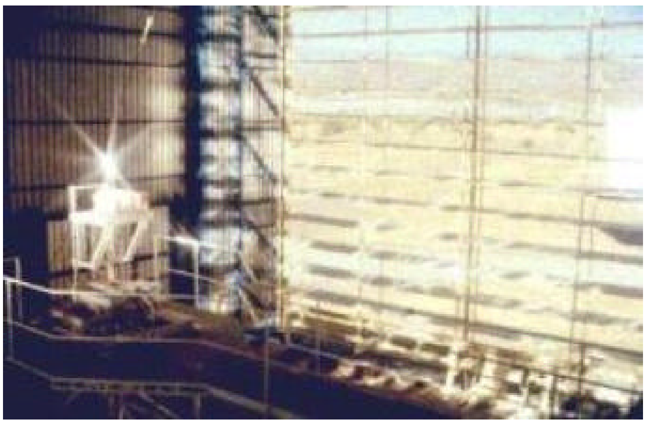
The concentrator disk is the main component of the solar furnace. It concentrates the incident light from the heliostat, multiplying the radiant energy in the focal zone. Its optical properties especially affect the flux distribution at the focus. It is composed of 89 spherical facets with a total surface 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.

## ATTENUATOR

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

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



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

## TEST TABLE

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

## DISTRIBUTION OF THE FLUX DENSITY IN THE FOCUS

The concentrator and distribution of the flux density in the focus is the element that 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].

# Solar Chemical Facilities

## DETOX/SOLFIN Facilities for Solar Photochemical applications

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

Later, other CPC (Compound Parabolic Collector) pilot plants were installed that can use diffuse radiation as well as direct. The CPC reflectors are made of anodized aluminum. At the PSA there are now three such plants. The largest has two modules, each with a 3-m$^2$ surface tilted 37º (local latitude) from the horizontal. The complete includes a pump, tank and connecting piping. The total system volume is approximately 190 L and the absorber tube (illuminated) volume is 72 L. At this time, a new 15-m$^2$ collector is being installed that will increase the volume to 300 L. Furthermore, two twin prototypes are also available for parallel experiments. Each reactor is made up of three modules of eight glass tubes each. The three modules (3.08 m$^2$) of each reactor are mounted on a fixed platform also tilted 37º . The total reactor volume is 40 L, of which 22 L is the total irradiated volume and the rest is in the piping and tank.

There are also three sensors for measuring ultraviolet solar radiation, one with a solar tracking unit for direct radiation and two horizontal units tilted 37º (the same angle as the CPCs) to the earth's surface for global. All the data are sent to a computer where they are stored for their later evaluation.

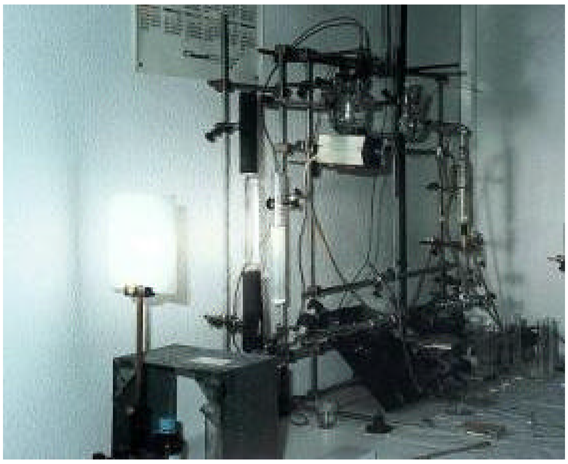
The solar collectors associated with the SOLFIN (*Solar Synthesis of Fine Chemicals*) facility is made up of CPC collectors of various sizes and geometries that allow study of the parameters affecting scale-up of chemical processes (basically organic synthesis) previously optimized in the laboratory. The system basically consists of a closed circuit in which a pump circulates the reagents and dissolvent through the photoreactors on the collector axis where they are irradiated. The whole system can be thermostatized by water that cir-

**General view of the Solar Photochemistry CPC facilities.**

culates through the internal reactor tube (made up of two coaxial tubes), the temperature of which is controlled by a heat-pump cooling system.

These experimental facilities are complemented by the PSA Solar Chemistry Laboratory, which has all the conventional chemical laboratory equipment: work tables, gas extractor fan hood, storeroom for small amounts of chemicals, central distribution of technical gases, UPS, safety systems, counter for precision scales, water ultrapurification system, ultrasound bath, centrifugal vacuum distillation system, as well as many other systems normally used in a chemistry laboratory. Furthermore, it has the following analytical equipment, all of them related to Environmental Chemistry: Liquid chromatograph (quaternary pump with automatic injector and diode detector), gas chromatograph (FID and TCD) with purge and trap system (analysis of volatiles dissolved in water), ion chromatograph, TOC analyzer (with automatic injector), UV-visible spectrophotometer, COD and BOD. The laboratory information system consists of four Pentium computers, three of them connected to the chromatographs. The fourth computer has the only Andalusian network (14 stations) node in Almería for UVB/UVA/PAR measurement

## Chemistry Test Bench



**Solar Chemistry Project test setup**

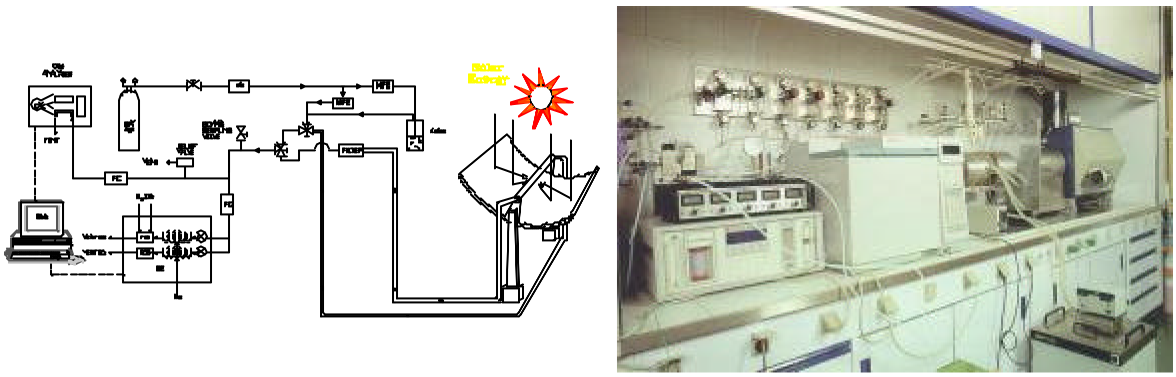
This test bench, located in the CIEMAT's Department of Renewable Energies (Madrid), enables laboratory-scale experimentation to determine the feasibility of processes that will later be carried out in the various solar facilities mentioned above. The use of this test bench has basically been to determine process thermodynamics and kinetics. The facility consists of Pyrex photoreactors that operate in recirculation or batch mode and use a solar simulator with a 1000-W Xenon lamp as the light source. All the parts of this system have been fabricated with inert materials that guarantee that the tests are carried out under nearly ideal conditions. Furthermore, the test bench analytical infrastructure guarantees continuous monitoring of all the variables under study.

Among the different laboratory-scale studies now underway, the following may be highlighted:

- Aging, deactivation and regeneration of the photocatalysts used in photocatalytic oxidation processes [Vidal y Martín-Luengo, 2001a].
- Feasibility of the detoxification process with concentrated radiation for the Fe+2 - $H_2O_2$ system [Vidal y col., 2002].
- $CO_2$ reduction studies with a view to its use in chemical storage of solar radiation [Vidal y col., 2001b].

## Gas Phase Detoxification Laboratory

The Gas Phase Detoxification Laboratory, also located in the Dept. of Renewable Energies in Madrid, allows testing under controlled conditions of any volatile organic compound (VOC) that can be destroyed by solar energy or UV lamps. It is provided with a gas inlet and control system, Xenon lamp solar simulator and analytical instrumentation made up basically of GC and GC-MS, associated with a system of thermal desorption system and continuous NOx, $SO_2$ and $CO_2$ analysis. This system allows complete control of laboratory as well as real solar radiation tests located on the roof of the building immediately above the laboratory. A diagram of the facility and partial view of it are shown below.



**The reactions activated by light take place on the surface of catalysts either in the form of structures with parallel channels called monoliths or tubular, that are inserted in parabolic trough reactors**

# Other Facilities

Among its other facilities, the PSA has a demonstration area for other technologies like photovoltaic panels, solar cookers and domestic water heaters, as well as the Laboratory for Energy Testing of Building Components (LECE). The LECE is part of the European PASLINK network for energy testing of building components. It consists of four test cells with thermal instrumentation for the complete monitoring of conventional and passive solar building components. The LECE makes use of the PSA infrastructure and its excellent conditions for solar applications, but it is integrated in and managed directly by the Solar Energy in Building Group of the CIEMAT Department of Renewable Energies.

**View of the solar collector used as a tilted enclosure**

The purpose of the LECE facility is to contribute to improving our knowledge of the energy quality of building elements through thermal characterization experiments, which find the overall heat transfer coefficient, solar gain factor or system response times, etc. Knowledge of such properties can help improve building design with a view to increasing energy savings without loss of comfort and predict their thermal behavior.

The LECE performs the following activities:

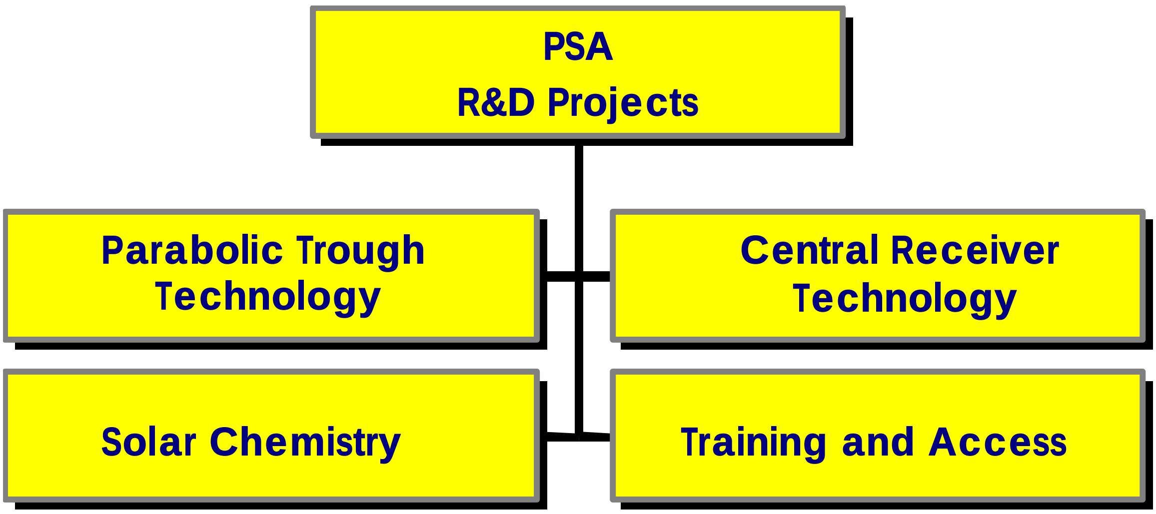
- Experimental support for the writing of policies and regulations.
- Experiments for the CIEMAT Solar Energy in Buildings R&D Group.
- Cooperation with and service to the manufacturers of building materials and components.

# R&D Projects

## Introduction

The R&D activity in solar thermal power plants during the period from 1999-2000, which showed an unquestionably spectacular increase in all activity indicators, was consolidated in 2001 [Romero, Zarza y Blanco, 2001]. A scenario of opportunities and expectations for Spanish as well as foreign business was generated by the expected approval this year of a Royal Decree regulating premiums for electricity produced with solar power plants and the Spanish Plan for Promotion of Renewable Energies in 1999, followed by annual announcements of subsidies for technical and industrial development by the Ministry of Science and Technology that have been opened to solar thermal technology, first with the ATYCA initiative and later with the PROFIT program. Essential tools for Central Receiver R&D assistance such as the EC 5th Framework ENERGIE Program and the announcements of ERDF funds for infrastructure and R&D have also contributed.

The Plataforma Solar de Almería has played a very active role during this entire period, with decisive involvement in the management of four projects now underway in Spain for the construction of as many Solar Power Plants. In Central Receiver Technology, the PS10 project for a 10-MW plant using the solar volumetric air receiver technology is promoted by the ABENGOA Company and the Solar Tres project for the construction of a 15-MW plant cooled by molten salts is promoted by the GHERSA and BOEING companies. In 1999, 2000 y




Projects that comprise PSA R&D activity

2001 a large part of the effort of the team of experts in central receiver technology (CRT) at the PSA has focused on assistance on all fronts to see that these unique projects are successfully completed. In the wake of these two projects a series of technological projects that receive domestic as well as EC subsidies have germinated for the development of components such as heliostats, receivers, thermal storage, control systems and design and modeling tools.

With all of the above ongoing, the interest of industry in solar thermal power plants continues to expand, and at the beginning of 2001, two more projects, based this time on the parabolic trough technology, were born. The EuroSEGS proposed by the Spanish company EHN and the American Duke Solar, is for the construction of a 15-MW plant in Tudela (Navarra) and the ANDASOL project, promoted by a European consortium in which the most active members are Flabeg, Solar Millennium and Abengoa, is for the construction of a commercial 50-MW plant within the municipal limits of Guadix in the province of Granada and which is based on the European EUROTROUGH technology tested at the PSA.

Equally outstanding are the Solar Chemical R&D activities, which the PSA has made the center of gravity of a large number of solar detoxification of gaseous and liquid effluents projects [Blanco, 2001]. The PSA has become the leader in the escalation of applications and systems from the laboratory to demonstration plants with real solar radiation, having culminated in the technology necessary for an ambitious European project called SOLARDETOX, which terminated in the year 2000. This solar detoxification technology development and transfer project, led by the PSA, is being continued in the CADOX project, which was approved in the year 2001 and will begin in 2002. In the field of applications, the PSA has also made an outstanding effort. As an introductory example, we mention that in the year 2001, the ALBAIDA and TREN-AGRO solar detoxification initiatives for the integrated treatment of residues from the recycling of pesticide containers in a pilot plant, have been approved by the EC LIFE program and the MCYT, respectively. Finally, within the non-electric applications new projects in solar desalination motivated by social demand have been initiated using a multi-effect (MED) system connected to a field of CPC collectors.

R&D activities are completed with the Training and Access Project that basically rotates around the PSA classification as an EC IHP (Improving Human Potential) Large Scientific Installation. Through this program, a total of 60 European research groups will have access to the PSA facilities in the period from 2000 to 2002.

This situation clearly shows a stable working environment, consolidated projects and clear objectives, with commitments that in some cases go through to a 2006 R&D horizon. In the national context, the PSA has closely cooperated with almost all of the companies working in concentrated solar energy for electric, thermal and chemical applications and with universities such as the University of Seville, University of Almería and the UNED. The PSA has human resources and infrastructures that are unique in concentrated solar technology and make the participation of CIEMAT available to any development or solar thermal plant project in Spain. In the international sphere, PSA participation in Tasks I, II and III of the IEA SolarPACES program may be highlighted. Under this program, information is exchanged and task costs are shared with analogous centers in the USA, Germany, Switzerland, Australia, Russia, Israel, France, etc. At present, it is the only network of experts in concentrating solar thermal technology and systems. Under the umbrella of the 5th Framework Energy Program and the Spanish-German Agreement, the already traditional collaboration with the German Aerospace Center (DLR) in joint projects is intense.

# Central Receiver Technology

Tower systems, or Central Receiver Technology (CRT), consists of a large field of heliostats, or mirrors, that track the position of the sun at all times (elevation and azimuth) and direct the reflected beam onto the focus at the top of a tower. The orders of solar concentration are from 200 to 1000 and the power from 10 to 200 MW. It is a technology in which the PSA has a long tradition of research, since it has two absolutely privileged facilities in the CESA-1 and CRS plants, which are both very flexible test benches for the testing and validation of components and subsystems.

Because of the high flux of the incident radiation (typically between 300 and 1000 kW/m$^2$), high working temperatures and thereby, integration into more efficient cycles, from Rankine with superheated steam to Brayton cycles with gas turbines are possible, easily admitting hybrid operation in a wide variety of options and have the potential for generating electricity with high capacity factors through the use of thermal storage, with today's systems exceeding 4500 equivalent hours per year.

Although the maturity of CRT systems was already validated by the successful demonstration projects carried out in the eighties and more recently, by the interest shown by cities, private venture companies and utilities in Europe and the Americas, which have placed them in the lead with projects such as the PHOEBUS-TSA, Solar Two, Solar Tres and PS10, their high capital cost is still an obstacle to the realization of their full commercial potential [Romero, Zarza y Blanco, 2001]. The first commercial applications, which are just starting out, still have an installed power cost of 2800 Euro/kW and for electricity produced of around 0.18 Euro/kWh. A reduction in the cost of the technology is therefore essential for the extensive number of commercial applications in potential sites. Conscious of this problem, the PSA permanently maintains an R&D project focused on the development of component and system technology in order to reduce costs and improve their efficiency.

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

- Significant improvement of the overall economics of central receiver solar thermal systems, through reduction in the cost of their components, especially those which bear the most weight in the total plant cost (heliostat field, receiver and control), and the simplification of associated O&M.
- Improvement of central receiver system integration in hybrid plants by developing advanced components that allow more efficient integration schemes and their adaptation for use in high-performance solar-only plants.
- Facilitate the development and the consolidation of an own industry, through technology transfer, performance of appropriate market studies and the definition of actions that tend to eliminate the non-technological barriers impeding the penetration of this technology.

The above objectives can be achieved by the following strategy based on three essential elements:

- Technological consolidation and cost reduction.
- Advanced integration component and concept development
- Technology transfer to boost feasibility.

Research activity carried out by the CRT group at the PSA in 2001 had at its nucleus the following projects:

1) Project: "SIREC: Central Receiver Solar Thermal Systems", ref. 1FD97-0957-C02-01. Financed by: ERDF Fund R&D projects published in, BOE 7-8-97. Participants: CIEMAT,

IAER-Univ. Seville. Principal Researcher Subproject 01: M. Romero (CIEMAT), Period: October 1999-Dicember 2001.

2) Project: "SOLAIR: Advanced solar volumetric air receiver for commercial solar tower power plants"; Ref. NNE5-1999-10012 Published: 1999/C 77/13. Financed by: EC DG RTD (ENERGIE Program). Participants: CIEMAT, INABENSA, IBERESE (Spain), STC (Denmark), DLR (Germany) y FORTH/CEPRI (Greece). Principal Researcher: Rafael Osuna (INABENSA). Period: February 2000/June 2003.

3) Project: “REFOS-II: Volumetric pressurized solar receiver for fossil fired gas turbine and combined cycle power plants”; Ref: Spanish German Agreement for cooperation in Research at the PSA. REFOS-II Project Annex. Participants: DLR-Stuttgart (Germany) and CIEMAT (Spain). Principal Researcher: Reiner Buck (DLR). Period: January 2000/July 2002.

4) Project: "SOLGATE: Solar hybrid gas turbine electric power system"; Ref. ENK5-2000-00333. Published: EC- DG RTD (ENERGIE Program). Participants: ORMAT (Israel), INABENSA, CIEMAT (Spain), DLR (Germany), Heron (Netherlands) and TUMA (Switzerland). Coordinator: C. Sugarmen (ORMAT). Period: January 2001/April 2003.

5) Project: "PS10: 10 MW Solar Thermal Power Plant for Southern Spain"; Ref. NNE5-1999-00356. Published: 1999/C 77/13. Financed by: EC- DG TREN (ENERGIE Program). Participants: CIEMAT, INABENSA, AICIA (Spain), DLR, Fichtner and Steinmüller (Germany). Principal Researcher: Rafael Osuna (INABENSA). Period: Enero 2000/Diciembre 2002.

