PLATAFORMA SOLAR DE ALMERIA (PSA)

THE EUROPEAN RESEARCH CENTER ON SOLAR THERMAL CONCENTRATING TECHNOLOGIES

April 2019

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1 General Presentation

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

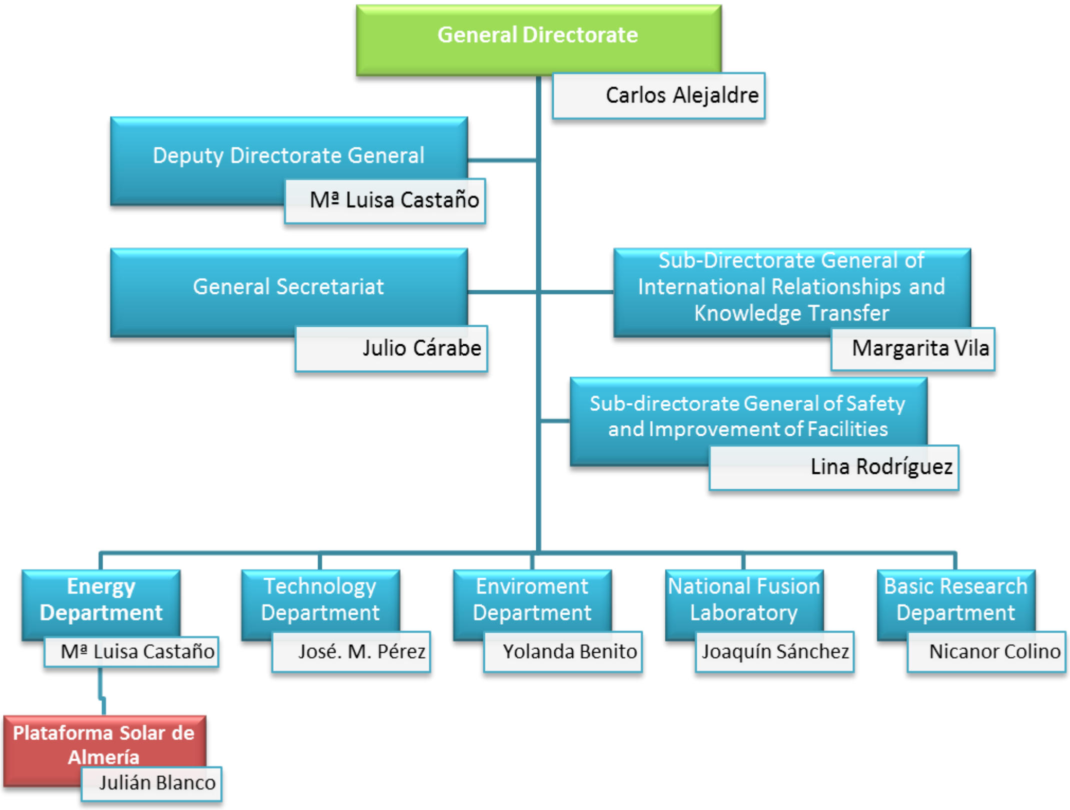


Figure 1. Integration of the PSA in the CIEMAT organization.

The following goals inspire its research activities:

- Contribute to establishing a sustainable clean world energy supply.
- Contribute to the conservation of European energy resources and protection of its climate and environment.
- Promote the market introduction of solar thermal technologies and those derived from solar chemical processes.
- Contribute to the development of a competitive Spanish solar thermal export industry.
- Reinforce cooperation between business and scientific institutions in the field of research, development, demonstration and marketing of solar thermal technologies.
- Strengthen cost-reducing techno-logical innovations contributing to increased market acceptance of solar thermal technologies.
- Promote international technological cooperation, especially in the Mediterranean Area.
- Assist industry in identifying solar thermal market opportunities.

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

Since 2018, research activity at the *Plataforma Solar de Almería* has been structured around four R&D Units under a Technical Coordinator, plus a strong unit to manage and also coordinate all facilities and laboratories, namely the PSA Management Unit. In addition to the different horizontal services (IT services, Instrumentation, Maintenance, Civil Engineering Operation, etc.), two additional facilities (METAS and LECE), physically allocated within PSA but with associated personnel formally outside PSA structure, are also included in this PSA Management unit.

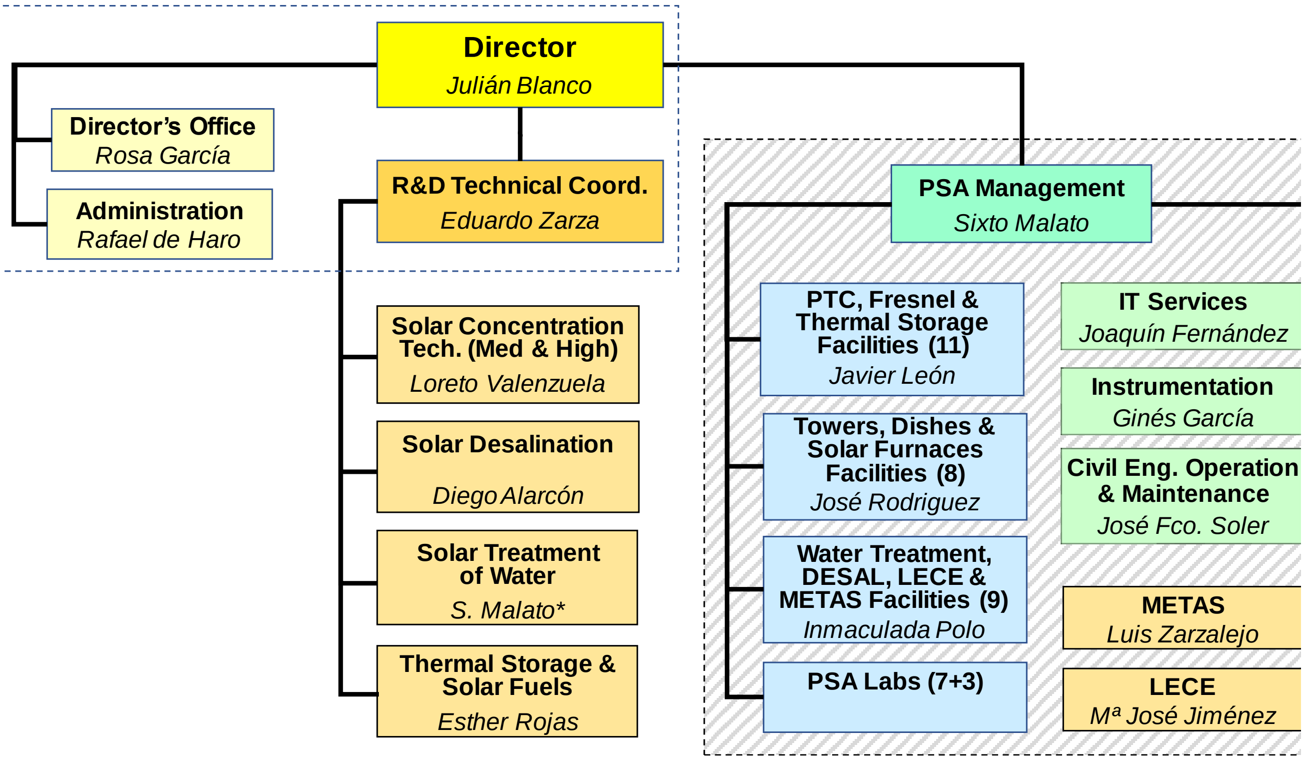


Figure 3. Internal organizational structure of PSA.

The four R&D Units are as follows:

- Solar Concentrating Systems. This unit develops and studies components for solar fields, complete systems and applications of concentrated solar thermal energy technologies, for electricity generation and industrial process heat.
- Solar Desalination. Its objective is to develop brackish water and seawater solar desalination.
- Solar Water Treatment. Exploring the chemical possibilities of solar energy, especially its potential for water detoxification and disinfection.
- Thermal Storage & Solar Fuels. The objective of this Unit is providing solutions to concentrating solar thermal systems to become a dispatchable technology, by thermal storage systems and/or Hydrogen production by thermochemical processes.

Supporting these R&D Units are the Direction and Technical Services Units mentioned above. These units are largely self-sufficient in the execution of their budget, planning, scientific goals and technical resource management. Nevertheless, the four R&D units share many PSA resources, services and infrastructures, so they stay in fluid communication with the Direction and Services Units, which coordinate technical and administrative support services. For its part, the Office of the Director must ensure that the supporting capacities, infrastructures and human resources are efficiently distributed. It is also the Office of the Director that channels demands to the various general support units located at the CIEMAT's main offices in Madrid.

The scientific and technical commitments of the PSA and the workload this involves are undertaken by a team of 135 persons that as of December 2018 made up the permanent staff lending its services to the *Plataforma Solar de Almería*. In addition to this staff, there is a significant flow of personnel in the form of visiting researchers, fellowships and grants handled by the Office of the Director. Of the 128 people who work daily for the PSA, 66 are CIEMAT personnel, 11 of whom are located in the main offices in Madrid.In addition, the 8 persons who make up the DLR permanent delegation as a consequence of its current commitments to the Spanish-German Agreement also make an important contribution. The rest of the personnel are made up of a no less important group given the centre's characteristics. These are the personnel working for service contractors in operation, maintenance and cleaning in the various different facilities. Of these 32 persons, 15 work in operation, 13 in maintenance and 4 in cleaning. The auxiliary services contract is made up of 5 administrative personnel and secretaries, 7 IT technicians for user services, and another 5 persons from the security contract, what makes a total of 17 persons.

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

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

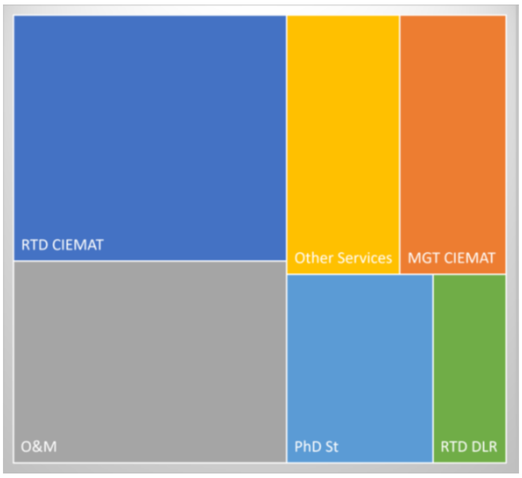


Figure 4. Distribution of permanent personnel at the PSA as of December 2018

2 Facilities and Infrastructure

2.1 Parabolic Trough Systems

2.1.1 The DISS experimental plant

This test facility was erected and put into operation in 1998 for experimenting with direct generation of high-pressure-high temperature (100 bar/400°C) steam in parabolic-trough collector absorber tubes. It was the first facility built in the world where two-phase-flow water/steam processes in parabolic-trough collectors could be studied under real solar conditions.