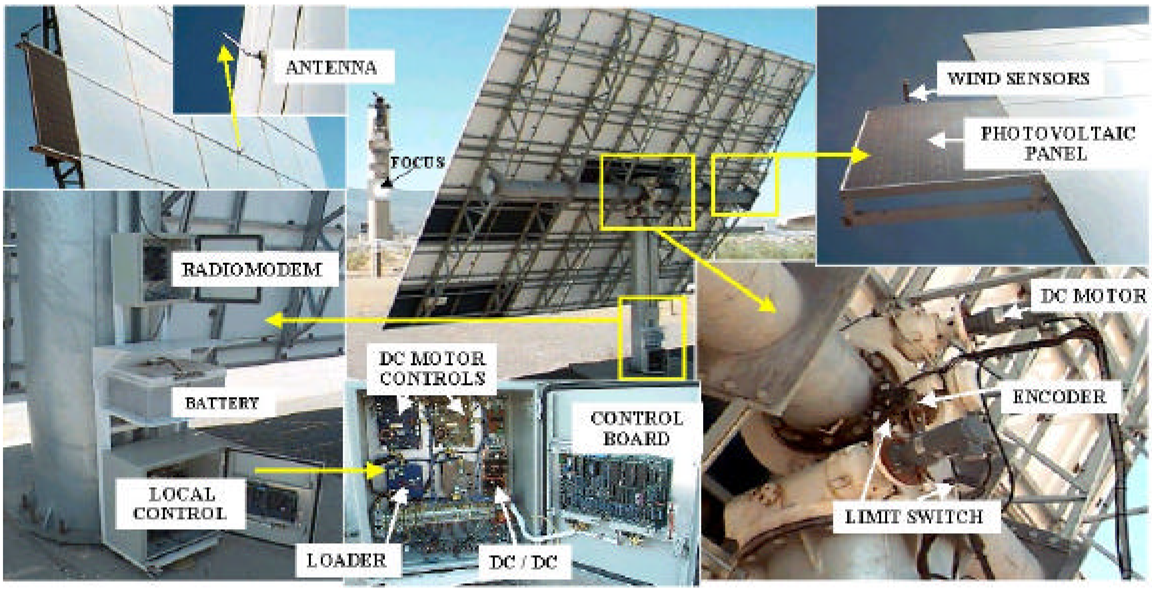
6) Project: “SOLAUT: Generación Eléctrica Termosolar mediante Módulos Autónomos”; Ref. FIT-120102-2001-7. Convocatoria PROFIT-2001, Ministry of Science and Technology. Participants: CIEMAT, INABENSA, IBERESE y SERLED. Period (January/December 2001).

## THE SIREC PROJECT

This ambitious project covers an entire set of Spanish component and tool activities linked to optimization of the central receiver technology in collaboration with the University of Seville and the INABENSA Company. The project really began in 1999 through the ATYCA project coordinated by INABENSA, in which CIEMAT was subcontracted for several tasks, and the final ATYCA report was published in 2000. When that project was over, the work started there was integrated into the SIREC project coordinated by CIEMAT and financed with ERDF funds, and which started in January 2000 and finished in December 2001. The program of work included new heliostat developments, such as a field of radio-controlled heliostats, new local and global control concepts, volumetric receivers with metal ceramic absorbers, a hybrid solar saturated steam receiver, development of software for optical characterization, plant design and feasibility studies. The most outstanding results are:

***First stand-alone heliostat field*:**

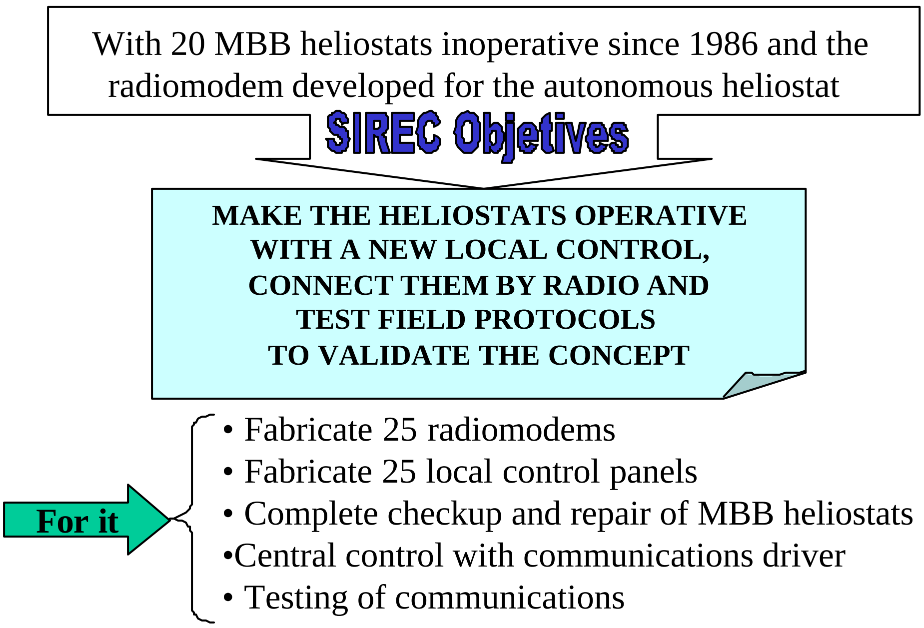
One of the objectives pursued in recent years at the PSA has been the evaluation of the technical-economic feasibility of the use of intelligent autonomous units. These units consist of an autonomous power system for the control and solar tracking actuators, with photovoltaic panels integrated in the heliostat, and a wireless communication system to control the heliostat field, during emergency and security operations as well as routine operation. This stand-alone heliostat concept is being patented by the PSA.




***Photographic composition of the main components of the autonomous heliostat tested.***

In the year 2000, the final report of the first stand-alone heliostat known, tested at the PSA, was prepared. The extensive evaluation carried out confirmed the durability and reliability of radio communication and low electricity consumption [García y Egea, 2000; García et al., 2000]. Daily electricity consumed by actuators in routine sunrise-to-sunset operation was about 200 Wh, a 35-Wp PV panel and storage in 25 Ah batteries being sufficient for operation of a 70-90 m² commercial heliostat. The extra cost of an autonomous heliostat is estimated at 570 Euro compared to the 1800 Euro of the avoided cost corresponding to cables, trenches, etc. for a conventional heliostat, so that the autonomous heliostat concept may turn out to be extraordinarily attractive for commercial plants. A special radio for the task, developed in collaboration with the University of Almería, was the subject of a doctoral dissertation.

In 2001 the autonomous heliostat concept advanced one more step with the successful demonstration of radio communications in a group of heliostats. The PSA field of 20 MBB heliostats was put into service as a test bench for this purpose. The control boxes were




***Activities under the SIREC project in 2001 for development of the autonomous heliostat***

modified with new communications cards; in 10 of them commercial radio modems were installed and in the other 10, specially designed radio modems. The most important conclusion of this study is that both types of radio modem can be used successfully for wireless communications in a field of around 1000 heliostats with the same ease as other supports like cable or optic fiber. This means that wireless communications in a field of 1000 heliostats must be able to assure reception and status processing (level 0) of all the heliostats in less than 10 seconds. The excellent results obtained have motivated the PSA to plan an even more ambitious objective for the years 2002 and 2003, the transformation of the entire CRS field of 92 heliostats into an autonomous field controlled entirely by radio, which would be without doubt a worldwide milestone.

***<u>Sanlúcar –90 Heliostat:</u>***

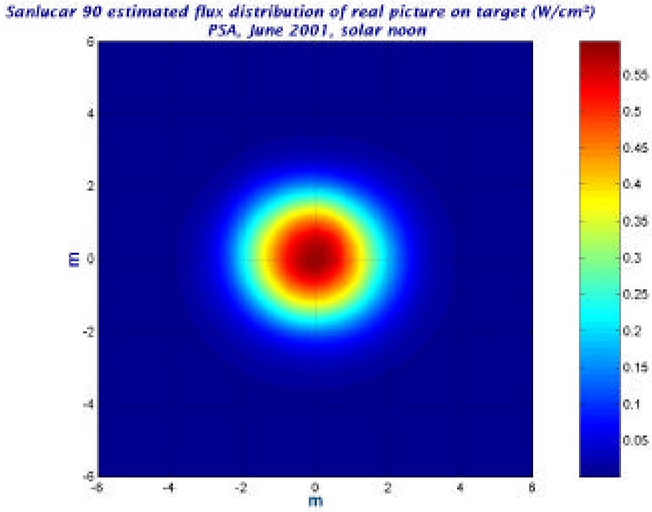
The basic objective of the PSA regarding heliostat development is to promote a moderately priced national technology, with the following criteria:

- Significant reduction (by around 40%) of the cost per $m^2$, based on the components which comprise the greater part of the cost, such as the drivers, facets and control elements. Basically, the introduction of standard low-cost linear or angular drivers, use of lightweight, low-cost reflective materials, such sol-gel mirrors, reflective polymers or thin mirrors and integrated configuration of central and local control to reduce control costs.
- Lightweight modular support structure to reduce the weight of the movable heliostat parts and gravity loads on the driver, pedestal and foundation. Modularity would facilitate transport, from the factory to the field as well as within the field itself, and thereby, its installation at remote sites or sites with difficult road access. It would also facilitate assembly and startup to receive modular pretested and calibrated components from factory or warehouse. The reflective surfaces (facets) must be as integral a part as possible of the structure.
- Easy installation and canting, so the system can be put into service and adjusted by technical personnel with little specific training, limited technical means and in a short time, thereby reducing current installation and startup costs. Such autonomous units with structurally integrated support/facets and modular configuration will greatly facilitate by design the work of installation and adjustment.

R&D activity on new heliostats has focused mainly on the development of the Sanlúcar heliostat [Romero, 2001]. This heliostat has been selected by the ABENGOA company for the 10-MW PS10 plant which it is promoting in Sanlúcar la Mayor (Seville), where about 1000 units would be necessary. In 2001, as a result of the fruitful collaboration of INABENSA and CIEMAT, two prototypes were built and installed at the PSA, one with worm/gear drive and the other with hydraulic drive. The Sanlúcar heliostat uses a mature glass-metal technology that adopts structural, facet and local control solutions previously tested in the GM-100 and COLON prototypes. The structure is especially lightweight with facets weighing less than 14 kg/$m^2$. The mirrors are held onto a metal frame by rods glued to the glass with a neutral silicone. There is also a new canting procedure that corrects any deformation of the reflective surface to typical solar tracking positions.

The heliostat is comprised of 21 4.33-$m^2$-surface facets. The outer dimensions are 9.57 m high by 9.67 m wide. The net reflective surface is 91 $m^2$ and it is supported by four trusses, a horizontal torque tube and a concrete pedestal. The total weight without foundation is 3500 kg and the reflectivity of the mirrors is 92%. The first of the prototypes has a Peerless-Winsmith drive mechanism and the other a hydraulic drive.

At present optical characterization is being completed, with first results showing a reflected-beam image quality of less than 2.4 mrad, which is considerably better than design, which placed it at 2.7 mrad. The Sanlucar-90 heliostat is a worldwide milestone in the




**Rear view of the Sanlúcar heliostat with hydraulic driver installed at the PSA and flux distribution obtained at 380 m on a 12 x 12 m Lambertian target**

glass/metal technology with costs of less than 140 EUR/$m^2$ for production of 1000 units and is today the best heliostat on the market, representing the culmination of the concept initiated by CIEMAT 10 years ago in the GM-100 and later improved in the COLON heliostat.

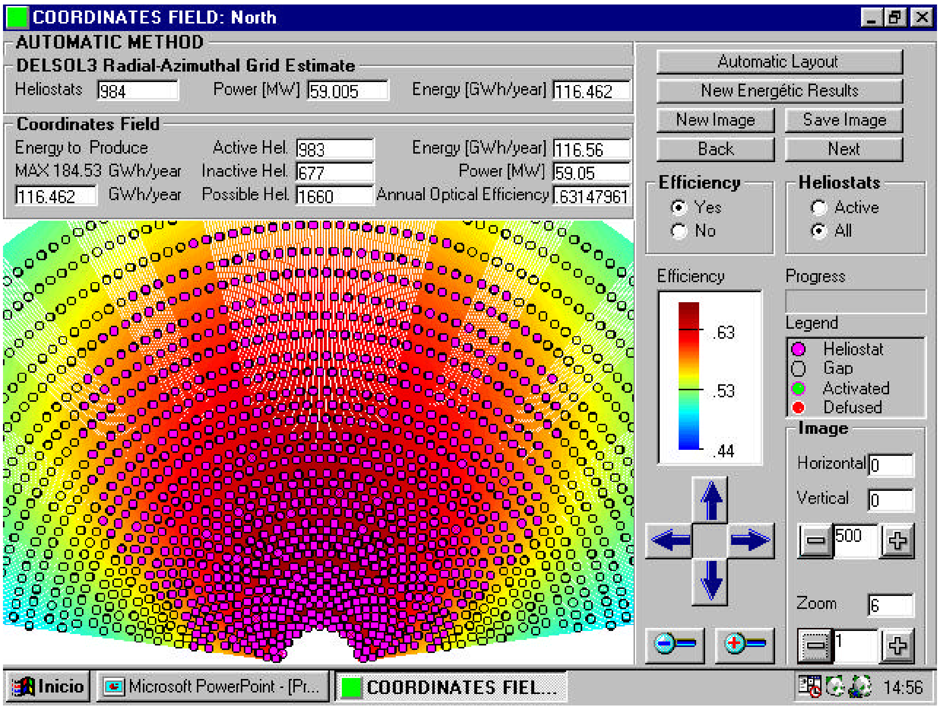
Furthermore, a simplified local control card specially developed for the Sanlucar-90 heliostat installed at the PSA has lowered the cost and facilitated fabrication over the previous GA2696A developed by CIEMAT. A novelty in the card is that it is based on the use of two master/slave microcontrollers.

***Development of software tools:***

The codes usually used for the design and simulation of solar thermal central receiver plants, HELIOS, ASPOC, HFLCAL, RCELL, DELSOL, MIRVAL, SOLERGY, etc., were all written in the eighties, and therefore their philosophy and structure are now out of date. In general, they are difficult to use, difficult to modify, adapt and maintain and are not appropriate for dynamic modeling. They are not very user-friendly codes and in some cases, documentation is deficient. Their structure is not modular so that new plant concepts cannot be introduced (such as those based on volumetric receivers or new types of heliostats) nor can hybrid or cogeneration plants be simulated. The majority of them are written in FORTRAN 77, they lack graphic output and obey a philosophy of saving computation time by which they study only a few days a year and only a few representative heliostats from the field.

In the years 2000 and 2001, considerable software development and improvement activity was carried out at the PSA, in design and optimization of plants as well as simulation of annual performance. The objective was to concentrate on the development of a new generation of more modularly structured codes that would overcome the deficiencies in current codes and provide a comparative advantage over possible competitors.

One of the most relevant milestones in 2001 was the creation of the new WinDELSOL code. Version 1.0 of the code has been generated in cooperation with the AICIA and the SOLUCAR company. WinDELSOL 1.0 has been validated by the IEA-SolarPACES Quality Assurance Group. The basis of the code is the old DELSOL3 of Sandia National Laboratories, presenting it in a Windows environment and adding new functions such as inputting data by filling in forms, making automatic layouts, obtaining the solar flux distribution on the




**Screen display of WinDELSOL 1.0 for optimizing power plants with heliostat fields. The picture shows an optimized array of heliostats with annual efficiencies map.**

absorber and graphic representation of optical parameters, heliostat field array, tower and solar receiver.

As plant design tools, also in cooperation with AICIA, two software modules have been created in the MATLAB environment, the first having a ray-tracing package for design and optimization of complex solar receivers, that allows windows and secondary concentrators to be included and the second, a package for calculating shading and blocking and optimizing the heliostat field for complicated terrains. This approach allows tools usually employed for design and optical optimization of heliostat fields and solar receivers to migrate to the MATLAB environment in the future.

Outstanding advances were also made in 2001 in the development of the Fiat-Lux and EnerTracer codes for 3D characterization and optical simulation of solar concentrators. The comparative assessment and validation of stand-alone version of Fiat_Lux for characterization of heliostats with the HELIOS code was presented at the Workshop on simulation codes organized by SolarPACES in September 2000.

Finally, and again with regard to software development, the PSA actively participated in the IEA-SolarPACES group in charge of developing new modules of Central Tower for the TRNSYS STEC Library, some of which will be incorporated into the international version of STEC. This library allows the well-known TRNSYS code to be used for the simulation of production and annual performance of a central receiver solar system, whether hybrid or with thermal storage, providing a tool of great interest for feasibility studies and annual plant energy analyses.

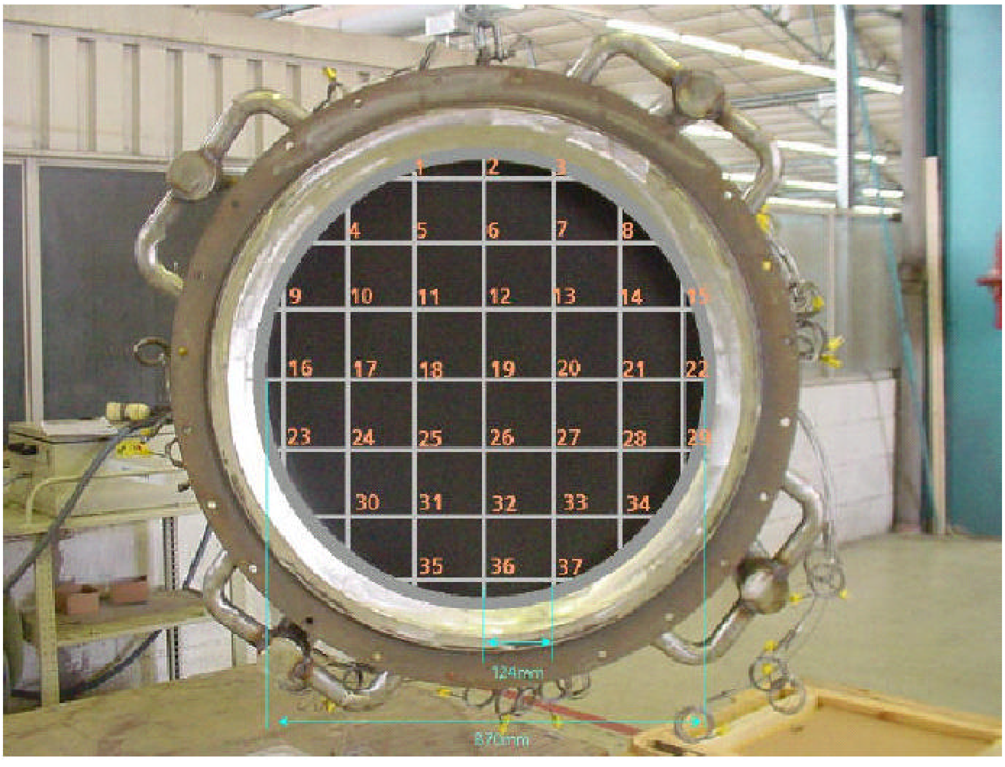
***SIREC-I Metal Volumetric Receiver:***

The main objective of R&D in receivers is the development of advanced receivers for their use in solar thermal plants for electricity production as an essential element of centralization and transfer of the energy collected by the heliostat field. Air-cooled volumetric receivers have demonstrated their reliability and easy operation during tests performed up to now at the Plataforma Solar de Almería. However, additional technology development is necessary to significantly reduce costs by improving such aspects as operating performance, temperature and flux. For this reason, all of the PSA activities in 2001 centered on the development and testing of different types of volumetric receivers. The SIREC project undertook the design, assembly and testing of a knit-wire 200 kW volumetric receiver absorber called SIREC-I [Téllez, Marcos y Romero, 2001].

The SIREC-1 receiver is based on the lessons learned in the 15 years of testing and evaluation of open volumetric receivers at the PSA, having been chosen as the appropriate option for Phoebus-type plants with superheated-steam Rankine cycle, a metal mesh absorber, which under normal conditions, supplies 850ºC air at the absorber outlet.

The receiver developed consists of a knit-wire mesh absorber and a recirculation system. The absorber is laid out as a series of overlaying screens screwed onto a ring that facilitates their replacement. The circular absorber aperture is 0.9 m in diameter and 15 mm thick. For the absorber design, a computer model was developed that enabled the selection of the most favorable wire diameter, separation between wires and the number of screens or layers. The use of this model and materials cost considerations led to selection of a 0.2-mm diameter wire with 0.72-mm separation between wires and a total of 15 superimposed screens. Due to the arrangement of the recirculation system covering part of the aperture area, the effective aperture surface was reduced to a 0.76-m diameter. The prototype receiver was built in the first half of 2001 and installed in the test bed in August. The thermal behavior assessment tests were carried out in September and October. The maximum absorber outlet air temperature reached during testing was 973ºC, although the main disadvantage observed was that the thermal maps showed a wide difference in temperatures between the center and the outer zones of the aperture. The air return ratio in the receiver aperture was also analyzed. Experimental measurements showed total coincidence with the values estimated by the FLUENT code, at 46% to 49%.

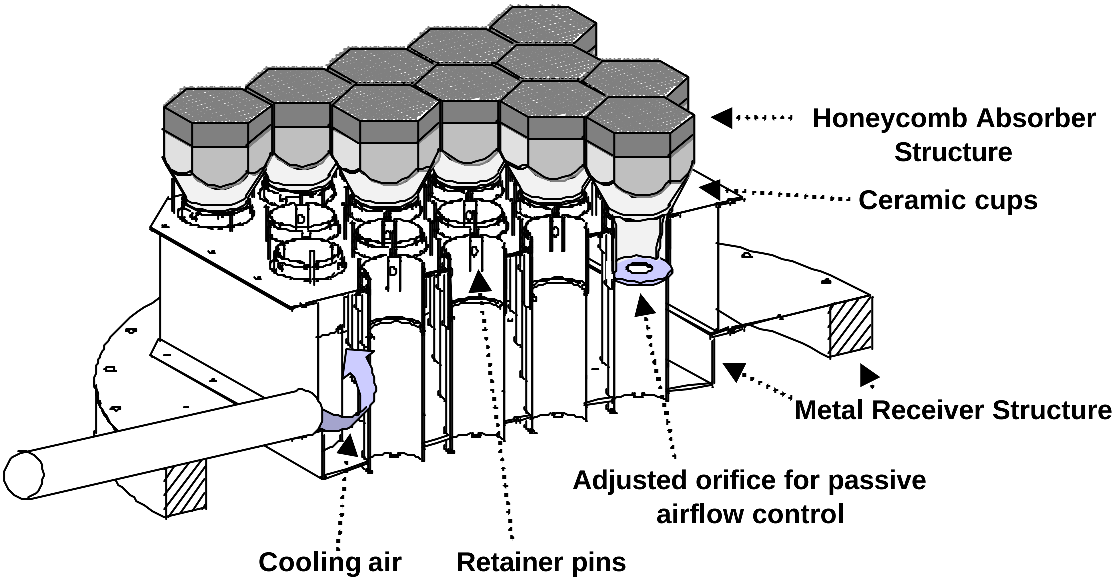
In spite of the thermal gradients observed, operating experience has served to validate the metal alloy selected for the absorber and has demonstrated the feasibility of the metal SIREC-I receiver concept for supplying air at 850ºC under nominal working conditions. Therefore, design and construction of an improved second prototype was begun in 2002.




**Front view of the SIREC-1 receiver with location of thermocouples at rear**

## THE SOLAIR PROJECT

The HitRec (High Temperature Receiver) project and its continuation in the SOLAIR project, attempt to achieve a volumetric air receiver with a SiC ceramic absorber able to work at high incident solar radiation flux, thus attaining outlet air temperatures of up to 1000ºC. The volumetric receivers are able, theoretically, to heat air at high flux densities of up to 2 MW/m$^2$ and thereby enable it to be used as the thermal fluid, however, 1 MW/m$^2$ has not yet been reached. High radiation flux would give rise to a more compact receiver design, leading to cost reduction. Furthermore, the smaller aperture surface favors reduction of thermal loss, protects it from the wind and facilitates improvement of the cool-air return system. On the other hand, operation at high radiation fluxes and temperatures near 1000ºC requires current metal screen absorber material concepts to be abandoned in favor of ceramic materials based on monolithic matrices. Research channeled through the SOLAIR project proposes ceramic matrix receivers for second-generation plants working at very high temperatures [Hoffschmidt et al., 2001].



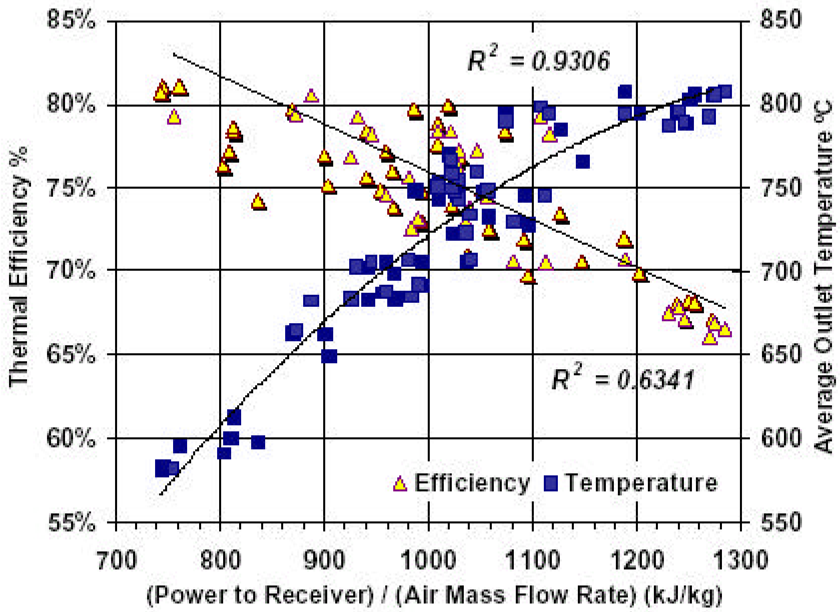

**Cross section of the HitRec II receiver**

The SOLAIR project is a European project financed by the EC with participation of CIEMAT, INABENSA and IBERESE (Spain), STC (Denmark), DLR (Germany) and FORTH/CEPRI (Greece).

The receiver absorber is made up of cup-shaped ceramic modules in a metal support frame and an air-return system for cooling the structure. 32 140-mm-diagonal hexagonal absorber modules are required. Each module consists of an absorbent matrix and a cup, both made of siliconized SiC. The 0.41-m$^2$ absorbent matrix has a porosity of 49.5%. The absorber design attempts to avoid flux instability at temperatures of 700ºC to 800ºC in atmospheric pressure output air.

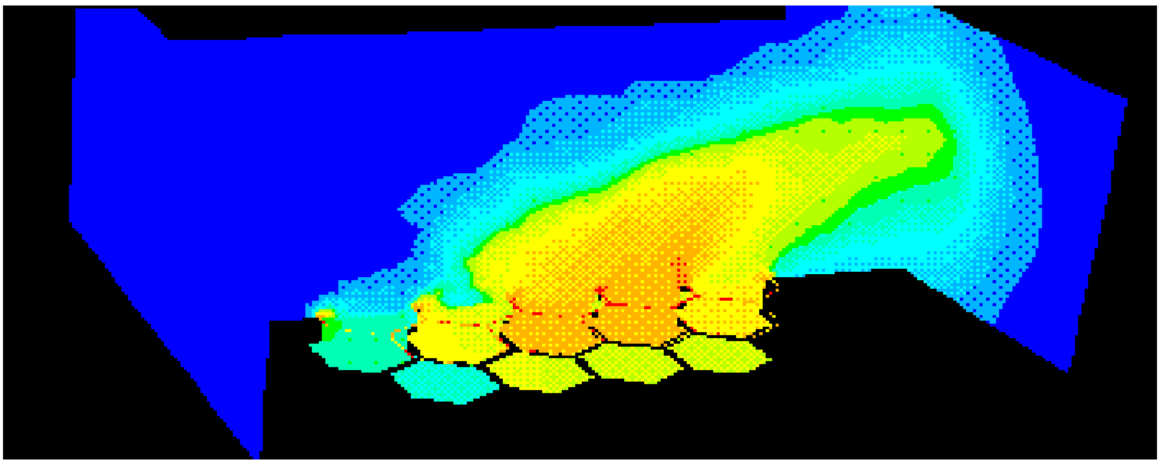
The HitRec II prototype was installed in the CRS SSPS tower at the Plataforma Solar de Almería and was tested from November 200 to May 2001, accumulating a total of 150 hours of testing under concentrated solar radiation. The results have demonstrated the thermomechanical resistance of the modified support structure. During testing, incident flux of up to 900 kW/m$^2$ and average outlet air temperatures of 840ºC and peak air temperatures of up to 950ºC were reached. The thermal efficiency calculated is (76±7)% at 700ºC, which are the nominal conditions for Phoebus-type plants. Other receiver characteristics estimated during the evaluation are a 46% air return rate and typical absorber response time of 70 seconds.

For the design and evaluation of fluidodynamic behavior and estimation of the air return rate in the HitRec-II and SIREC-I, an own methodology has been developed for analysis and simulation employing the FLUENT code, which could be experimentally validated later. CIEMAT has adjusted a tool that improved markedly the studies carried out previously by other research groups in this subject. The FLUENT code, together with the MATLAB environment modules for absorber design, provides CIEMAT with some volumetric receiver design tools and capabilities that were unavailable until now.




**Thermal efficiency and average outlet air temperature compared to the quotient of incident power and air flow for the HitRec-II Receiver.**

After testing of the HitRec-II receiver, the engineering and fabrication of the 200-kW SOLAIR prototype was completed and was installed at the PSA in November of 2001. The prototype uses the same concept tested in the HitRec-II, but with rectangular monoliths measuring 16 cm per side. In contact with the Danish manufacturer, CIEMAT has optimized the geometry of the ceramic cups to improve the air recirculation rate, again using the FLUENT code for this task. Finally, it should be pointed out that the engineering for a 3-MW SOLAIR prototype, based on a cluster of several modules analogous to the 200-kW prototype was begun in September 2001and is due to be completed in April of 2002. The 3-MW prototype will be installed in the PSA CESA-I tower in 2002 and it is supposed to be a real milestone in ceramic volumetric receiver technology.

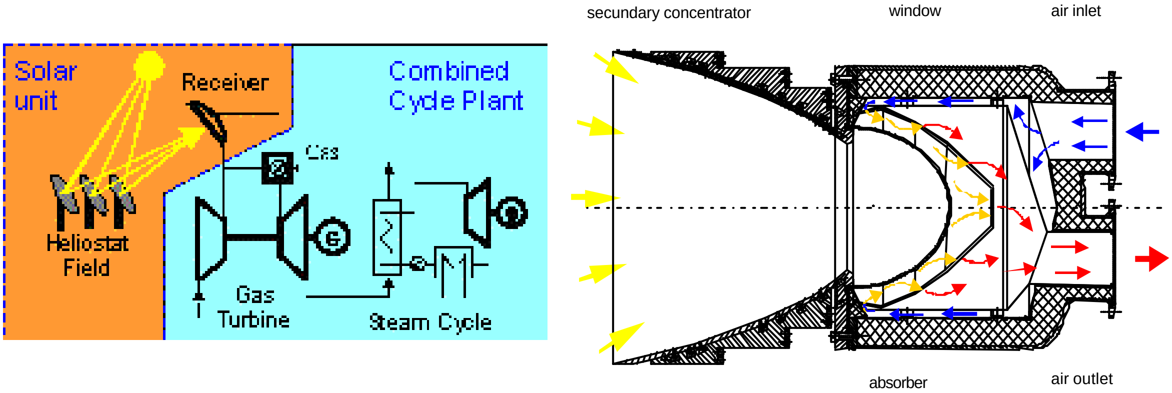


**Influence of lateral wind on Hitrec-II receiver thermal losses. 3D simulation performed with FLUENT.**

## THE REFOS AND SOLGATE PROJECTS

The SIREC and SOLAIR volumetric receivers are both open to the atmosphere and therefore produce hot air at atmospheric pressure. In both cases, their intended use is integration in a Rankine superheated steam cycle through the heat exchanger in a steam generator. Along with this option, there is a second line of longer-term research in which the pressurized volumetric solar receiver is to be integrated into a Brayton cycle with gas turbine. This alternative has as its main objective the design of hybrid solar plants with gas turbine. Hybrid solar thermal plants have significant potential for reducing costs up to 30% over solar-only plants.

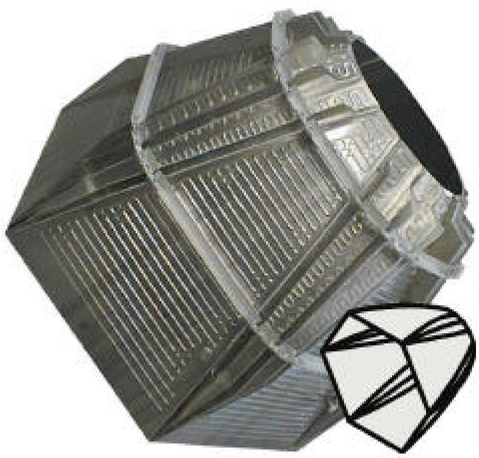
This is the proposal that underlies the REFOS pressurized volumetric receiver development project, which is used to heat compressed gas turbine air before it enters the combustion chamber [Buck et al., 2001].




**Pressurized volumetric receiver integration scheme as preheater in a gas turbine cycle and detail of the REFOS receiver with quartz window and secondary concentrator.**

The REFOS project was begun in 1996, promoted by DLR EN-TT of Stuttgart and was the object of long collaboration with CIEMAT at the PSA. The receiver module was designed to operate at 15 bar pressure, 800ºC outlet air temperature and solar power absorption of 350 kW. The module was installed in the CESA-1 tower at the PSA for testing and evaluation. Instead of a gas turbine, the receiver was hooked up to an experimental pressurized air loop. The accumulated operating time under solar radiation at the end of 2001 with this first module was 500 hours, and is the volumetric receiver with the most hours tested since the TSA. Nominal operating conditions were reached and maintained repeatedly and the receiver under those conditions reached 70% thermal efficiency. On August 9th, testing of the first module was completed and the second phase of the REFOS project was begun with the installation of a cluster of 3 modules. At the end of 2001, it had only been operated 32 test days due to problems with the pressurization loop.

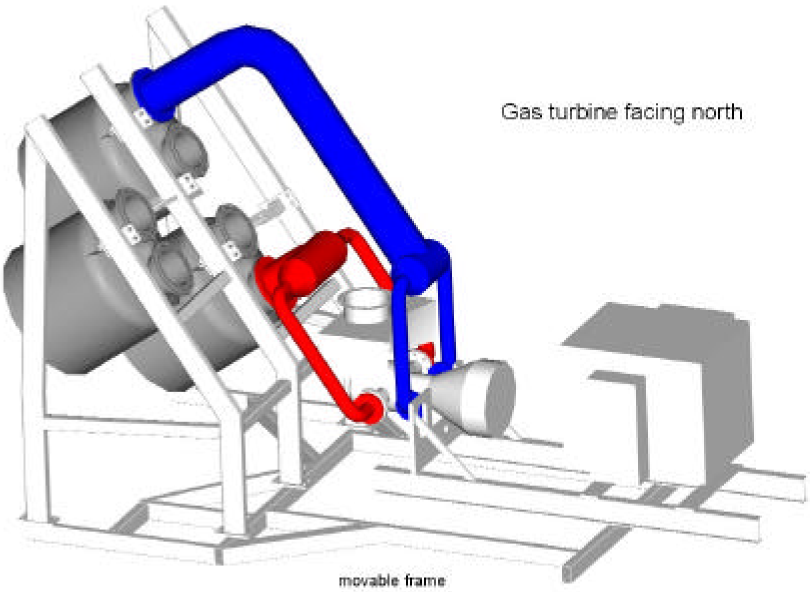
At the same time as this testing was going on, a new secondary concentrator was being developed. The new geometry allows multiple trapezoidal faceting of the original reconcentrator to be replaced by curved mirrors. The hexagonal shape of the aperture has been kept. Evaluation was completed at the end of 2001 with performance near to the initial goal of 90%, surpasses by far the 84% performance of the first reconcentrator. For a new phase of tests, thermal insulation of the receiver vessel is



**New secondary concentrator.**

to be improved and the metal absorber will be completely oxidized in laboratory beforehand. With this it is expected that overall efficiencies measured for the entire receiver module will reach 80%. One additional advantage of the new reconcentrator is its light weight, which is 75% less than the previous one leading to rather lower fabrication costs.

Simultaneous with the development of Phase 2 of the REFOS Project and as a natural complement to it, the SOLGATE project was begun in January 2001. This project pursues the solarization of a 280-kW turbine and its connection to the REFOS-2 receiver cluster, as well as several feasibility studies to identify possible applications of the REFOS technology in commercial gas turbines [Schwarzbözl et al., 2001]. The SOLGATE project is jointly financed by the EC, DLR and CIEMAT, with participation of ORMAT (Israel), INABENSA (Spain), Heron (Netherlands) and TUMA (Switzerland). Engineering of the new installation and modification of the turbine was completed by ORMAT in Israel in 2001. The PSA has prepared the infrastructure for the fuel connection to the turbine. The system is to be assembled in April 2002.

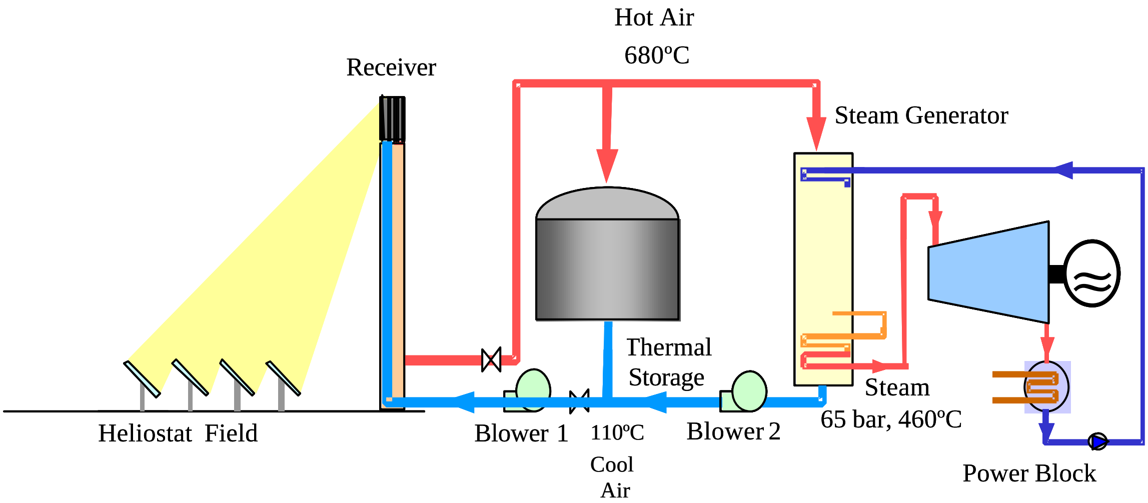



**Artist's view of the cluster of three REFOS receivers connected to a solarized turbine which will be tested at the PSA in 2002 under the SOLGATE project.**

## THE PS10 PROJECT

Together with the development of components and software, the third group of activities carried out under PSA Central Receiver R&D program is participation in the conceptual design and basic engineering of demonstration and commercial application projects. In 2000 and 2001, the most relevant project in so far as time spent on it was without doubt the PS10 Project. The basic objective of the PS10 (Planta Solar 10), also known as Sanlúcar, is the design, construction and commercial operation of a 10-MW STP, to be installed near Sanlúcar la Mayor in the province of Seville, and which will produce electricity following the well-known PHOEBUS configuration that uses the atmospheric pressure volumetric air solar receiver integrated in a Rankine cycle [Romero et al., 2000b]. The plant is promoted by the ABENGOA Company through their operating company Sanlúcar Solar, which has received a subsidy of 5 million Euros from the EC for it. CIEMAT participates in the project together with DLR and the German Fichtner Company. The coordinator is the SOLUCAR Company.