The facility (see Figure 5 and Figure 6) consists of two subsystems, the solar field of parabolic-trough collectors and the balance of plant (BOP). In the solar field, feed water is preheated, evaporated and converted into superheated steam at a maximum pressure of 100 bar and maximum temperature of 400°C as it circulates through the absorber tubes of a 700-m-long row of parabolic-trough collectors with a total solar collecting surface of 3.838 m^2. The system can produce a nominal superheated steam flow rate of 1 kg/s. In the balance of plant, this superheated steam is condensed, processed and reused as feed water for the solar field (closed loop operation).

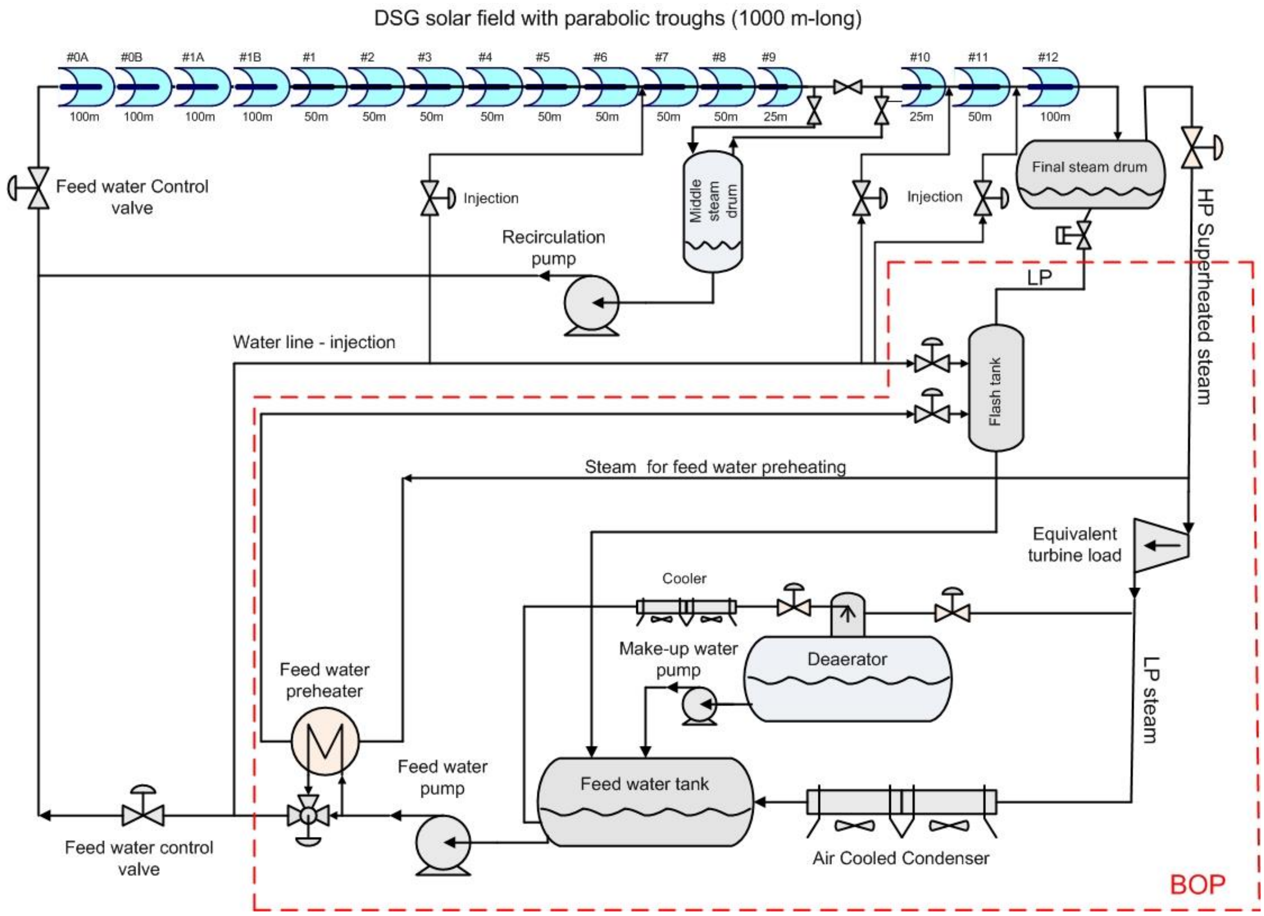


Figure 5. Simplified flow diagram of the PSA DISS loop.

In 2012, within the DUKE Project, three additional parabolic-trough collectors were installed in the solar field and all the absorber tubes were replaced by new ones, to increase up to 500°C the temperature of the superheated steam produced, enabling to generate direct steam at 100bar and 500°C.