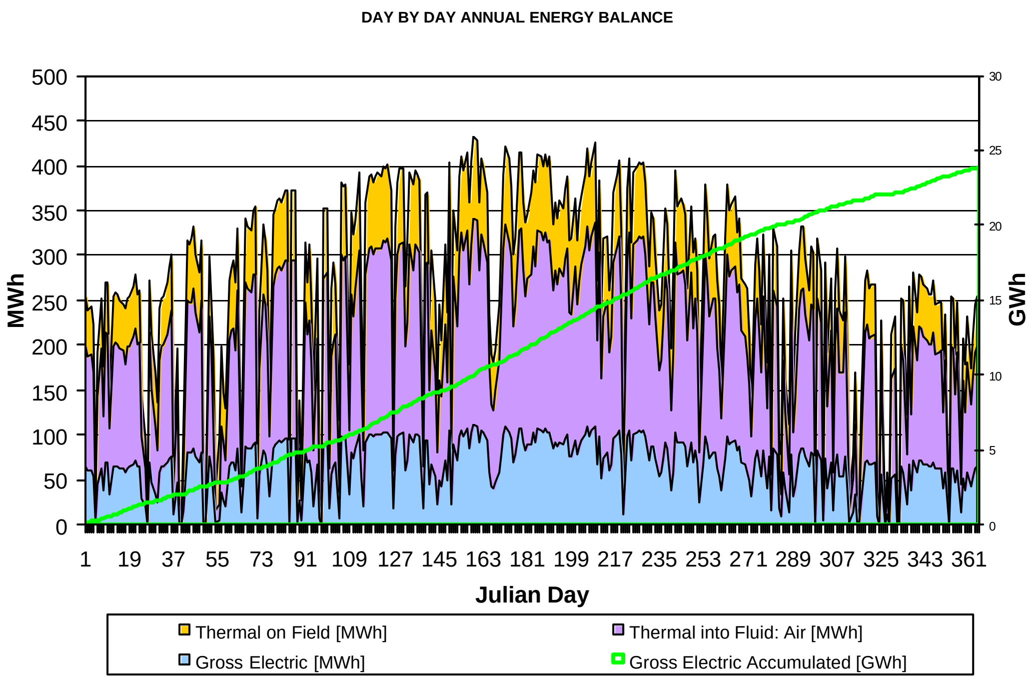
The project makes use of already sufficiently proven available technologies, such as glass-metal heliostats (Sanlúcar-90 heliostat), a volumetric air receiver with metal mesh absorber, an air/ceramic thermocline thermal storage system and a steam generator, all




**PS10 plant layout as promoted by ABENGOA based on the Phoebus technology with volumetric air receiver applied to a Rankine steam cycle.**

of which were previously developed by European companies under the TSA project and tested at a 2.5 MWt scale at the Plataforma Solar de Almería from 1993 to 1994. In this sense, it may be said that the project minimizes the technological doubts and gives priority to those aspects related to the up-scaling of the technology, the integration of the different subsystems, demonstration of despatchability, O&M cost reduction and collecting information for the preparation of standards.

The system will use a total of 981 heliostats developed by the INABENSA company, a 90-m-tall metal tower and a volumetric receiver with an absorber surface of 173 $m^2$ developed by the German company, Babcock Borsig. The basic configuration of the PS10 consists of a north-type heliostat field, with the receiver located at the top of the tower, a generator and a thermal storage module at its base, the power block, two blowers and the corresponding piping and valves. The heliostat field layout, the height of the tower and the dimensions and shape of the receiver were optimized by the PSA and SOLUCAR using WinDelsol, a version of the DELSOL3 code developed by Sandia Laboratories in the USA, adapted to the Windows environment.




**Annual daily production of PS10 plant as estimated by SOLERGY**

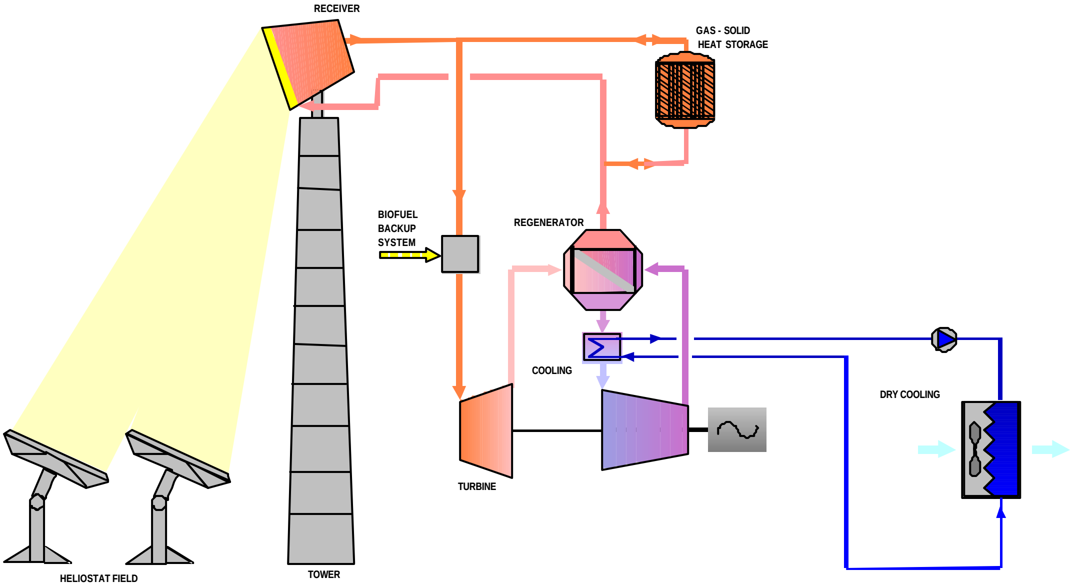
The performance of the solar system at the turbine inlet is 54% and the total net efficiency of the solar-to-electricity conversion is 13.2% at design point. The system is penalized by the small size of the turbine and its performance (30%), so that larger plants will have a considerably better performance. At design point, the solar receiver will load about 5 MWt to storage. In a reference year, 22.1 GWh gross (12% efficiency) and 19.2 GWh net (10.5% efficiency) will be produced, which would be equivalent to around 2000 hours operating at nominal capacity (22% Capacity Factor). The daily thermal power supplied by the receiver to the fluid varies between 200 MWh in winter and 325 MWh in summer. Considering the conversion of the power block, the daily electricity produced will oscillate between 70 and 100 MWh. To model the annual plant performance, the PSA used the SOLERGY and STEC-TRNSYS codes.

In 2001, the technical report on the basic plant engineering and operating strategies was prepared and detailed engineering was begun. The next phase of the project will include ordering of the main plant subsystems and starting of civil construction work. This phase has been paralyzed by the Coordinator until the publication of the definitive regulation of the electricity tariff for solar thermal power plants. As this problem has nothing to do with the development of the project itself, a year-and-a-half extension has been received from the European Commission. The establishment of a legal framework regulating the tariff for these plants in 2002 is essential for the viability of the PS10 Project as indeed it is for the rest of the solar thermal power plant projects.

## THE SOLAUT PROJECT

In the PSA's permanent search for integration of central receiver systems into the most efficient electricity generation schemes, in 2000 a new project called SOLAUT was begun with financing from the Ministry of Science and Technology PROFIT Program. The main goal of the project is to design and build a pilot facility that allows the technical-economic feasibility of solar thermal electricity generation with autonomous 1-MWe units installed in a large solar field of hundreds of these modules with continuous electricity generation through thermal storage.

The new solar thermal electric technology proposed is based on the volumetric atmospheric air receiver with solid storage elements, but eliminates the steam cycle and uses as the conversion system fluid the same air heated in the receiver at atmospheric pressure in an inverse regenerative Brayton cycle, with or without intermediate cooling of compres-




**Functional diagram of the SOLAUT Plant**

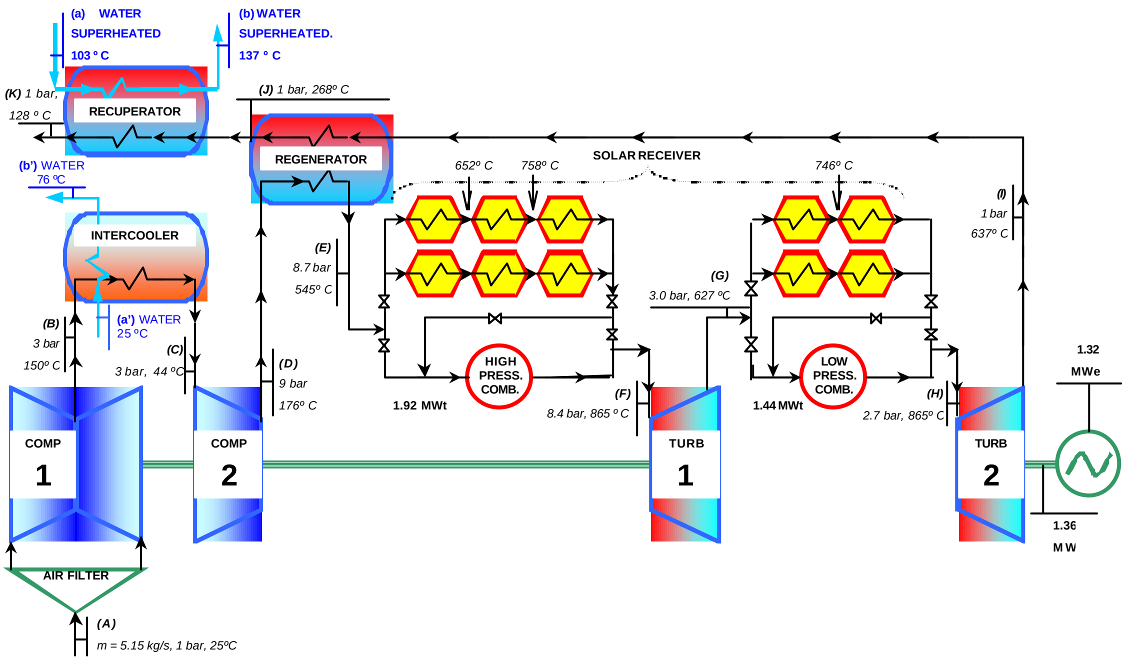
sion and without consuming water for cooling. This allows the optimum thermal level of concentration of the radiation to be taken direct advantage of for high performance in a power cycle of around 1 MWe, which is very compatible with the optimum size of the solar field and yielding much better performance than larger fields, with excellent land-use factors and a wide capacity for adapting to any terrain or application. The overall net average annual incident solar-to-electric conversion performance of such a 1-MW module could be as high as 21%, far surpassing the values foreseen for current demonstration plants (10.6 to 13.2%) and even the maximum values foreseen for large 200-MWe commercial plants (15%). Under optimum conditions, the scheme proposed could even attain a peak solar-to-electric performance of 30%.

In 2001, with financing from PROFIT, a feasibility study and definition of the plant layout with solar receiver and thermal storage were completed.

## MODULAR PLANTS APPLIED TO ISOLATED COGENERACION SYSTEMS (MIUS)

While the SOLAUT project proposes the development of small modular plants using volumetric receivers at atmospheric pressure with a solar-only layout based on high-capacity solar storage and an inverse Brayton cycle, a complementary alternative would be modular hybrid solar-gas plants. Under the SIREC Project, the MIUS (Modular Integrated Utility Systems) study examined the feasibility of this second option based on the use of the REFOS pressurized receiver concept, with optimized integration into modular applications with non-industrial cogeneration. In this work a solar thermal power tower plant was proposed which by its reduced dimensions is ideal for cogeneration and supplying self-producers, and furthermore is a scaled solution for achieving high capacities module by module without all the financial disadvantages associated with strong initial investment in new technologies. Its hybrid use with natural gas also reduces the financial risk and increases reliability of system response [Marcos et al., 2000].

To be viable in industrial applications, small cogeneration systems must operate continuously, which is a clear disadvantage for the integration of solar plants. On the other




**Example of MIUS system integration of 10 REFOS receiver modules and a gas turbine. The study is based on an H-1 turbine developed by Schelde Heron B.V. (http://www.heron.nl). It is a two-stage gas turbine with intercooler and heat recovery, having a nominal capacity of 1400 kW.**

hand, applications in office buildings, hospitals, shopping centers, residential areas and communities in general typically require operation of less than 4500 hours. It is therefore possible to propose integration of distributed production in such cases with an annual solar share of up to 50%.

Design and optimization of the small solar power tower plant for its application to cogeneration has provided the following characteristics [Baonza et al., 2000]:

- Tower (26 m) and small-size heliostats (19 m$^2$) to reduce the visual impact and guarantee better flux distribution on the receiver aperture, thereby achieving high field performance.
- Use of air as the energy transfer medium in a pressurized volumetric receiver (3.36 MWt output) with a cluster of 10 REFOS receivers.
- Use of an H-1 Schelde Heron high performance (39,5%) 1.33-kW net gas turbine with intercooler and heat recovery working at a relatively low temperature (860ºC).
- Waste heat recovery (500 kW from the intercooler and 850 kW from the regenerator) to heat water and heater/cooler.
- Automatic operation, reducing operation y maintenance costs.

A second MIUS study selected a shopping center as an application, since 85% of its electricity consumption is during the day, using a hybrid solar-natural gas system with gas turbine and waste heat recovery for heating or cooling depending on seasonal demand [Romero et al., 2000a].

SOLAUT and MIUS have the great advantage for the promoter of proposing applications that make economic sense and high energy efficiency for investments under three million Euros.

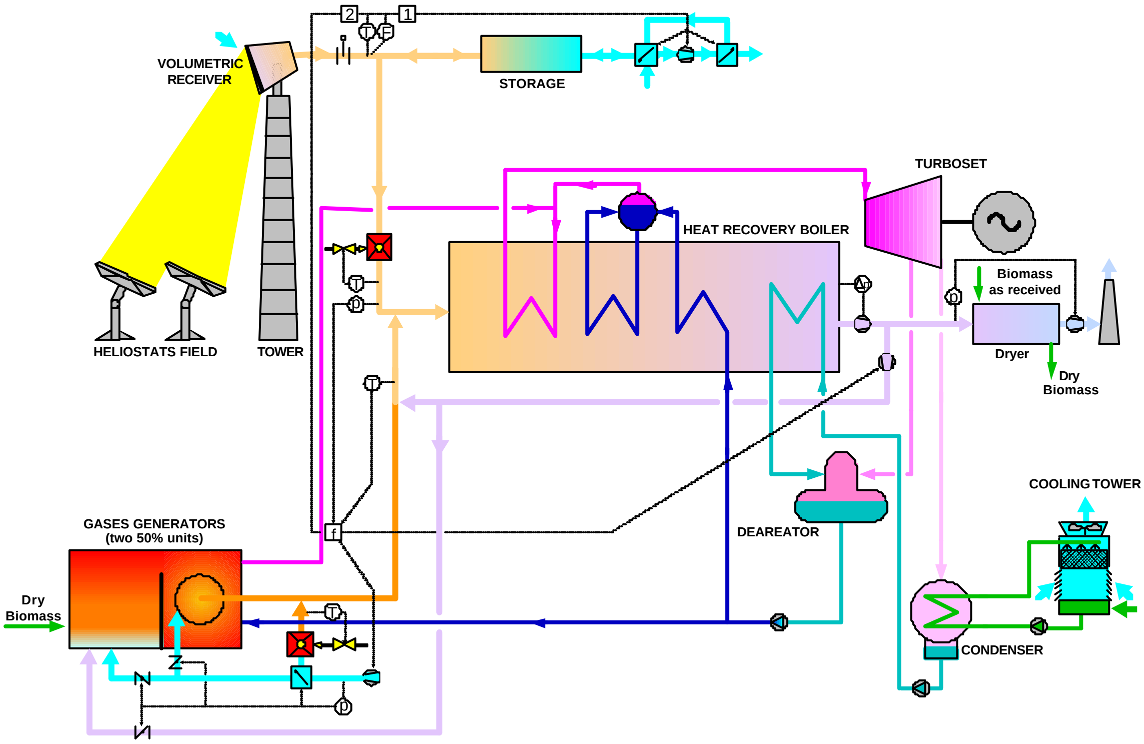
## SOLBIO HYBRID SOLAR-BIOMASS THERMAL POWER PLANT

The objective of the SOLBIO project, financed with ATYCA funds, was a feasibility study of a hybrid solar-biomass thermal power plant [Romero et al., 2001]. The study came out of the desire of CIEMAT, INABENSA, SERLED and IBERESE to find out the most efficient hybridization schemes for central receiver solar thermal power plants with biomass combustion or gasification technologies for electricity generation. The study includes an analysis of the combined resources of solar radiation and biomass in Andalusia with a selection of potential sites found with the Geographic Information System (GIS).

Two systems were taken as the basis for integration with biomass, a PS10-type plant with volumetric air receiver and a COLON SOLAR-type plant with saturated steam receiver. For the case of the saturated steam receiver, the most effort was focused on obtaining a significant solar share and in how to solve the problem of solar transients given the relatively high inertia of the biomass burner. In the option selected, the saturated steam produced in the solar receiver was mixed in the boiler of the biomass combustion chamber. To optimize the percentage of the solar share, a turbine with flow regulation was selected, which allows operation with 140% overloads by means of two admission valves. With this operating strategy, an annual solar share of 23% was obtained.

The second integration layout with volumetric receiver showed fewer restrictions with regard to transients and the solar share. The steam is produced, in this case in a heat recovery boiler, consisting of an air/water exchanger. The hot air is obtained by mixing receiver outlet air with biomass gasifier exhaust gas. The design includes two gasifiers each working in parallel with a technical minimum load in operation of 40% of the nominal load. Depending on the nighttime operating strategies, the percentages of solar annual share vary between 12 and 33%.

The economic analysis for a 10 MW plant with the solar shares mentioned above and annual production of 76-110 GWh gave rise to an estimated LEC of 0.08 EUR/kWh. For this reason, the SOLBIO scheme may be considered an interesting option for Spain at those sites where the prices of biomass are competitive (0.5 EURO cents per kWh), and when mixed plants that combine both renewable energies are legalized.

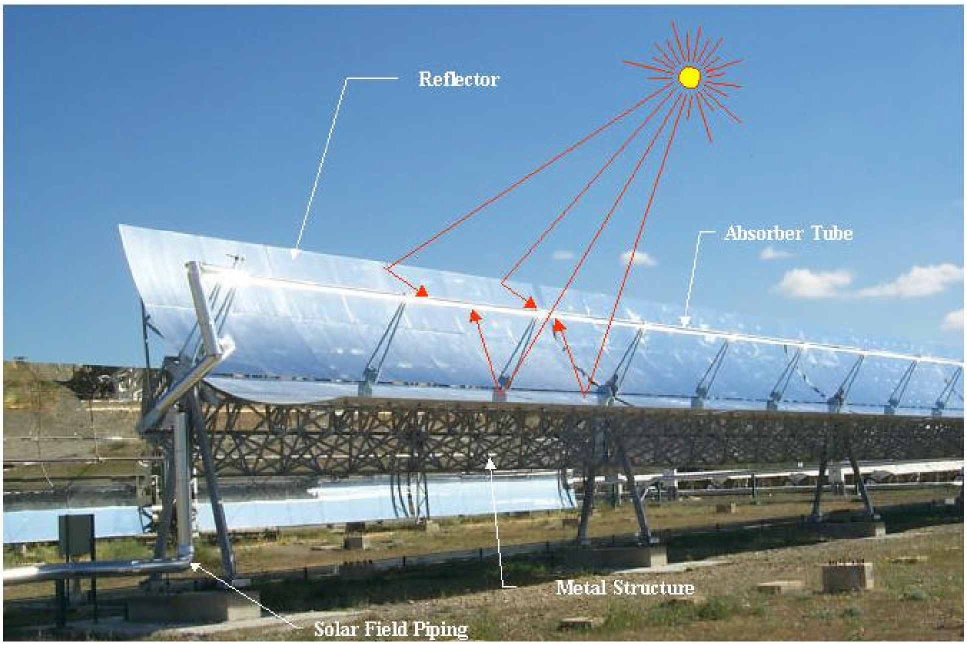



**Solar-biomass plant with volumetric receiver**

## Parabolic-Trough Collector Technology

Parabolic-trough collectors (PTC) are linear-focus concentrating solar devices that convert direct solar radiation into thermal energy and are ideal for working in the 150ºC-400ºC-temperature range. Thanks to concentration of the direct solar radiation incident on the aperture plane of the collector, the temperature of the working fluid is efficiently raised to around 400ºC. Such temperatures make PTC ideal for integration in a large number of industrial processes in the mid-temperature range.