Facility operation is highly flexible and can work from very low pressures up to 100 bar. It is also equipped with a complete set of valves allowing the solar field to be configured for Recirculation (perfectly differentiated evaporation and superheating zones), for Once-Through (the intermediate water-steam separator and the recirculation pump located in the solar field are not used in this operating mode) and in Injection mode (feed water is injected in different points along the collector row). The facility is provided with a wide range of instrumentation for full system monitoring (flow rates and fluid temperatures in the various zones of the solar field, pressure drops in collectors and piping, temperature and thermal gradients in the cross sections of the absorber tubes, etc.) and a data acquisition and process control system which has a database where 5-s process data are recorded 24 hours a day.

Among the capacities associated with this facility are the following:

- Component testing for parabolic-trough collector solar fields with direct steam generation (DSG) in their receiver tubes (receivers, ball joints or flexholes, water-steam separators, specific instrumentation, etc.).
- Study and development of control schemes for solar fields with DSG.
- Study and optimization of the operating procedures that must be implemented in this type of solar field.
- Thermo-hydraulic study of two-phase of water/steam in horizontal tubes with non-homogeneous heat flux.

Figure 6. View of the DISS plant solar field in operation

2.1.2 The HTF Test Loop

The HTF test loop was erected in 1997 and it is an ideal facility for evaluating parabolic-trough collector components under real solar energy operating conditions. The facility is appropriately instrumented for qualifying and monitoring of the following components:

- New designs of parabolic-trough collectors (up to 75 m long)
- Parabolic-trough collector mirrors
- Parabolic-trough collector absorber tubes

- New designs of ball-joints or flex-hoses for connecting parabolic-trough collectors in the solar fields.
- Solar tracking systems.

The facility consists of a closed thermal-oil circuit connected to several solar collectors of 75-m long connected in parallel (up to three collectors can be installed in parallel), being able to operate only one at a time (see simplified diagram of the facility in Figure 7). The east-west rotating axis of the solar collectors increases the number of hours per year in which the angle of incidence of the solar radiation is less than 5°. The thermal oil used in this facility (Syltherm 800®) has a maximum working temperature of 420°C and a freezing point of - 40°C.

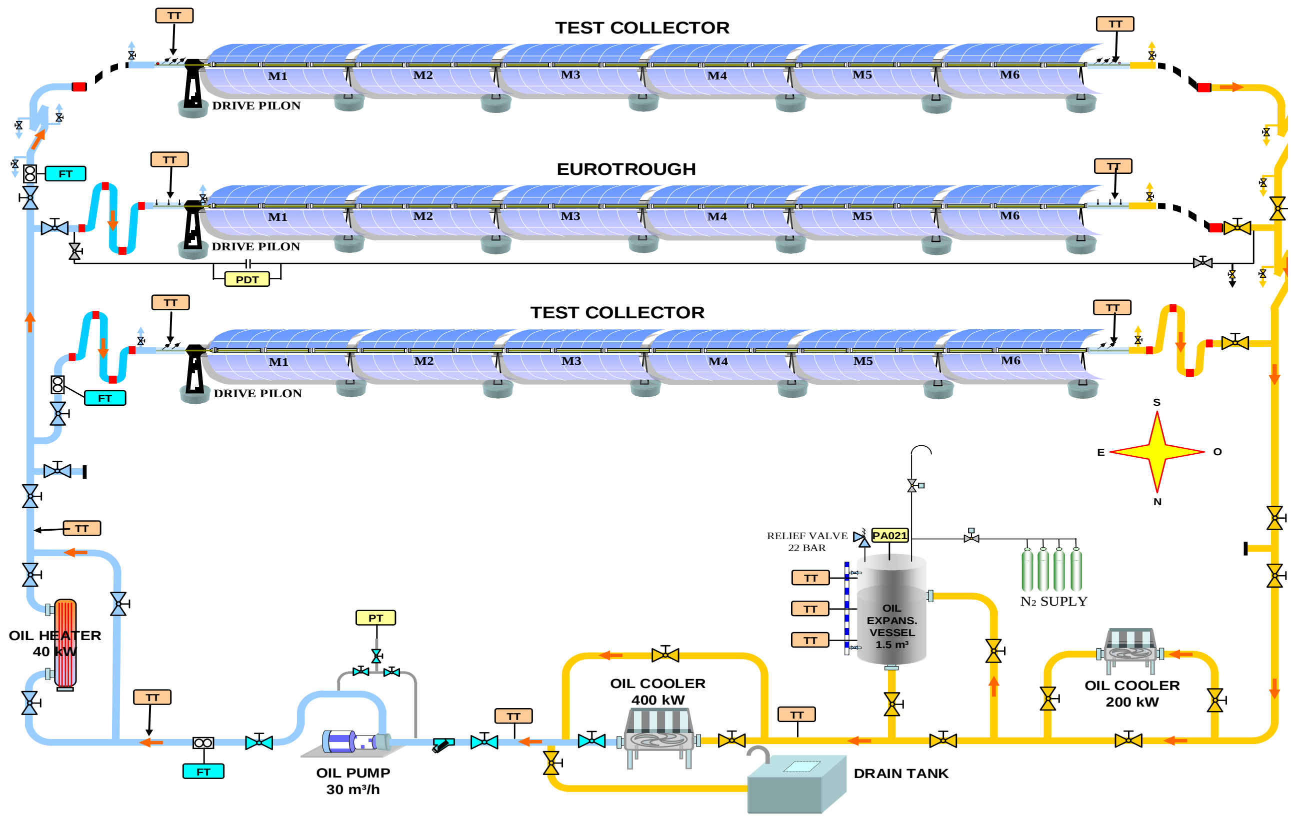


Figure 7. Diagram of the PSA "HTF test Loop".

The facility's oil circuit, which has a maximum working pressure of 18 bar, is made up of the following elements:

- 1-m^3-capacity oil expansion tank, with automatic nitrogen inertisation.
- Oil circuit sump tank.
- Mechanical-draft oil cooler, with air speed control and 400-kW maximum cooling.
- Centrifugal oil pump, with a flow rate of up to 8.3 litres per second.
- Two 40-kW electric oil heaters.

The first EUROtrough collector prototype developed by an European consortium with the financial aid of the European Commission was installed and evaluated under real working conditions at this facility in 1998 and it this collector is now used to evaluate and qualify new designs of receiver tubes, reflectors and other components for parabolic-trough collectors.

Main activities at the HTF test loop are related to study the optical and thermal performance of complete parabolic-trough collectors (optical efficiency, IAM coefficient, and global efficiency/heat losses) and receiver tubes.

2.1.3 The Parabolic Trough Test Loop (PTTL) facility

This large test facility is implemented in a 420mx180m plot of the PSA and it is composed of two solar fields:

- the North field is designed to install with a E-W orientation complete parabolic trough collectors with a maximum unit length of 180 m. Up to four complete collectors can be installed in parallel.
- the South field is designed to install complete loops of parabolic trough collectors (PTCs), i.e. several collectors connected in series, with a maximum length of 640 m and oriented North-South. Up to four complete loops can be installed in parallel.

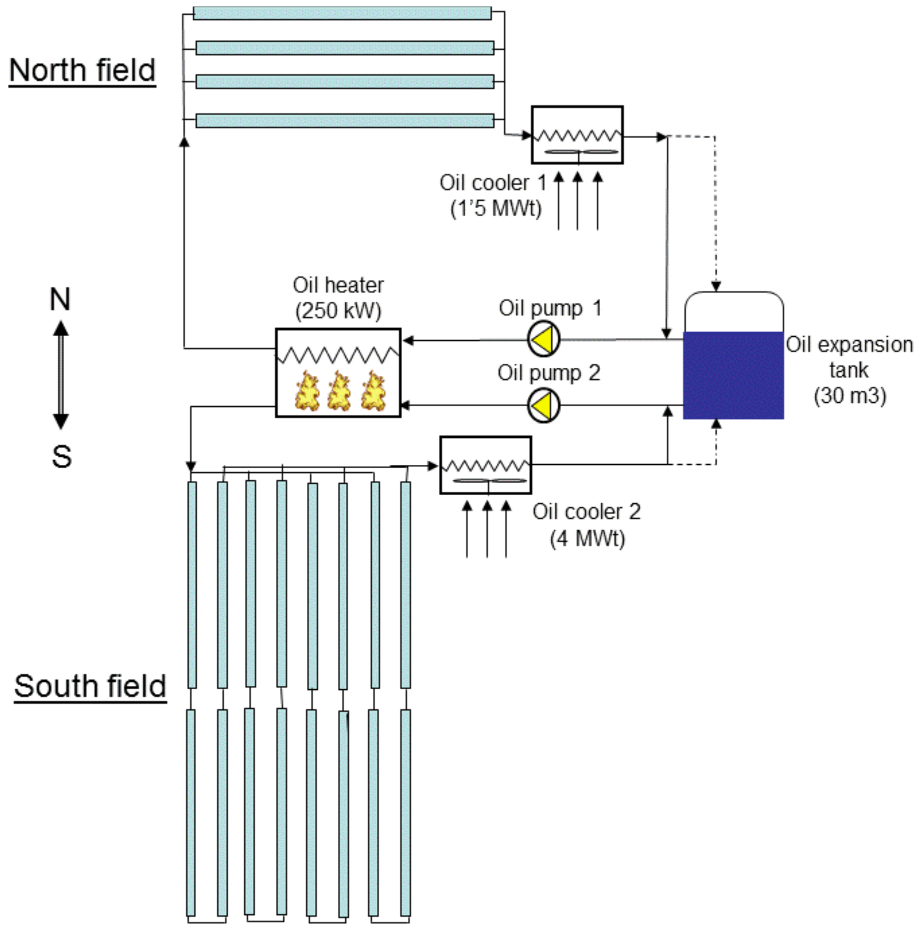


Figure 8. Simplified scheme of the PTTL facility

Each field is provided with a complete oil circuit installed on a 30mx30m concrete platform between the two fields, and both circuits share: an oil expansion tank with a capacity of 30 m^3, a gas-fired oil heater with a thermal power of 250 kW, a meteorological station equipped with solar radiation, ambient temperature and wind sensors, and the data acquisition system (DAS). Additionally, to these common elements, the oil circuit associated to the North and South fields are composed of:

- North field: one oil pump (75 m^3/h) provided with speed control, one oil cooler refrigerated by air (1.5 MWt) able to cold the oil down to 70°C when the ambient air temperature is 40°C, oil piping connecting the circuit to the common elements (i.e., expansion tank and oil heater).