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



**The parabolic-trough collector principle**

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

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

Given the complexity and reach of each one of these three points, the activities developed by CIEMAT in this R&D program are distributed among various projects, each of which has its own group of partners. The final results pursued in this R&D program are a 26% reduction in the cost of electricity generated by this type of solar thermal plants. Furthermore, a series of interesting byproducts may be obtained, as for example: selective mirrors for photovoltaic energy, anti-diffusion coatings, colored glass for buildings, etc.

The improvements in parabolic-trough collector components and the direct steam generation process could be applied not only to electricity generation, but also to any other industrial solar energy application in the mid-temperature range.

The 2001 CIEMAT parabolic-trough collector technology activities were carried out within three projects, EUROTROUGH, DISS-Phase II and Solar Façades. The most relevant results obtained are described below:

## EUROTROUGH Project:

The final *EUROTROUGH* objective is a European parabolic trough collector structure design, ideal not only for electricity generation in solar thermal plants, but also for delivering energy to any industrial process with a thermal demand between 150º and 400ºC.

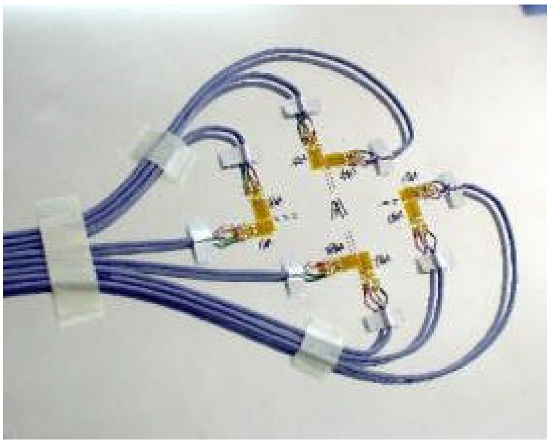
In 2001 the PSA improved the one-axis solar tracking hardware and software for the system that had been developed in 1998, leading to increased system precision to 0.04º [García, Egea, 2001]. At the beginning of 2001, a prototype of the new solar tracking system was fabricated and assembled on the EUROTROUGH prototype collector for its evaluation. The results obtained were excellent, proving it to be totally reliable and highly accurate in collector positioning.

In the first semester of the year, the PSA actively participated in the erection and startup of the EUROTROUGH collector prototype. This prototype was hooked up to the PSA LS-3 loop oil circuit and was evaluated during the second semester of the year. The picture below shows a view of the EUROTROUGH collector installed at the PSA.

**View of the EUROTROUGH prototype collector at the PSA**

Another activity carried out by the PSA in the EUROTROUGH project in 2001 was the design and fabrication of an electronic system for measuring angular deformations in parabolic trough collectors [García, Egea, 2001-bis]. The high sensitivity of the system developed enabled detection of rotation of 0.003º, which is very useful in optimizing the bearings and structural balance of the collector.

The PSA has also studied the stress produced in the glass mirror supports used for the LS-3-type parabolic trough concentrators. To do this, strain gages were installed on all the supports of one EUROTROUGH collector mirror, and stress induced by wind loads on the glass is being measured so that the mirror supports can be improved and reduce the current percentage of breakage in commercial solar plants. The figure below shows the strain gages installed on the mirror.



**Detail of the installation**

**Gages installed on the collector mirror**

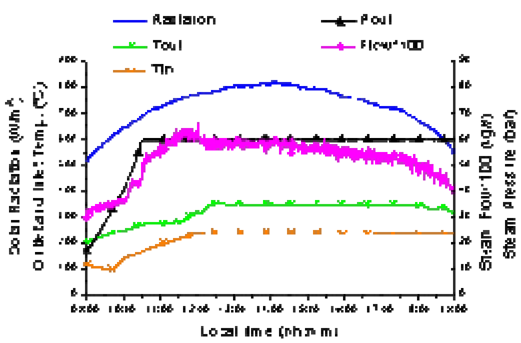
**Strain gages installed on the EUROTROUGH collector mirror**

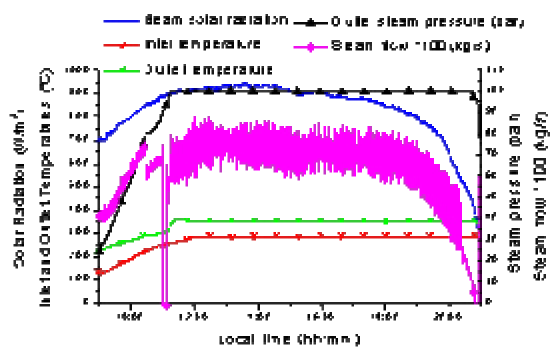
## DISS Project Phase II:

CIEMAT activities in the *DISS* (DIrect Solar Steam) project in 2001 had three main objectives: the development of new absorber tubes for parabolic-trough collectors, the development of direct steam generation technology in the solar collectors themselves (process known by the initials DSG), and the development of simulation software for parabolic-trough collector field operation. The main activities carried out and results achieved in 2001 are summarized below [Zarza et al., 2001].

Continuing the intensive operation begun in 2000, a total of 1,369 hours of operation were accumulated in the DISS test loop from January to December, having operated the plant to sunset on workdays and for 8 hours on Saturdays, Sundays and holidays, when the weather was favorable. This intensive operation has been very fruitful and has allowed many tests to be carried out. The main results were the following:

- The ball joints developed to connect the tubes with fluids at 100 bar/400ºC continue to function without problem after more than 3000 hours of operation.
- All the Recirculation and Once-Trough tests planned have been completed.
- Numerous superheated steam pressure and temperature control algorithms have been developed and evaluated for the Recirculation and Once-Through processes [Valenzuela 2001], [Valenzuela 2002-bis]. The Recirculation and Once-Trough processes are controllable, while, on the other hand, the injection process is difficult and expensive to control, which considerably reduces its feasibility for commercial plants. The following figure shows how well controlled steam temperature and pressure were in the Recirculation and Once-Through modes.





**Once-through at 60 bar (11/07/2001)** **Recirculation, at 100 bar (05/07/2001)**

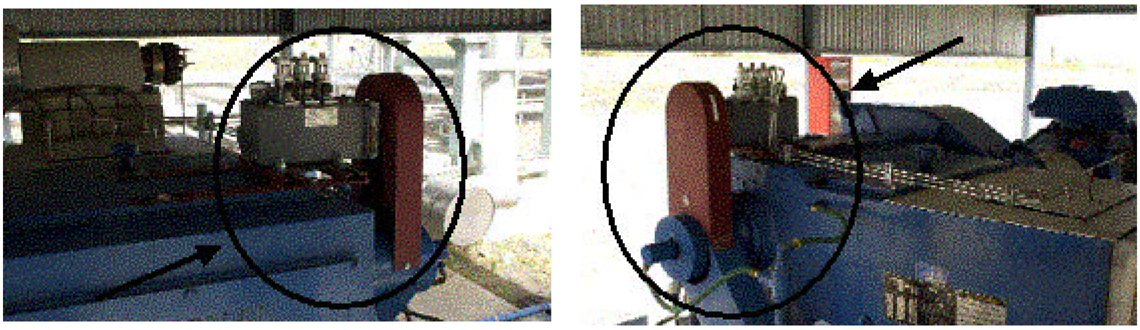
**Direct superheated steam generation in the DISS loop, in Recirculation and Once-Through modes**

- The interface between the evaporation and superheating zones in each row of collectors moves continuously for several meters during Once-Through operation, causing strong stress in the absorbers affected [Rheinländer 2000].
- The recirculation mode, with a recirculation rate of only 20%, shows some excellent perspectives for feasibility in commercial plants, since the drops in pressure in the solar field are much lower than those in current plants operating with oil as the working fluid in the solar field. Another positive feature is the low recirculation flow rate that is sufficient for good control of the solar field under solar radiation transients, making it possible to use small, compact water/steam separators, which are 90% more economical than the type installed in the DISS loop.

In 2001, many improvements were made in the DISS test loop: Instrumentation was increased with the installation of three new differential pressure transmitters in the solar field and a new steam flow meter in the feed-water preheater [Valenzuela 2001-bis], the processing speed of the two work stations managing the data acquisition and control systems was increased from 200 MHz to 930 MHz, another microprocessor was installed and the RS232C communications line was replaced by an SCSI line, which increased the communications capacity [Valenzuela, 2002]. The water degasification system was also improved, reducing the conductivity of water from 14 to 4 µS/cm.

A very important achievement in the DISS project was solving the problem with the recirculation pump, which did not work at high pressure (100 bar). The solution consisted of implementing self-aligning plungers and oil lubrication in the packing. This allowed the certificate of proof of operation to be obtained from EUROCONTROL for DISS test loop operation at 100 bar.

The figure below shows two views of the lubricating system installed on top of the recirculation water pump. The low oil flow rate (a few drops per minute) injected by this system inside the packing, is enough to substantially reduce the friction between the plungers and the packing. After the many tests and parts replacements in previous years, the packing lubrication has proven to be the only solution to the problem that prevented the pump from working properly at high pressure.

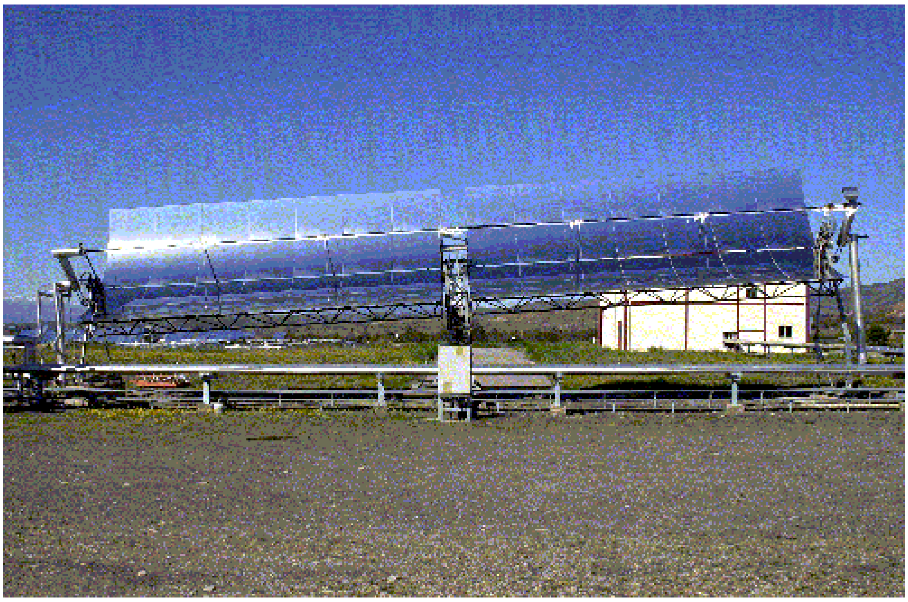


**Details of the packing lubrication system installed on the water recirculation pump**

Installation of the system shown in the figure above ended the continual pump failures at high pressure. Since May, 1999, the pump had failed on numerous occasions due to improper selection of the graphite packing and excessive friction between the connecting rods and packing, so that packing temperatures rose to over 800ºC, which not only damaged the packing, but also the rods. The following figure shows the condition of packing and plungers every time the pump broke down.

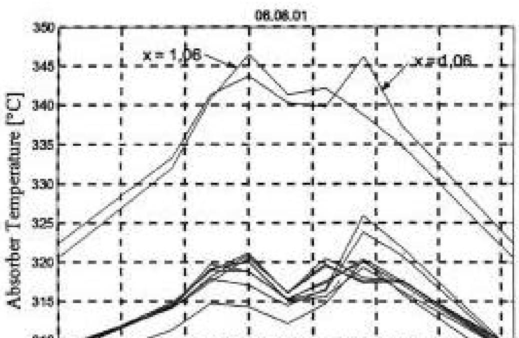
**Recirculation pump packing and plunger after one of the frequent failures**

In August, DISS collector nº9 was tilted 4º to investigate the influence that tilting the collector absorber tube has on the thermodynamic parameters of the two-phase flow inside the tube. The following figure shows collector 9 after it was tilted. During the last four months of the year, testing was carried out at different working operating pressures (30, 60 and 100 bar) and with different mass flows. The experimental results obtained at the PSA indicate, contrary to what was expected, that it is not worthwhile tilting the solar collectors, since the temperature gradients are very similar to those in horizontal tubes. This is good news for the technical and economic feasibility of solar thermal plants with direct steam generation in the parabolic trough collector tubes, as the need to tilt the collectors would have meant a significant increase, not only in the investment, but also in plant operating and maintenance costs.

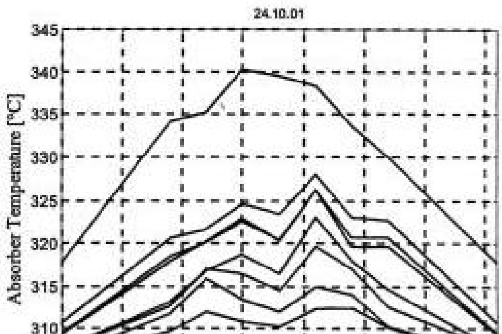


**DISS collector number 9 after tilting it 4º**

Although theoretical studies carried out in the mid nineties indicated that thermal gradients in tilted absorber tubes would be much lower than those in horizontal tubes when the liquid phase of the steam/water flow stratified, experimental results obtained at the PSA have demonstrated that the thermal gradients are very similar in both cases, as may be observed in the figure below.




**Horizontal absorber tubes**

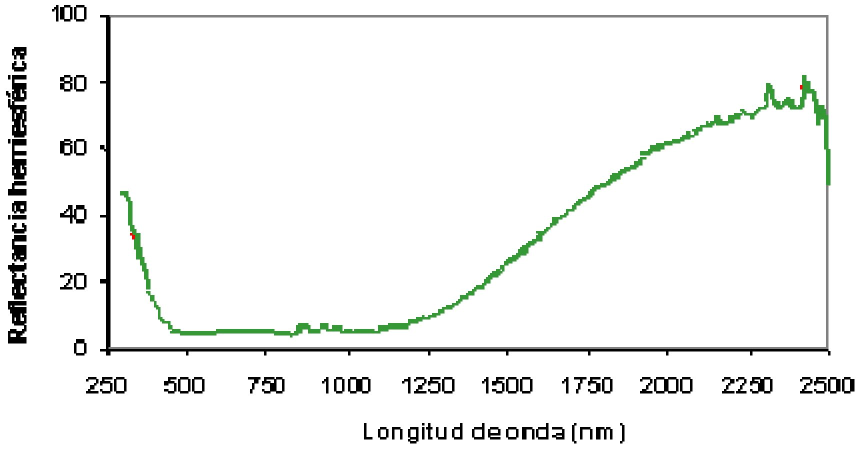



**Absorber tubes tilted 4º**

**Comparison of thermal gradients measured in horizontal absorber tubes and tubes tilted 4º**

2001 PSA activity in the DISS project was also very intense in the development of antireflective and selective coatings for parabolic trough absorber tubes. The PSA employs the sol-gel technique, which is a very economical technique for obtaining thin coatings with diverse optical properties.

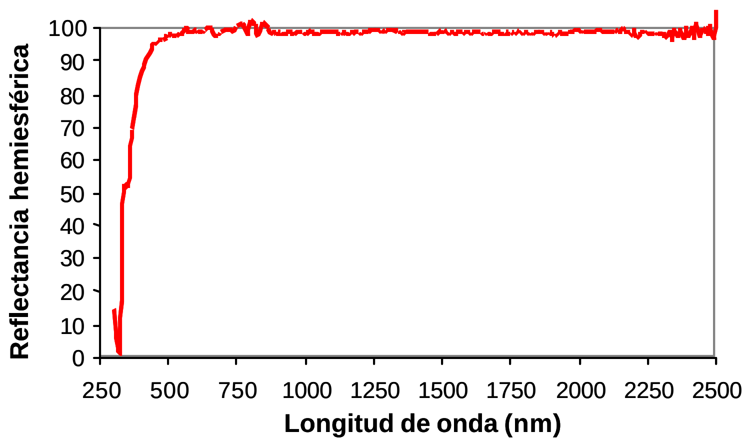
By applying the sol-gel technique, a $SiO_2$/Pt/$SiO_2$ interferential-filter-type solar absorber with a solar absorptance of 0.91 and thermal emissivity under 0.15 at 400ºC was produced. The following figure shows the reflectance of this absorber, which also has excellent thermal stability at 400ºC. The platinum layer is 100 nm thick and is deposited by dip-coating on a silica-coated steel substrate. This platinum layer, which is thermally stable over 500ºC and has good optical properties, will in short term be able to replace the 5000-nm gold infrared-reflective layer used up to now, reducing the reflector cost 25 times. As the gold layer represents 20% of the total absorber cost, this cost reduction is an important step forward in achieving a new commercial absorber tube for parabolic trough collectors. To deposit the platinum layer, a new type of precursory solution, also developed by the PSA, is employed that enables metal or dielectric layers to be deposited without using metal alcoxides.




**Reflectivity of the new selective absorber developed by the PSA.**

In 2001, the PSA also improved antireflective coatings deposited on glass substrate by the sol-gel technique, achieving an increase in solar transmittancy of glass from 0.927 to 0.972, with good mechanical properties that allow it to be cleaned without degradation. The development of these coatings began several years ago and work continues to improve their mechanical and optical properties.

Another of the PSA's achievements with regard to the sol-gel technique has been the development of a new formula for electroless deposition of silver reflector films, with high reflectivity in the solar spectrum. This will allow optimization of first surface reflector properties and improvement of industrial preparation conditions. The figure shows 0.965 hemispherical reflectivity of the silver film developed by the PSA, compared to the theoretical maximum of 0.97.




**Reflectivity of the new silver film developed by the PSA.**

This new reflector film has a diffuse component of less than 1% when deposited on glass. When a stainless steel substrate is used, the diffuse component value depends on how highly polished the surface is. With commercial-polish stainless steel sheets, 2% has been measured for the diffuse component. Another important advantage of this film is its excellent reproducibility and homogeneity.

Another field in which the PSA has been working in 2001 is the development of calculation and simulation tools. Using the TRNSYS environment, a software package to simulate the thermal and hydraulic behavior of a parabolic-trough collector field with oil as the working fluid and the software modules for collectors with direct steam generation has been begun. The software developed for collectors with oil has been validated using TRNSYS with real data from the SEGS VII plant in California and has simulated the behavior of a 10 MWe field with LS-3-type parabolic trough collectors, using Therminol VP-1 thermal oil as the heat carrier between the solar field and the power block.

To conclude the description of the activities carried out by the PSA in 2001 in the framework of the DISS-II Project, it must be said that study of the improvement of heat transfer in absorber tubes with internal capillary coatings was continued in 2001. The number of measurements has been increased and a sample of tube with a smooth interior has been evaluated in a wide range of temperatures and pressures. This sample will then be the experimental reference for comparison of the results obtained from the tube samples with internal porous capillary coatings. It has been attempted to evaluate a tube with a porous $CaCO_3$ coating sintered at 900ºC fabricated by the CSIC, but the coating was destroyed when submitted to the temperatures of direct solar steam generation. At present, there are still two more porous coating samples left, one with $CaCO_3$, sintered at 1000ºC and another with a nickel-based coating. Testing of these two samples will be the next PSA activity in this area.

## Solar Façades:

In this project, the aim of which is basically the development of selective absorptive materials for building façades and the passive collection of solar thermal energy, in 2001, the PSA focused on improving optical characteristics and weather resistance of the various sol-gel products developed in previous years. The main successes have been:

- We have improved the thermal emissivity of the solar selective absorbers developed by the PSA for building façades from 0.3 to 0.09 emissivity at 100ºC.
- We have also improved the weather resistance of the absorptive materials and reflectors prepared for the project. Although the durability of the absorbers is not yet as good as desired, the aluminum reflectors protected by sol-gel deposited silica [Guillén et al., 2001), have passed all the accelerated weathering tests and this material was the only one prepared in the project that passed the durability tests with no degradation whatsoever.
- In our laboratory in Madrid, ten 200-x-200-mm façade absorber elements have been fabricated which have excellent homogeneity, for fabrication of a complete 2-x-1-m façade unit and other partners in the project are now studying its weathering.
- Given the excellent properties of our sol-gel-prepared thick silica films, they have been used to coat the commercial low-temperature solar absorber, called *Sunselect*, manufactured by the German company *Interpane*, improving optics and weathering.

## Other activities in 2001:

In addition to the activities carried out in the EUROTROUGH, DISS-II and SOLAR FAÇADE projects, the PSA has also been active in three other areas:

- Developing a new absorber tube for parabolic collector absorbers in collaboration with the IBERDROLA and VIESSMAN companies. This activity has as its basic objective ending the current lack of market availability of absorber tubes that can work efficiently at temperatures of up to 400ºC. The selective surface of the new absorber tube will be coated by the sol-gel technique.
- Technical assistance and consulting to those Spanish companies that have shown interest in the parabolic-trough collector technology and its commercial applications.
- Preparing and planning new projects to continue the PSA's main lines of work in the field of parabolic trough collectors. We have participated in the preparation of three new important projects that have been presented to the EC 5th Framework Program for grants. One of these projects (INDITEP) was evaluated favorably and has been approved, with activities due to commence in mid 2002.

# Solar Chemistry

## Introduction

PSA Solar Chemistry Area has been working on photochemical processes and applications based on the use of solar radiation since 1990, participating in a multitude of national and international projects and technological initiatives. Of special interest have been the detoxification activities, or photocatalytic treatment of pollutants in both aqueous and gas phases. The experience accumulated in this field has allowed the development and continual enlargement and improvement of the most important experimental solar detoxification facility in Europe. This facility has been widely used during recent years by a large number of European research groups under the various European Commission Access to Large Scientific Installations programs.

These facilities, along with the experience, knowledge and large number of research groups and companies with whom relations are maintained, have allowed the Solar Chemistry team to carry out during recent years a significant number of scientific and technological projects to develop the technology on the one hand [Blanco y col., 2001a] and applications of solar detoxification processes for degradation of non-biodegradable pollutants on the other. This important task, together with a large amount of international publications, has meant that the Solar Chemistry team today enjoys a recognized prestige and its work is internationally well known.

With this background, in the year 2001, the Solar Chemistry team carried out a policy of expanding its sphere of action, while retaining its main focus on development of solar photocatalytic processes, by increasing their activity with solar desalination processes and solar disinfection. The overall project took on a new approach and now clearly centers its activities on processes combining water and solar energy issues. This task has also been strongly supported and approved by various national and international projects (very important and providing high-level financing), which guarantees the activity of the team for the next 4 years.

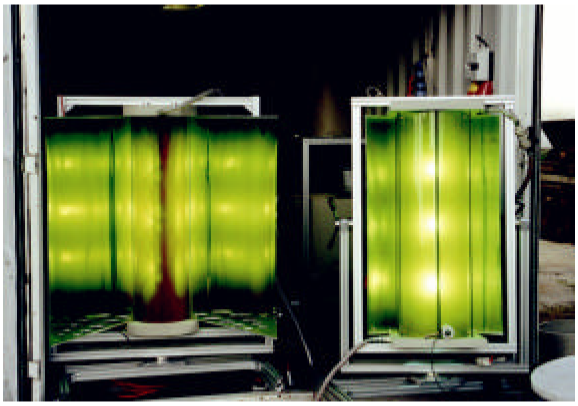
These new projects also mean the creation of numerous industrial consortia with which the PSA's already considerable national and international collaboration will increase significantly. In this sense, it should be highlighted that such cooperation has been very important locally within the province of Almería, as it is actively involved in the projects of several departments at the University of Almería, local companies, such as Albaida, agricultural cooperatives such as Coexpal, irrigation communities, such as Cuatro Vegas de Almería, the financial institution Cajamar through its Instituto de Estudios and the Las Palmerillas experimental station, as well as the DSM-Deretil company among others.

The sections below summarize the most outstanding achievements and activities in 2001 in the field of solar chemistry and give an idea of the work carried out during the year.

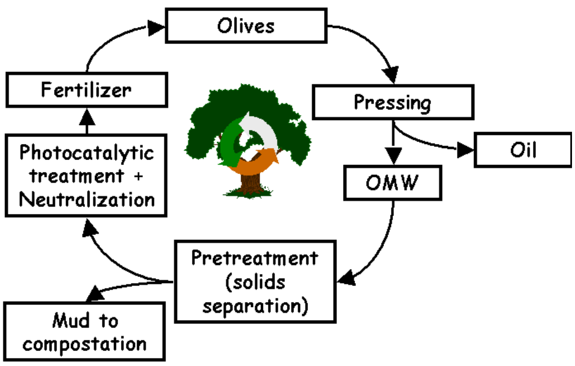
## Reuse of alpechín after photocatalytic treatment

The project "Water recovery from olive mill wastewaters after photocatalytic detoxification and disinfection" LAGAR (financed by EC DG RDT, nº FAIR-CT98-3807) finalized in August 2001. The Plataforma Solar participated in this project together with the Technical University of Vienna (TUW, Austria), the National Institute of Industrial Engineering and Technology (INETI, Portugal) and NAIAS S.A. (a Greek company). The main purpose was to demonstrate the feasibility photocatalytic treatment of olive mill waste to reduce the phenolic content and obtain irrigation water containing non-toxic organic components that may be used for fertilization. Project was divided into several different phases:

- Characterization of olive mill wastewater
- Development of photocatalytic process for its treatment and reuse as fertilized irrigation water
- Design, erection and testing of photoreactors for treatment of olive mill wastewater
- Demonstration of technical feasibility
- Installation of photoreactors in olive mills in Greece and Portugal



**"Combined" photoreactor based on CPC collectors and UV lamps installed in a Portuguese olive mill (left) and "flat collector"-based photoreactor installed in a Greek olive mill (right)**




**Olive mill waste treatment Sequence proposed in the LAGAR Project**

Due to the high opacity of olive mill wastewater and that the most successful method tested has been the Photo-Fenton ($Fe/H_2O_2$), photoreactors have had to be specially designed for its treatment. It was unquestionably demonstrated [Gernjak y col., 2001] that photocatalysis is able to substantially reduce the phenolic content in olive mill wastewater and even its usefulness as irrigation water in phytotoxicity experiments carried out at the Plataforma Solar in a greenhouse built for the purpose using barley as the model crop.

## Industrial wastewater treatment

Within the activities of the Solar Detoxification team, the studied carried out in 2000 and 2001 under the Spanish Ministry of Science and Technology's PROFIT program for Promotion of Technological Research[6] in collaboration with the ECOSYSTEM company is outstanding. The project, entitled "Application of solar photocatalytic degradation to *in situ* treatment of industrial effluents", has been financed by two consecutive programs (FIT-140100-2000-43 y 140100-2001-112) with a total budget of 87,000 Euros.

An experimental mobile plant has been built, equipped and evaluated at the CIEMAT-DER facilities prior to its use by ECOSYSTEM for exhaustive testing at three selected companies. At these companies, different types of industrial wastewater and pollutants were

[6] Programa de Fomento de la Investigación Técnica (PROFIT)

treated *in situ* [Vidal, 2001c]. These *in situ* treatments open a significant future commercial option for this technology for the following reasons:

1) The lack of confidence of many companies in sending their waste outside their facilities for feasibility testing.
2) The difficulty of transporting toxic and hazardous waste for later treatment to comply with legislation in force.
3) The reliability of the results of the experiment given that the characteristics of the effluent remain unaltered.

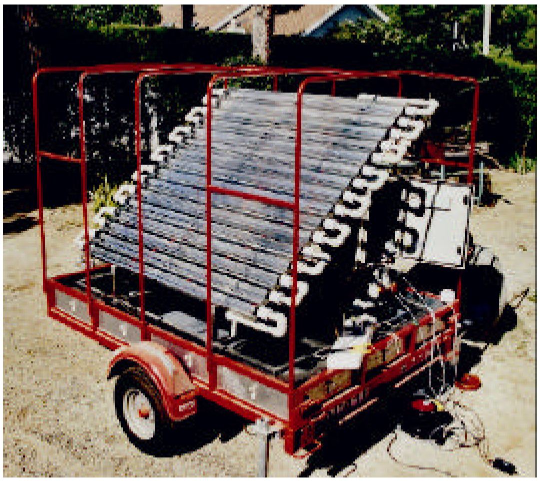


**Photo of the mobile pilot plant taken during monitoring tests**

Finally, the project was conceived in such a way that testing may be monitored by company personnel, which facilitates access and easy understanding of the technology. To date, several tests with two clearly differentiated types of waste have been performed:

- Treatment of a lixiviate from an RSU dump managed by CESPA in Alcoa (Alicante).
- Study performed in a town with a population of 15,000 in the el Vallès area, concerning sanitizing treatment of underground water polluted by chlorinated organic solvents using the solar photocatalytic technology.

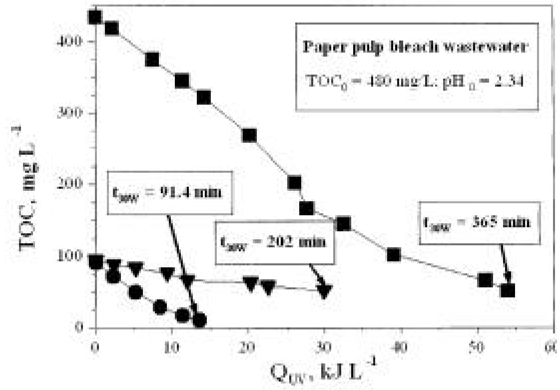
This project has recently concluded and at present the final report is being prepared.

## Treatment of paper mill wastewater

This project of the Spanish Ministry of Science and Technology entitled "Application of photocatalysis to treatment of paper mill effluents; design of a solar treatment facility" (Project: AMB1999-1212-C03-03), is being carried out in collaboration with the Autonomous University of Barcelona and attempts to apply photocatalysis to the elimination of organic pollutants present in the effluents from bleaching paper pulp by developing new photocatalysts and adding certain substances in dissolution to increase the efficiency of the degradation process. It is also intended to perform tests using sunlight in a pilot plant to enable design of a facility for the treatment of these waste effluents. The objectives of the project are the following.

1) Obtain and characterize effluents
2) Synthesize, characterize and test photocatalysts,
3) Determine the optimum experimental conditions for photocatalytic degradation of the pollutants,
4) Perform photocatalytic tests in pilot plant and
5) Design a solar facility for the treatment of said effluents.

Testing was performed in one of the PSA experimental facilities, adding 200 mg per liter of $TiO_2$ to the sample wastewater effluent from a paper mill and circulating it through the collector. In some of the tests, persulfate was added to favor degradation of the recalcitrant organic compounds present in the sample. The figure, below left, which represents the variation in the sample as a function of the parameter $Q_{UV}$ (representing energy accumulated in the photochemical reactor throughout the experiment) shows the results obtained. It also shows the $t_{30W}$ (equivalent experiment time under constant radiation of 30 W/m$^2$) at the endpoints of each test in order to give an idea of the approximate time that would be required in each case.




**TOC in the sample with regard to energy available $Q_{UV}$ under different conditions: ● Water diluted 5 times. $[S_2O_8^{2-}]0$ = 15 mM; ■ Undiluted water. $[S_2O_8^{2-}]0$ = 67 mM; ▼ Water diluted 5 times and $TiO_2$ only.**

**General view of the PSA CPC collectors used in the experimental part of the project**

The figure shows that the addition of this oxidant is substantially beneficial since it leads to a significant reduction of at least 6 times in the energy necessary for total mineralization of water with initial TOC of 100 mg/L (diluted 5 times). This reduction is also applicable to the collector surface necessary to degrade organics in the processing water. The consumption of persulfate is, furthermore, a linear function of the amount of TOC degraded and not of TOC existing at the beginning of degradation. The results demonstrate that by adding persulfate, two effects are achieved in the degradation of paper mill wastewater:

- Increase the reaction rate by one order of magnitude compared to $TiO_2$ alone) in all the initial concentrations tested,
- There is no "saturation" effect at high initial concentrations of organic carbon; this result is important since it permits different initial concentrations without losing efficiency in the degradation rate.

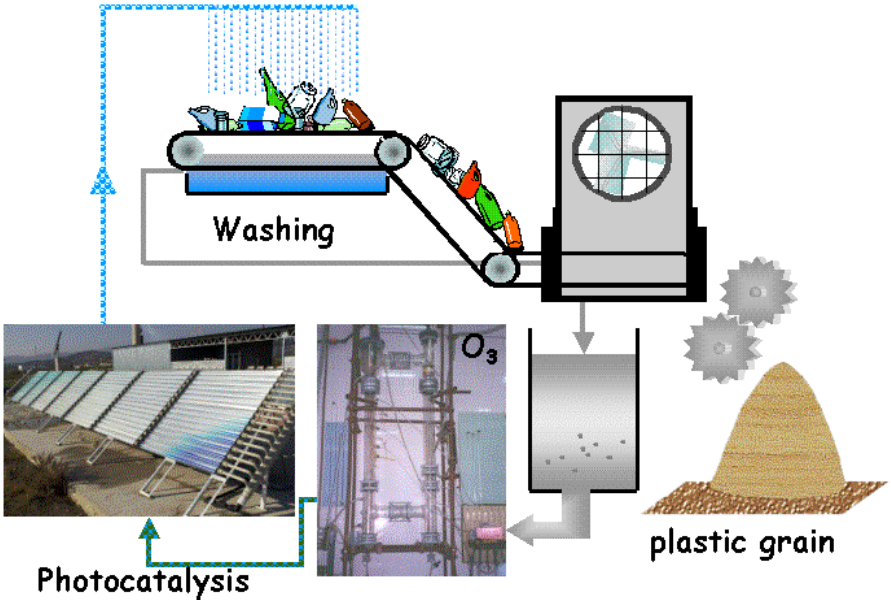
## Design and optimization of a pilot plant for integral treatment of pesticide residue during recycling of the containers

This project (called TREN-AGRO) is financed by the Spanish Ministry of Science and Technology (Call for R&D Projects, BOE of March 8, 2000, Project PPQ2000-0126-P4-05) and began in November 2001. In this project, the Plataforma Solar participates along with the Analytical Chemistry Department of the University of Almería (coordinator), Aragonesas Agro S.A., Fruit and Vegetable Exporters Cooperative of the Province of Almería[7] and the Department of Chemical Engineering of the University of Alcalá.

The work proposed attempts to develop a treatment process for pesticide container residues that allows them to be recycled, and that can be used for other applications in the plastics industry. The process consists of two basic steps of several operations each (i) direct treatment of the containers: shredding, washing, drying and compressing to properly inertize the waste and (ii) treatment of the rinse water; chemical-physical treatment to eliminate toxic components such as pesticides and transformation products [Blanco y col., 2001; Malato et al., 2001a]. In this way plastic waste can be included in the Integrated Management Systems for the usual nonhazardous waste plastic container programs in urban areas and the rinse water can be reused in new washing operations in the process proposed. The physical-chemical treatment will be based on Advanced Oxidation Processes (AOP): treatment with ozone/$H_2O_2$ or photocatalytic treatment, based on the use of solar radiation as the source of photons with UV/$TiO_2$ or Photo-Fenton [Malato et al.,

[7] Cooperativa de Exportadores de Frutas y Hortalizas de la Provincia de Almería, COEXPHAL

2001b]. Both treatments will have a capacity of approximately 500 L so that the reactors or solar collectors [Funken et al., 2001] will have to be designed specifically for this application [Malato et al., in press b]. The physical-chemical treatment that will finally be applied will depend on the overall treatment capacity and a detailed study on the context of the specific application to be considered [Malato y col., 2001c]. The integration of the operations into a single process and the know-how will be the main scientific-technological results and the evaluation of the feasibility conditions of a recycling plant adapted to the specific need will be the main result for business [Malato et al., 2001d, 2001e]. The process proposed will allow European Directive 94/62/EU to be applied and its transposition to the Spanish laws on Packaging (11/97) and Waste (10/98).




**Sequence of treatment for pesticide containers proposed by the TREN-AGRO project.**

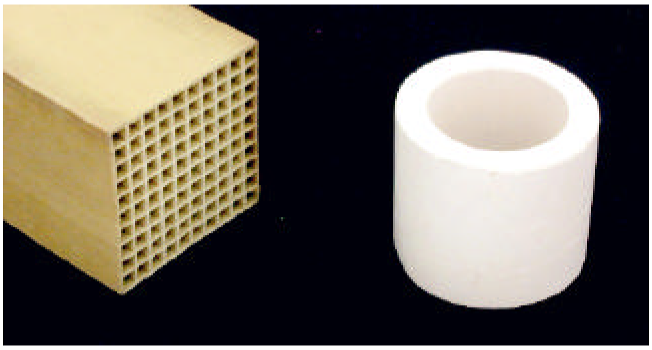
The final goal of the project is to design, build and optimize a pilot plant that includes quality control of the final product, as well as of the effect of the overall process on the environment, necessary for the transformation of plastic containers with pesticide residue into plastic with no pesticides and reusable for other applications. This study will obtain data on the design, efficiency (kinetics, stability, flexibility for the different kinds of containers and products), quality and economic feasibility. All of this will lead to scale up to plants easily located in different geographic areas where the agricultural sector is relevant.

## Destruction of gas-phase organic pollutants

The activities carried out during this period have been related to the development and optimization of solar collectors based on high-quantum-efficiency catalysts for application in the reduction of gaseous toxic emissions (project financed by the Spanish Ministry of Science and Technology and the Community of Madrid, together with CIEMAT and the CSIC).

The goal of the project is the design of gas purification units based on solar collectors and monolithic catalysts with physico-chemical and fluidodynamic characteristics appropriate for industrial use. With regard to the catalyst, an attempt has been made to optimize the design of the monoliths with a honeycomb structure that allows an appreciable reduction in the problems derived from the loss of load and mechanical resistance generated by the use of conventional fixed beds.

Besides improving the morphological characteristics of the catalysts, their efficiency is being optimized by improving the distribution of their active phase. A comparative study has been begun for this on the behavior of catalysts in which $TiO_2$ forms part of the mass with which the monolith (massic) are made and catalysts in which the $TiO_2$ has been deposited as a coating on a monolith prepared from a silica matrix (coated).