- South field: one oil pump (125 m^3/h) provided with speed control, one oil cooler refrigerated by air (4 MWt), oil piping connecting the circuit to the common elements (i.e., expansion tank and oil heater).

Each oil circuit is also provided with an oil draining tank big enough to receive all the oil existing in the circuit, a complete set of instrumentation to monitor: oil mass flow, pressures and temperatures, as well as control valves to regulate the oil flow to desired values according to the tests.

This outdoor life-size test facility offers the following capacities:

- qualification of complete PTC prototypes assessing their optical peak efficiency, incidence angle modifier and thermal losses,
- evaluation of durability and reliability of PTC mirrors, receiver tubes, ball-joints, flex hoses, sun tracking systems and all the elements installed in complete rows of collectors,
- Evaluation of PTC solar field control algorithms

2.1.4 PROMETEO: Test facility for checking new components and heat transfer fluids for large-parabolic troughs

An experimental closed loop is installed at the North-East area of the *Plataforma Solar de Almería*. It was designed and erected by the company *Iberdrola Ingeniería y Sistemas* in 2010 starting the test campaign along the following year. The pilot plant was transferred to CIEMAT-PSA to be used as testing loop.

The East-West oriented test loop allows the qualification of all collector components and complete collectors of a length of up to 150 m, i.e. structures, reflectors, receivers from 70 to 90 mm and movable joints. It enables sun tracking covering all solar radiation incidence angles in one day thanks to its orientation. It is equipped with high precision instrumentation and controls for precise, quick and automated measurements. Currently there are two parabolic troughs 100 m-long and with an aperture of 7.5 m each one installed in the pilot plant.

Figure 9. View of the PROMETEO test facility.

The collector modules are connected to the balance of plant (BOP) in parallel or in series configuration using the ad hoc set valve. A pump circulates the silicone heat transfer fluid (SHTF) with a mass flow similar to that of commercial power plants. Mass flow is measured directly using Vortex and differential pressure flowmeter types. A controlled air cooler unit dissipates the collected energy and ensures a constant HTF temperature (±1K) at the inlet of the collector. Sensors for measurement of inlet and outlet temperatures are highly precise and may be calibrated on site. A meteorological station delivers accurate radiation and wind data.

2.1.5 TCP-100 2.3-MWth parabolic-trough facility

This test facility was implemented in 2014, and it is composed of the TCP-100 solar field and a thermocline storage tank with 115 m^3 of Santotherm-55 oil.

The TCP-100 solar field is composed of six parabolic-trough collectors, model TERMOPOWER, installed in three parallel loops, with two collectors in series within each loop, see **¡Error! No se encuentra el origen de la referencia.**. Each collector is composed of eight parabolic trough modules with a total length of 100 m and a parabola width of 5.77 m. The total solar collecting surface of each collector is 545 m^2. The focal distance is 1.71 n, the geometrical intercept factor is ≥0.95, and the peak optical efficiency is 77.5%. The receiver tubes used in this solar field were delivered by Archimede Solar Energy (Italy) and the working fluid is Syltherm®800.

The solar field is connected to a 10 m^3 oil expansion tank for a maximum temperature of 400°C. Thermal energy can be transferred from the solar field primary circuit to a thermocline oil storage tank with a total volume of 176 m^3 and 115 m^3 of Santotherm 55 oil with a maximum working temperature of 300°C.

This test facility is specially designed to perform studies related to control systems for parabolic trough solar fields. This is the reason why two collector loops are provided with the solar tracking system developed by PSA, while the third loop is provided with a commercial solar tracking system with continuous movement.

2.1.6 Innovative Fluids Test Loop (pressurized gases) in parabolic-trough collectors

The purpose of this experimental facility is to study the use of pressurized gases as heat transfer fluid in parabolic-trough collectors, evaluating their behaviour under a diversity of real operating conditions.

The experimental test loop (see Figure 10) is located north of the DISS experimental plant control building, which houses the equipment necessary for its control and data acquisition.

Figure 10. View of the IFL experimental facility (with parabolic-troughs) using compressed gas as heat transfer fluid.

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

- Two East-West-oriented EUROtrough parabolic-trough collectors, each 50 m long with a 274.2-m^2 collector surface. The collectors are connected in series.
- A 400-kW air-cooler able to dissipate the thermal energy in the fluid delivered by the collectors. It has two 4-kW motorized fans.
- A blower driven by a 15-kW motor which supplies the gas flow rate necessary to cool the receiver tubes adequately.
- A data acquisition and control system that allows the temperature, flow rate, pressure, beam solar irradiance and humidity in the system to be completely monitored.
- Automatic control valves that allow precise, safe variation in the collector fluid feed flow rate.
- An auxiliary circuit for filling the main test loop with the gas used as heat transfer fluid.

Since testing at 400°C was successfully completed at the end of 2009, this facility was then upgraded to achieve temperatures of up to 515°C and it was connected to a two-tank molten-salt thermal storage system to test their joint capacity for collecting and storing solar thermal energy with a view to making use of them in dispatchable high-performance thermal cycles. This increase in test loop design conditions to 100 bar and 515°C made the implementation of different improvements necessary (conventional absorber tubes in one of the two collectors were replaced with advanced high-temperature tubes, stainless steel pipes were installed for the high temperature zone and changes were made in the control system).