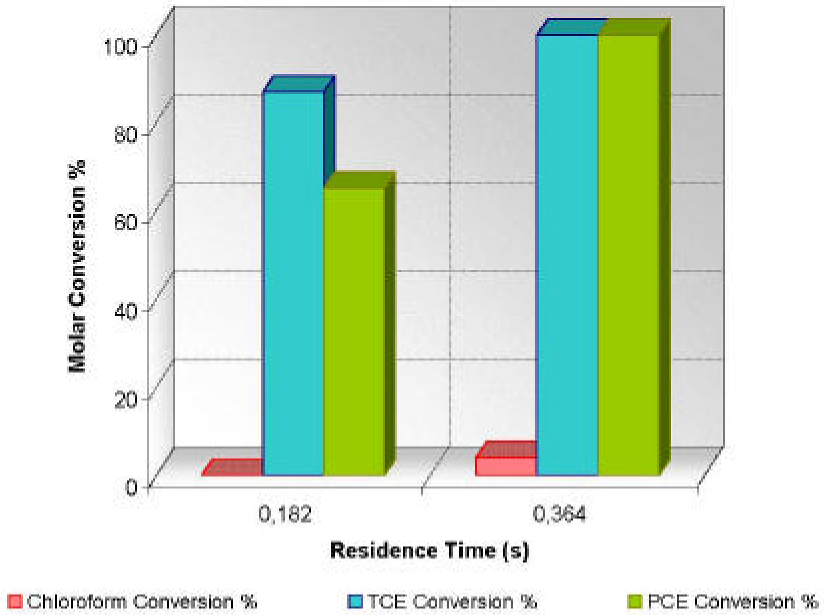


**Monolithic catalysts, with channels (left) and tubular (right) fabricated by the ICP-CSIC and used in different tests**

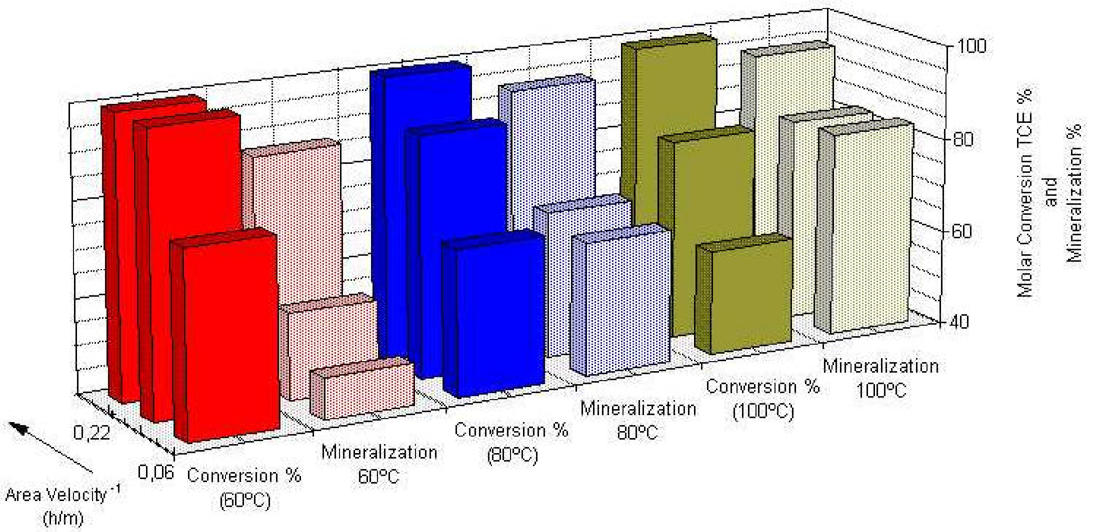
**Tubular catalyst impregnated with $TiO_2$ and placed in the interior of a parabolic trough collector absorber tube. System configuration allows solar radiation to be used on the outside while UV lamps simultaneously irradiate the inner surface of the catalyst**

The goal with regard to photons is to investigate the influence of the different parameters such as temperature, linear velocity and photonic intensity, as well as the capacity of formation of hidroxyl radicals and promotion of redox reactions that the solar radiation presents when it irradiates the titanium dioxide on the various structures, such as monoliths, flat plates or parabolic-trough collectors.

An important factor, has been that the destructive efficiencies of the different families of compounds after photocatalytic treatment. In the trials carried out to date, the response of Type BTX aromatic compounds (Benzene, toluene and xylene), at residence times of less than 2s are practically irrelevant, while 0.4 s is sufficient to treat chlorinated compounds such as trichloroethylene or perchloroethylene. This significant differentiation demonstrated the non-universality of photocatalytic treatment for gases in its present state, requiring that each one of the compounds to be destroyed be individually tested.




**Efficiencies of photocatalytic destruction for the various chlorated compounds**




**Influence of temperature on the conversion and mineralization of Trichloroethylene on tubular catalysts**

The photocatalytic process presents a complex response to changes in temperature. On one hand, mineralization of $CO_2$ from converted TCE is significantly boosted by an increase in temperature, while on the other, degradation of TCE decreases rapidly at temperatures over 125ºC. Therefore, TCE adsorption/desorption processes on the catalyst at temperatures of 125º are definitely identified as key factors in catalysts based on $TiO_2$+natural silicates. A very useful range of low working temperatures has thus been identified for the use of low- or very low concentrating solar systems.

## Access to the PSA as a Large European Scientific Facility

The European Project "Trans-national Access to the Plataforma Solar de Almería: the European Solar Thermal Test Centre" of the Improving Human Potential Program, began on February 1, 2000 and will last to June 30, 2004. This project consists of making the Plataforma Solar de Almería available to different European research groups for performing tests related to Solar Energy with the advice and collaboration of PSA's scientific staff. In this project, solar photochemistry activity is one of the most successful areas, with a scientific production [Augugliaro y col., 2001; Parra y col., 2001; Sarria y col., 2001; Szulbinski y col., 2001ª, 2001b], which has allowed the Solar Chemistry team to become a reference point in Europe [Malato y col., 2002 b]. In fact, in 2001, 11 European groups were received at the PSA in 7 test periods (4 in the DETOX facility and 3 in the SOLFIN facility), very similar to the activity during 2000. Such activity is expected to continue to be the same or even more intense, in coming years. The tests carried out in 2001 in photocatalytic detoxification, basically addressing decontamination of water, were the following:

1) Lab. Phys. Chem.-Univ. of Thessaloniki (Greece). Photocatalytic treatment of municipal wastewater. The intention was to develop a simple method of treating water in small cities on the islands of the Aegean Sea, where differences in summer and winter populations are enormous and conventional biological treatment is difficult. The photocatalytic experiments at the PSA consisted of reducing organic material, as well as converting organic N into inorganic ($NH_4^+$, $NO_3^-$, $NO_2^-$) in municipal wastewater prepared from typical components. The methods tested were: $TiO_2/H_2O_2$, $TiO_2/Na_2S_2O_8$, Photo-Fenton y modified photo-Fenton with ferrioxalate and $H_2O_2$.

**Cascade Photoreactor used to test titanium deposited on a fiber support prepared by the AHLSTROM PAPER company**

2) AHLSTROM PAPER GROUP/ Lab. Photocatalyse, Catalyse and Environment-E. Centrale de Lyon (France). *Testing with titanium dioxide on fixed support developed by the AHLSTROM PAPER company.* Experiments were performed with titanium deposited on a fiber support prepared by the AHLSTROM PAPER company and using a "cascade" reactor. The tests were related to: activity, durability, reactivation, cleaning, regeneration and frequency of replacement of the catalyst. The compounds used as models were: formetanate, fenamiphos (both pesticides), methylene blue, indigo and Congo red (dyes).

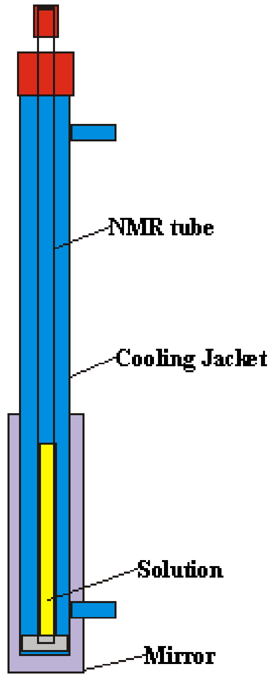
3) Dip. di Eng. Chim. dei Processi e dei Materiali-Univ. Palermo/Dip. di Chimica Anal.-Univ. di Torino. (Italy). Photocatalytic degradation of acetonitrile dissolved in water by $TiO_2$ suspensions. Acetonitrile is a very stable toxic compound which is often found in wastewater since it is a common chemical laboratory waste product (widely used as an eluent for HPLC). The kinetics of its degradation have been studied as a function of: initial concentration of the compound, of the catalyst and of the ionic strength of the medium. Oxidants such as $H_2O_2$ y $Na_2S_2O_8$ have been used and a detailed study of reaction intermediates has also been carried out.

4) Lab. Env. Biotech.-Swiss Fed. Inst. Technol./Lab. Photoch. Moléc. et Macromoléc.-Univ. Blaise Pascal. (Switzerland/France). These two groups have performed diverse experiments among which may be highlighted the application of the photo-Fenton and $TiO_2$ process to photoinduced degradation of organic substances representative of disinfection by-product precursors (DBPPs), as an alternative method for treating drinking water and degradation of pollutants by Fe(III). They also investigated the degradation of Diuron (a pesticide considered as a priority pollutant by the EU) in the CPC reactor starting with photo-excited aqueous Fe(III) complexes that generate $^{\bullet}OH$ radicals.

SOLFIN experiments, basically directed at synthesis of compounds using solar radiation, were:

1) Department of Chemistry, University of Pavia (Italy). Additive reactions using new sensitizers (pigments) inorganics (tungstates), which are hydrogen subtractor compounds. The stability of different organic substances that are solar filters was studied.
2) National University of Ireland (Ireland). Photosensitized functionalizing of cycloalkanes using alkynes and intramolecular reaction of Dienes with dissolved and supported sensitizers. Different alkynes with $C_5$-$C_6$ cycloalkanes using different polymeric sensitizers were irradiated.
3) Faculty of Chemistry, A. Mickiewicz University (Polonia). Application of supported molybdenum sulfate and oxysulfate for the photocatalytic production of hydrogen from water. The support used was mesoporous MCM-41 material.

## Selective catalyzed functionalizing of terminal acetylenes by coordination compounds in aqueous medium.




**Photoreactor designed for reactions in Nuclear Magnetic Resonance tubes (NMR)**

This project is financed by the General Directorate for Research (Spanish Ministry of Science and Technology, Project PP2000-1301) and began in December 2000. In this project, the Plataforma Solar participates together with the Department of Inorganic Chemistry of the University of Almería (coordinator), DLR-PSA and the Department of Organic Chemistry of the University of La Laguna.

The homogenous dual-phase (aqueous/organic) catalysis is the solution for many of the traditional problems of catalysis in a homogeneous medium, without losing any of its advantages. The processes are equally selective, but as the catalyst is dissolved in water, the products of the reaction, soluble in organic phase or insoluble in water, are easily separable, and the catalyst may be reused repeatedly. On the other hand, the unsaturated carbenes are important intermediates, often C-C bonding catalysts. In spite of the untiring effort made to develop the chemistry of these compounds due to their importance, practically no unsaturated carbene complexes soluble in water have been synthesized. This project attempts to study the chemical and catalytic properties of the metallic vinyl and allenylidenes soluble in water. The synthesis and study of new vinyl and allenylidenic compounds with bonds that allow their solution in water, in which the donor and acceptor properties of the donor atoms and its tensoactive properties make them optimum catalysts in dual phase systems. Together with this objective solar radiation has been proposed as a source of energy for the reactions developed in the laboratory by traditional systems. This second objective requires optimization of all the parameters and making it something practical and economical in the future, thus making the entire system (dual phase catalysis – solar energy) a highly selective, economical and ecological system.

## Solar desalination of seawater

The regional imbalance of water resources in many of the Mediterranean regions leads to a serious problem of lack of water in certain parts of Europe. In particular, this question becomes especially important in semi-arid zones where the lack of water is considered a growing problem together with the progressive deterioration of the quality of the water available for human consumption and for agriculture. The aquifers, which are the main source of water in these regions, are overexploited causing the quality of the water to diminish, as well as a series of additional problems such as intrusion of seawater in the aquifers, salinization of soils, desertification, acceleration of erosion, etc. These areas often have a good supply of seawater available as well as high levels of solar radiation, which can be very useful for producing drinking water by desalination of seawater. Since water is the main factor in economic development, the only sustainable option in the mid-to-long term is, in the majority of the cases, the desalination of seawater at an acceptable cost. In order to achieve this goal, the development of a desalination technology that is at the same time energetically efficient and environmentally friendly is necessary.

Two research projects in the field of solar desalination of seawater were recently approved, one national (SOLARDESAL Project: Advanced Hybrid Solar-Gas Desalination Technology based on Static Solar Collectors) and another European project (AQUASOL: Enhanced Zero Discharge Seawater Desalination using Hybrid Solar Technology).

The objective which both of these projects have in common is the development of a hybrid seawater desalination technology based on multi-effect desalination (MED) that is at the same time energy efficient, low cost and a zero discharge process. In spite of the fact that the reverse osmosis technology is the most adequate process for the treatment of saline underground water, its use for seawater is still expensive, since the energy required for the process increases exponentially with the concentration of salt. On the other hand, the processes of conventional desalination produce a waste brine that has a strong negative impact on the local marine ecosystem. Although the enormous potential of solar thermal energy in desalination processes is fully recognized, this technology has not been developed commercially due to its high cost.

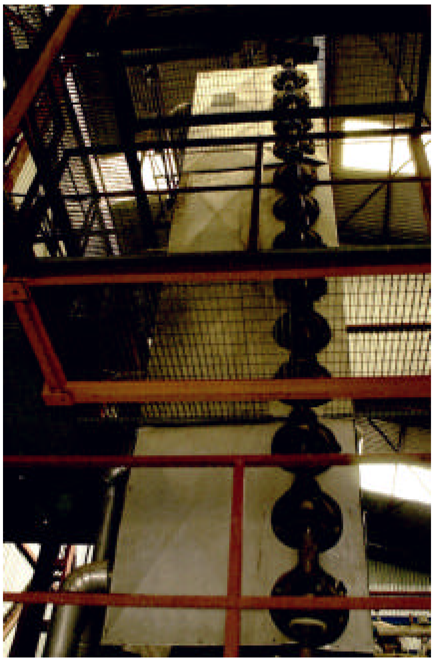
Participants in the SOLARDESAL project are: CIEMAT (coordinator), University of La Laguna, INABENSA and ECOSYSTEM. The duration of this project is three years, starting in November 2001. The specific objectives of this project are:

1) Review and evaluation of the different static solar systems (compound parabolic collectors, vacuum tubes, flat collectors, solar ponds, etc.)
2) Comparative study of the diverse possibilities for using static solar collectors combined with conventional thermal energy (gas) to power a multi-effect desalination plant.
3) Comparative study of static and tracking technologies for multi-effect desalination applications.
4) Selection of the most appropriate solar-gas hybrid system.
5) Implement, test and evaluate an experimental system that will enable validation of the technology proposed.
6) Identification of specific operating problems in the experimental system implemented in order to optimize it.
7) Technical and economic evaluation of the technology proposed, analyzing facility operation and maintenance costs.
8) Evaluation of the environmental aspects of the pre-designed system with regard to conventional processes and technologies.
9) Offer alternatives to the problem of the water deficit considering the principles of economy of fossil fuels and respect for the environment.
10) Dissemination and adequate diffusion of publishable results of the project.

Participants in the AQUASOL project are: CIEMAT (coordinator), AOSOL and INETI (Portugal), National Technical University of Athens and HELLENIC SALTWORKS (Greece), WEIR-ENTROPIE (France) and INABENSA, CAJAMAR and CUATRO VEGAS Irrigation Community of Almería (Spain). The project will last four years divided into two phases: a first research phase lasting two-and-a-half years, and a second demonstration phase, lasting a year and a half. The project starts in March, 2002.

The AQUASOL project focuses on the technological development of three basic aspects, which contribute significantly to the improvement of the techno-economic efficiency of MED systems and thereby reduce cost of desalinated water:

1) Develop a double-effect absorption heat pump optimized for the MED process which allows the energy consumption to be reduced;
2) Reduce to zero any kind of process waste by recovering the salt from the brine;
3) Incorporate a hybrid solar/gas energy supply source based on high-efficiency low-cost compound parabolic solar collectors.



Outer view of the plant with thermocline thermal storage tank in the background (above)

PSA 14-effect multi-effect desalination plant (left).

The successful achievement of the objectives of both these projects is expected to have considerable environmental as well as social benefits, since even without considering the environmental aspect, the technology to be developed has great potential for becoming competitive with conventional reverse osmosis technology. Altogether it will permit the quality of life of many people to be improved, as an effective tool for solving environmental problems associated with the lack of water.

## Training and Access

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

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

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

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

Finally, as a '**large international scientific installation**', the PSA assumes the following obligations:

- Make proposals in answer to calls or announcements that concern the center as a large scientific installation.
- Manage the quality of technical and scientific services given, including those given users or other third parties as well as CIEMAT projects.
- Public education programs.

## Activities within the 'Improving Human Research program

The 'Improving Human Research Potential' Program (IHP) is a concerted activity of the European Commission Directorate General for Science, Research and Technology Development (DG-RTD). Its main objective is to give the European scientific community an opportunity to use any large research infrastructure, in whatever member country it may be located.

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

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

Participation in the IHP program is for three years from February 2000 to January 2003. The PSA offers eight facilities for access and 68 research groups will have been received in them by the end of the three-year period.

As the first activity of the year, the independent expert selection panel met at CIEMAT-Moncloa on February 20, 2001, at which time 30 research groups from other European countries were selected for award of free access to the PSA test facilities during the year.

For the first time, the annual New Users Meeting at the PSA was organized together with the Workshop for Users from the year before in an attempt to make the event more fruitful for both. This combined event, which was attended by more than 50 researchers, took place in Almería on March 14 and 15, 2001. Workshop lectures were collected in a book

**IHP Users Workshop. Solar chemistry session.**

**Annual New IHP Users Meeting at the PSA**

published by the CIEMAT. [Improving Human Potential Programme, 2002].

On the other hand, the European Commission published a new announcement of this program at the beginning of the year, to which institutions with access contracts already in effect could apply. The PSA did so and has won a new contract for a 24-month period with financing of 517,500 EUROs for 48 weeks of access offered.

2002 will be the last year of the program, so that this last season will have to be used to correct any unbalance that may have arisen in the management parameters, such as number of users committed, number of weeks of use or user travel and allowances to be justified. As announced in the contract signed with DG RTD, there will be a follow-up technical audit in Brussels. The new IHP Phase 2 contract will be signed soon, although the only activity to be carried out will be the publication of the call for proposals for access in 2003.

In 2001 a **proposal for a 'Special Action'** was submitted to the **Spanish National Plan for RD&D**, precisely to facilitate the labor of searching for potential users. The object of the proposal is the organization of a series of informative meetings at the PSA in July, 2002, to which prospective European research groups who are interested in submitting a proposal as possible users in 2003 would be invited.

## The 'EuroCARE' Scientific Infrastructure Network

In its endeavor to join efforts and optimize resources dedicated to research, the European Commission promotes a series of research infrastructure networks that are grouped by subject matter. The PSA thus forms part of the 'EuroCARE' network, which is made up of those centers that study energy-related subjects.

Other members of the 'EuroCARE' network are:

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

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

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

Quarterly meetings in 2001 were held in Livorno (March) and Paris (December). The reports corresponding to the first and second study panels were published in 2001, while the report corresponding to the third panel will be published in 2002.

A web page was also created to publicize the contents of those study panels and the opportunities related to access programs developed by each of the members. The address of this page is www.euro-energy.net.

With a view to the 6th Framework Program, the objective of 'EuroCARE' will be to widen its activities, with new members and going into further detail into the collaboration on research matters of common interest.

## Training Activities

The purpose of the European Commission's DG-RTD access programs, aimed especially at benefiting young researchers, is usually the transnational mobility of researchers and their **training. This is the same principle behind the Plataforma Solar de Almería's own training program**. Around thirty students of different nationalities are admitted to this program each year, thus giving new generations of professionals the experience of the Plataforma Solar in solar thermal technologies accumulated during twenty years of experimentation. This project is going to be continued and reinforced if possible. Such training activities are also a CIEMAT priority.