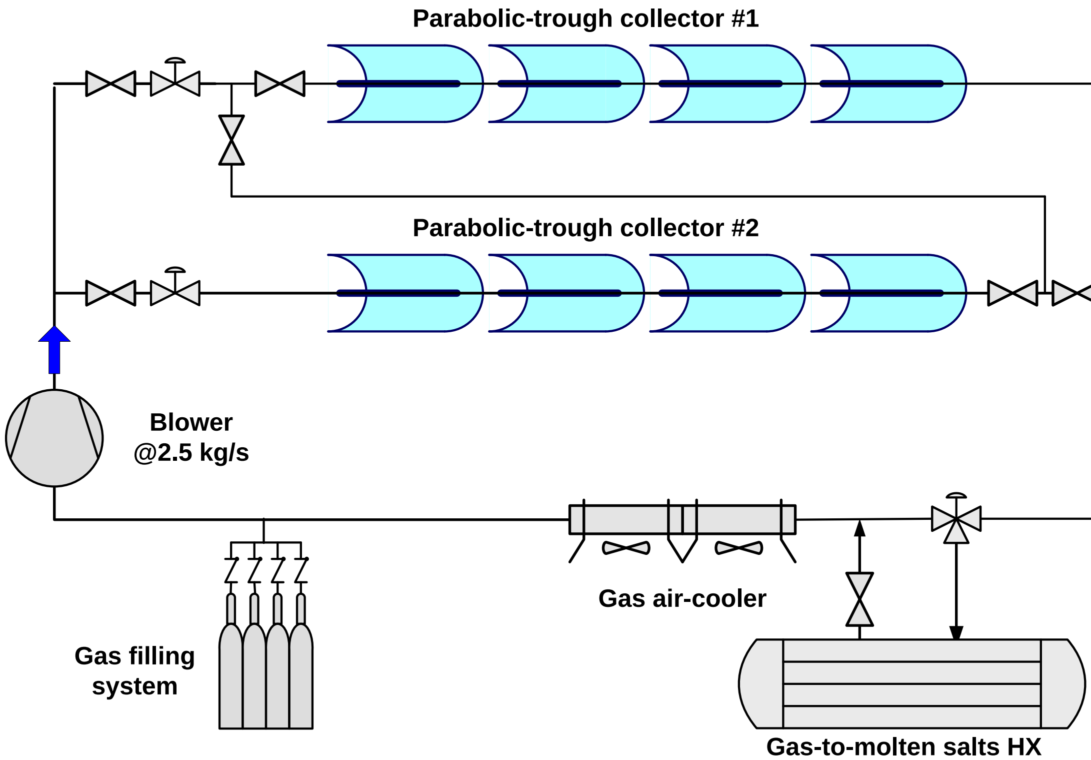


Figure 11. Simplified system diagram of the IFL experimental facility located at the PSA.

2.2 Installations associated with Parabolic Trough Systems

2.2.1 KONTAS: Rotary test bench for parabolic trough ststems

A rotary test bench for parabolic trough collector components, KONTAS, was erected at Plataforma Solar de Almería in 2009. The concept was developed by DLR and within the framework of the Spanish-German agreement between CIEMAT and DLR this test facility is now jointly used by both institutes.

The test bench allows the qualification of all collector components and complete modules of a length of up to 20 m, i.e. structures, reflectors, receivers and flexible joints. It enables for a tracking at any desired angle of incidence of the solar radiation. It is equipped with high precision instrumentation and controls for precise, quick and automated measurements.

The test bench rests on rails directly mounted on top of the foundation. These rails form an inner and an outer ring. The collector itself is mounted on a steel platform with six steel wheels. The rotation of the platform on the rails around the central bearing is performed by motors driving four of these wheels.

The collector module is connected to a heating and cooling unit, which is also situated on the platform. A pump circulates *Syltherm 800®* thermal oil as heat transfer fluid (HTF) with a mass flow similar to that of commercial plants. Mass flow is measured directly using the Coriolis measuring principle avoiding uncertainties of the density. The heating and cooling unit dissipates the energy the hot HTF collected on the way through the module and ensures a constant HTF temperature (±1K) at the inlet of the collector. Sensors for measurement of inlet and outlet temperatures are highly precise and may be calibrated on site. A high precision meteorological station delivers accurate radiation and wind data.

Figure 12. Side view of KONTAS test bench and the heating cooling unit.

2.2.2 Accelerated full lifecycle tests of rotation and expansion performing assemblies (REPAs) for parabolic troughs systems