**Training program** activities were:

- Management of the scholarship/grant program under the annual agreement signed with the University of Almería (UAL).
- Management of agreements for EC 'Leonardo da Vinci' grants.
- Management of specific educational agreements with other institutions to accept students at the PSA: e.g., ENCP, Univ. Cambridge.

**The training of university students in solar thermal technology is a priority activity at the PSA.**

For 2002, both the agreement with the UAL for management of the scholarship program and continuation of the 'Leonardo da Vinci' program for foreign students are expected to be renewed

## Representation of the PSA as a Large International Scientific Installation

This facet of the project registered intense activity in 2001. In the first place, a 400,000-EURO subsidy to finance improvements in scientific infrastructure was awarded the PSA by the Spanish Secretariat of State for Scientific Policy based on the acceptance of a proposal issued in response to the call for 'Special Actions' under the national RD&D program in 2000. The majority of these activities, related to another project responsibility, quality management of PSA services, took place in the year 2001. The funds were specifically awarded to contract outside consulting services necessary to carry out the first phase of an ISO-9000-standard quality management system for third-party clients as well as within the PSA itself. This activity is in line with the CIEMAT management systems.

Opening of the photography exposition "Heliostats"

On the other hand, several educational initiatives have also been carried out. The first of them consisted of signing a framework agreement with the *Instituto de Estudios Almerienses*[8] for matters of common interest. The first fruits of this agreement were the parallel photography exposition "Heliostats" and conference series "Technologies of the Plataforma Solar de Almería". Both activities took place in the provincial government building during the second half of September 2001.

There were two other activities during the celebration of European 'Science and Technology Week', from the 5th to the 18th of November 2001. The first was the erection of the stand-alone 'Colón Solar' heliostat in the center of the city of Almería where it was on show during the entire week. It was accompanied by informative posters and a video on the PSA and brochures about CIEMAT and INABENSA, the manufacturer of the heliostat, were passed out to spectators.

The prototype stand-alone heliostat set up in the city of Almería during "Science and Technology Week"

The second action opened the PSA to the public on November 8th and 9th.

[8] Institute of Almería Studies

## Testing in the Solar Furnace

The Solar Furnace test facility is devoted to thermal treatment of materials. It is within the Access project because most of the activity is related to third-party users.

**View of the PSA Solar Furnace**

The first event in 2001, was the contract signed with Brussels for financing of the project entitled ‘Development of Numerical and Experimental Methods of Investigation of Heat Transfer in Porous Thermal Protection Materials’ under the European INTAS 2000 program for scientific cooperation with other countries.

Other partners in this project were:

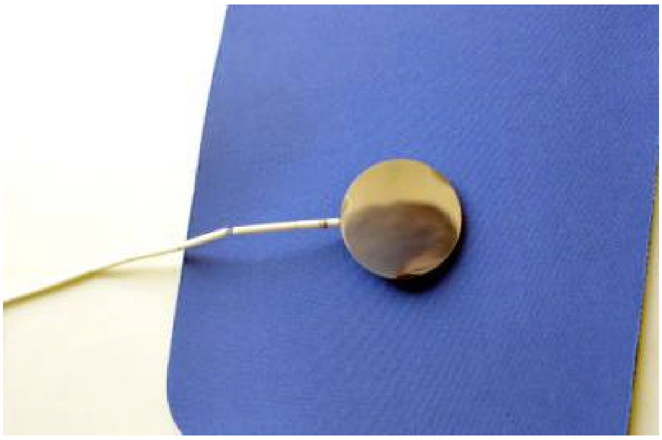
- ASTRIUM GmbH (Germany, coordinator),
- Ecole Nationale Supérieure de Mécanique et d'Aérotechnique (France),
- Central Aero-Hydrodynamic Institute (Russia),
- Bauman Moscow State Technical University (Russia)
- A.V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus (Byelorussia).

Work began in 2001.

The main activity in the facility is the IHP program, under which 3 to 5 research groups are received every year. In 2001, the PSA materials group closely cooperated with research personnel from the following institutions:

- Universidade do Minho (UM) of Braga (Portugal)
- Lithuanian Energy Institute (LEI) of Kaunas (Lithuania)
- Instituto Superior Técnico (IST) de Lisboa (Portugal)
- Helsinki Technical University (HUT) (Finland)

Several different metal and ceramic test pieces were tested with and without coating, in controlled atmosphere and in ambient air at temperatures between 450ºC and 1650ºC.



A sample tested for the Universidade do Minho

Testing carried out for the **Universidade do Minho** addressed thermal shock treatment at very high temperatures of the surfaces of test pieces with ceramic coatings that would act as a thermal barrier coating on materials used in advanced applications of great interest such as gas turbines.

One way of increasing the efficiency of energy conversion in gas turbines is by increasing the temperature of combustion and reducing the cooling system. The main objective of these tests was to develop and study the thermomechanical behavior of new advanced composite nanostructured multi-layered coatings for the protection of components working under these conditions. Thermal sprayed coatings (TSC) normally consist of a thin outer coating of $ZrO_2$, $Y_2O_3$ deposited by atmospheric plasma spray (APS) on a Ni superalloy with an adhesive metal precoating (normally Ni Cr Al Y) applied by vacuum plasma spray (VPS).

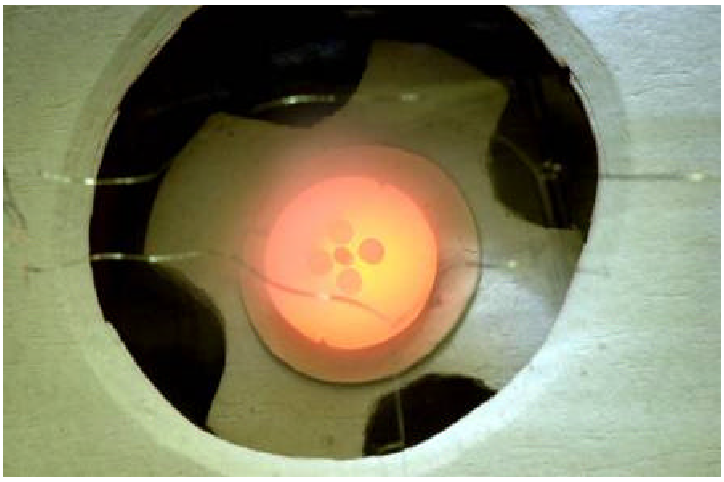
This group mainly focuses on research and development of the physical vapor deposition (PVD) technology for the production of new alternative functional coatings, and development of advanced characterization techniques in non-destructive testing (NDT).

With regard to the testing for the **Lithuanian Energy Institute (LEI)**, first it should be pointed out that thin zirconium oxide films are excellent candidates as coatings for various materials and applications, for example, as diffusion barrier coatings in nuclear reactors, protective layers on metal tools, insulation in microelectronics, optic filters, in sensor technology and as a stabilizer in solid oxide fuel cells (SOFC).

The work of the LEI focuses on research in the possibilities of PVD techniques in the development of different parts of SOFC for which the techniques are employed in the form of plasma spray, magnetic spray or magnetic plasma arc spray. A solid oxide fuel cell basically consists of a dense $ZrO_2$ membrane stabilized with $Y_2O_3$ (YSZ) and a porous electrode. The object of these tests was to investigate the possibilities of synthesizing YSZ thin films from a predeposited layer of Zr-Y, by thermal treatment in ambient air in the solar furnace. During this first test campaign with the LEI, 55 tests were carried out on samples with different substrates, e.g., steel, quartz and Si, with ZR-Y and $Al_2O_3$ coatings. Later the surface microstructure was characterized using such techniques as XRD, AFM and SEM.

A second test campaign was carried out later for the same institute, also on zirconium applications. Zirconium alloys are used in nuclear reactors that operate at high temperatures and pressures. During service, the corrosion of zirconium leads to the capture of hydrogen and the formation of hydrides in the Zr matrix. The presence of hydrides is an important factor for potential fragilization (retarded breakage of the hydride and formation of hydride bubbles) in components fabricated with these alloys. In the tests carried out in this second LEI campaign, they studied the behavior of hydrogen in Zr alloys and structural changes under thermal shock conditions, as well as the characterization and analysis of different microstructures and properties of these alloys. Modeling and predictive methodologies for Zr alloys subjected to thermal treatment are also objectives of these tests. A total of 42 tests were carried out on Zr-2.5Nb alloy samples containing up to 150 ppm of $H_2$.

The tests performed for the **Instituto Superior Técnico of Lisbon (IST)**, on the other hand, attempted to obtain carbides and carbonitrides from Si and d-group transition metals, except Hf, by solar synthesis, by exposing the samples to high-energy flux in the solar furnace.



Test setup for simultaneous testing of four IST samples

The results obtained up to now show interesting evidence that indicates that solar furnaces have good potential, as yet unexploited, for use as new solar synthesis reactors for materials that cannot be produced by conventional industry or laboratory processing.

During this campaign, 20 tests were performed in which samples of W+aC and Cordierite were treated. The first series of samples was exposed at the focus in the 'MiniVac' mini vacuum chamber in an Ar stream at 1.5 bar and 1600ºC for half an hour. The samples in the second series were exposed for the same time as the first but at 775ºC in ambient air and in a horizontal position.

The last test campaign of the season was performed for the group from the **Helsinki Technical University (HUT)**. In hot-work operations such as forging, tools tend to fail, as is the case when powdered or prefabricated materials are forged. Hot forging is used more and more, for example on prefabricated extruded materials. During hot forging, the tools heat up and cool off rapidly and at the same time are subjected to compression, which causes them to fail. Furthermore, conditions between the cutting tool and the piece to be machined have to be considered.

In this test campaign, the reaction of the piece worked with the cutting tool was investigated using three different powdered materials. The objective of testing was to examine the degree of diffusion of copper and aluminum in powder under simulated forging conditions and the sintering of powdered AlSiNi.

HUT Test pieces in the vacuum chamber before thermal treatment with concentrated sunlight

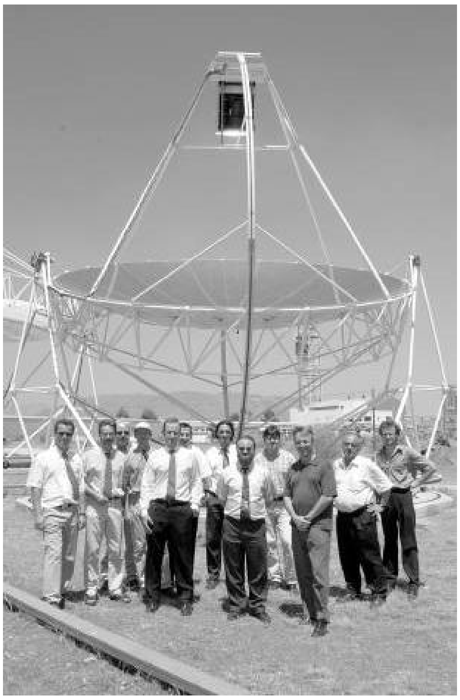
The samples were prepared in the laboratory by compressing the powder between two steel cylinders inside a steel tube. In this process the ends of the tubes were sealed and the powder was compressed. During testing, several cycles at different temperatures were performed. Thirteen tests were made in each of which three samples were treated for a total of 39 samples tested, 13 samples for each type of powdered material.

## Test Activities in DISTAL Facilities

As with the Solar Furnace, the DISTAL facility for testing and evaluation of parabolic dish and Stirling motor systems, is in this project because most of the activities carried out in it are related to non-CIEMAT users.

In the first place, the 'EUROdish' project, which is financed by the EC 'JOULE' PROJECT, was carried out at the PSA from 1997 to 2001. The objective was the development and demonstration of a third generation of these systems to decrease production and maintenance costs while increasing their reliability and autonomy.

Partners in the EUROdish project are: MERO, Klein & Stekl, Schlaich-Bergermann und partner (SBP) and DLR-PSA (Germany), INABENSA and CIEMAT-PSA (Spain).



**Final EUROdish meeting and inauguration of the new units**

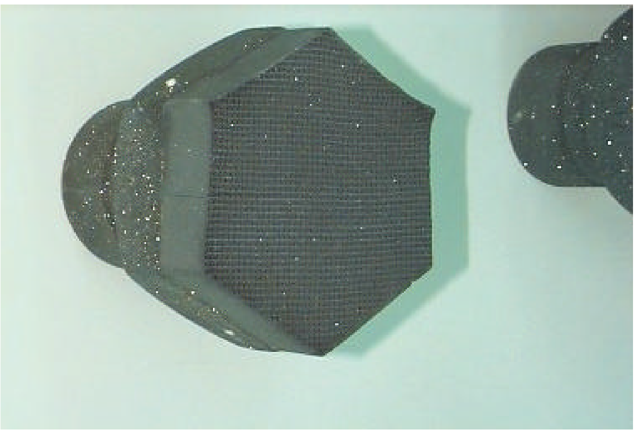
The last project meeting took place on July 26, 2001. All the partners were represented, including the scientific officer from DG-RDT in Brussels, Philippe Schild, who communicated final approval of Brussels to the project coordinator, Wolfgang Schiel of SBP. Results obtained in the project were presented in the final report, which was distributed at the meeting [Schiel et al., 2001].

Continuation of activities in this PSA facility now depends on CIEMAT decision.

The DISTAL facility also receives third-party research groups under the IHP access program, this year with researchers from the Danish firm, HelioTech Aps.

SiC carbide is acknowledged to be one of the most appropriate materials for manufacture of volumetric air receives for central solar systems for the generation of solar thermal electricity. This material has been tested by 'HelioTech' since the nineties, but its durability in working conditions still has to be evaluated.

For this purpose, a double-walled stainless-steel support tube about 1 m long was mounted in the focus of a DISTAL I unit for insertion of the ceramic samples. The tube also has an integrated multi-tube heat exchanger and fan. The removable front end where the ceramic test piece, or cup, is held is made of Incoloy steel. At the other end, a removable high-temperature (>900ºC) multi-speed fan sucks air into the system.



**Ceramic element from a volumetric receiver**

The purpose of these trials is to subject the material to the maximum operating temperature to test its durability. The maximum temperature foreseen under real working conditions (as part of a tower receiver) is 650ºC. The ceramic module (cup) trials in the DISTAL I unit were performed at temperatures of between 900º and 1000ºC.

The durability tests in the dish were performed on a SiC sample with a square base (127 x 127 x 62 mm) perforated like a grid so that air could pass through it. The trials lasted a total of 43 hours over a seven-day operating period, at the end of which the sample cracked due to thermal stress.

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# List of Acronyms

| | |
|---|---|
| AFM | Atomic force microscopy |
| AICIA................... | Asociación de Investigación y Cooperación Industrial de Andalucía |
| IEA....................... | International Energy Agency |
| ATYCA................. | Technology Safety and Industrial Quality Support Initiative (E) |
| BOE..................... | Official State Bulletin (E) |
| BRITE EURAM ........ | EC Industrial and Materials Technologies Programme |
| CPC..................... | Compound parabolic collector |
| CE....................... | European Commission |
| CESA................... | Central Electrosolar de Almería |
| STP....................... | Solar thermal power plants |
| CG-MS................. | Gas chromatography mass spectrometer |
| CIEMAT................ | Center for Energy Environment and Technology Research (E) |
| CNRS................... | National Center for Scientific Research (F) |
| TOC..................... | total organic carbon |
| CRES................... | Center for Renewable Energy Resources (Gr) |
| CRS..................... | Central Receiver System |
| CSIC.................... | Council for Higher Scientific Research (E) |
| CYTED ................. | Iberoamerican Program for Science and Technology for Development |
| CHA.................... | Spanish-German Agreement |
| BOD .................... | biochemical oxygen demand |
| DCS..................... | Distributed Collector System |
| DER..................... | CIEMAT Department of Renewable Energies |
| DG RDT............... | Directorate General Research, Development, Technology |
| DG TREN.............. | Directorate General of Transport and Energy |
| DISS..................... | Direct Solar Steam |

| | |
|---|---|
| DISTAL.................. | Dish Stirling Test Facility Almería |
| DLR ..................... | Deutsches Zentrum für Luft- und Raumfahrt e.V. (D) |
| COD ................... | Chemical Oxygen Demand |
| EHN..................... | Energía Hidroeléctrica de Navarra |
| ETH ...................... | Swiss ERDFal Institute of Technology |
| FAIR..................... | EC Fisheries, Agriculture and Agro-Industrial Research Programme |
| ERDF.................... | European Regional Development Fund |
| FID....................... | flame ionization detector |
| PV ....................... | photovoltaic |
| HDPE................... | high density polyethylene |
| HitRec ................. | High Temperature Receiver |
| HTF ...................... | heat transfer fluid |
| IAER..................... | Instituto Andaluz de Energías Renovables |
| ICMAB ................. | CSIC Institut de Ciència de Materials de Barcelona (E) |
| ICP...................... | CSIC Instituto de Catálisis y Petroleoquímica (E) |
| IHP ...................... | Improving Human Potential programme (EC) |
| INABENSA ............ | Instalaciones INABENSA, S.A. |
| INETI .................... | Instituto Nacional de Engenharia e Tecnologia Industrial (P) |
| INTA..................... | National Institute for Aerospace Technology (E) |
| LAGAR................. | Water recovery from olive mill wastewater after photocatalytic detoxification and disinfection (EC) |
| LECE.................... | Energy Testing of Building Components Laboratory |
| LS-3...................... | "Luz System 3" parabolic trough collectors |
| MBB..................... | Messerschmitt Bolkow-Blohm |
| MCYT................... | Ministry of Science and Technology (E) |
| MED .................... | multi-effect desalination |
| O&M ................... | operation and maintenance |
| PAR ..................... | photosynthetically active radiation |
| POA .................... | Advanced Oxidation Processes |
| PROFIT................. | Program for the Promotion of Technical Research (E) |
| Prohermes II ........ | Programmable Heliostat and Receiver Measuring System II |
| PS10 .................... | 10 MW Solar Thermal Power Plant for Southern Spain |
| PSA...................... | Plataforma Solar de Almería |
| REFOS.................. | Volumetric receiver for solar/gas hybrid combined cycle systems |
| SUW..................... | solid urban waste |
| SBP ...................... | Schlaich Bergermann und Partner (D) |

| | |
|---|---|
| SEGS.................... | Solar Electric Generating Systems |
| SEM | Scanning electron microscopy |
| SENER.................. | SENER Grupo de Ingeniería S.A. |
| IMS ...................... | integrated management systems |
| SIREC................... | Central Receiver Solar Thermal Systems |
| SOLAIR................. | Receptor Solar Volumétrico de Aire Avanzado para Plantas Comerciales de Torre Central |
| SOLAUT ................ | Solar Thermal Electricity Generation with Autonomous Modules |
| SOLFIN................. | Solar Synthesis of Fine Chemicals |
| SOLGATE.............. | Solar Hybrid Gas Turbine Electric Power System |
| SSPS..................... | Small Solar Power Systems project (IEA) |
| STC ...................... | Society for Technical Communication (Dk) |
| STEC .................... | Solar thermal electric Component |
| TCD..................... | Detector de conductividad térmica |
| TNO..................... | Netherlands Organization for Applied Scientific Research |
| TRAWMAR............ | Targeted Research Action on Waste Minimization and Recycling |
| TRNSYS................. | Transient Energy System Simulation Tool |
| TSA ...................... | Solar Air Receiver Technology Program |
| TUMA................... | Turbomach S.A. |
| TUW..................... | Technical Univ. of Vienna (A) |
| UAB ..................... | Autonomous University of Barcelona |
| UNED................... | National University for Education by Correspondence (E) |
| UV ....................... | ultraviolet |
| VIS....................... | visible irradiation spectrum |
| VOC.................... | volatile organic compounds |
| XRD | X-ray diffraction |
| ZSW .................... | Zentrum für Sonnenenergie- und Wasserstoff-Forschung (D) |

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