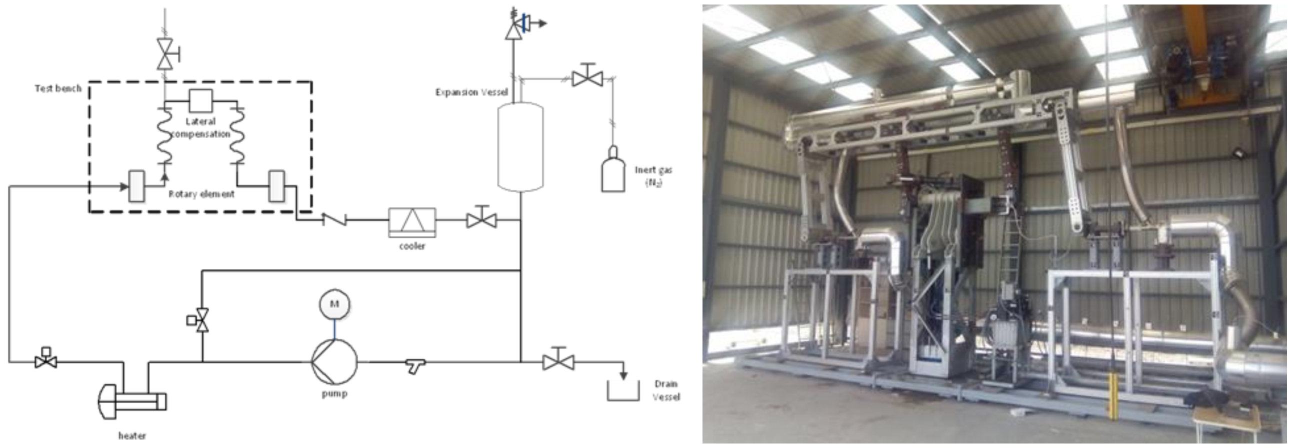
The REPA test facility is the result of merging CIEMAT activities in Task 14.4 of the European project SFERA-II (finished in 2017) and DLR activities within the national German project StaMeP. The facility is now used by CIEMAT-PSA and DLR in the framework of a joint collaboration.

The test bench is divided into two functional sections, the so called kinematics unit, to hold and move the pieces REPAs to be tested, and the balance of plant unit for supplying the conditioned heat transfer fluid (see Figure 13, a).

The balance of plant unit is composed of a variable speed HTF pump which circulates the HTF through a pipe with an adapted electrical heater collar type before passing through REPA to be tested, placed in the kinematics unit. The return line runs directly to the suction side of the pump closing the circuit. The system is connected to an expansion vessel able to compensate the volume difference caused by the density variation of the working fluid when its temperature changes.

The kinematics unit (see Figure 13, b) is prepared to accommodate test samples of ball joints and flexible hoses with varying and adjustable geometries, e.g. focal lengths. It is prepared to accomplish both rotational and translational movements with the following characteristics:

- Drive pylon: modified EuroTrough drive pylon structure
- Rotating angle is 205° and stow position in 25° facing down
- Up to 45° of lateral motion, representing absorber tube thermal expansion
- Prepared for dimensions of new PTC designs (focal lengths from 1m to 2.3m)
- Measurement of the reaction forces and torques of the assemblies under testing



(a) (b)

Figure 13. Schematic diagram of the REPA test loop at PSA (a) and north view of the test facility (b).

2.3 Central Receiver Systems

The PSA has two exceptional facilities for the testing and validation of central receiver technology components and applications. The SSPS-CRS and CESA-1 facilities enable projects to be undertaken and technologies validated in the hundreds of kilowatts range. They are outdoor facilities specially conditioned for scaling and qualifying systems prior to commercial demonstration.

2.3.1 The 6 MWth CESA-1 Plant

The CESA-1 plant (see Figure 14) was inaugurated in May 1983 to demonstrate the feasibility of central receiver solar plants and enable the development of the necessary technology. At present, the CESA-1 plant is a very flexible facility operated for testing subsystems and components such as heliostats, solar receivers, thermal storage, solarized gas turbines, control systems and concentrated high flux solar radiation measurement instrumentation. It is also used for other applications that require high photon concentrations on relatively large surfaces, such as in chemical or high-temperature processes, surface treatment of materials or astrophysics experiments. Direct solar radiation is collected by the facility's 330 x 250-m south-facing field of 300 39.6-m^2 heliostats distributed in 16 rows. The heliostats have a nominal mean reflectance value of 0.91, the solar tracking error on each axis is 1.2 mrad and the reflected beam image quality is 3 mrad. The CESA-1 facility has the most extensive experience in glass-metal heliostats in the world, with first generation units manufactured by SENER and CASA as well as second generation units with reflective facets manufactured by ASINEL and third generation facets and prototypes developed by CIEMAT and SOLUCAR. In spite of its over 20 years of age, the heliostat field is in good working condition due to a strategic program of continual mirror-facet replacement and drive mechanism maintenance and replacement.

Figure 14. The CESA-I facility seen from the North.

To the north of the CESA-1 solar field are two additional areas used as test platforms for new heliostat prototypes, one located 380 m away from the tower and the other 500 m away from the tower.

The maximum thermal power delivered by the field onto the receiver aperture is 6 MWth at a typical design irradiance of 950 W/m^2, achieving a peak flux of 3.3 MW/m^2. 99% of the power is focused on a 4-m-diameter circle and 90% in a 2.8-m circle.

2.3.2 The SSPS-CRS 2.5 MWth facility

The SSPS-CRS plant was inaugurated as part of the International Energy Agency's SSPS (Small Solar Power Systems) project in September 1981. Originally conceived to demonstrate continuous electricity generation, it initially used a receiver cooled by liquid sodium that also acted as the thermal storage medium. At present, this test facility is mainly devoted to testing small solar receivers in the 200 to 500 kWth capacity range.

The heliostat field is composed of 91 39.3 m^2 first generation units manufactured by Martin-Marietta. A second field north of it has 20 52-m^2 and 65-m^2 second-generation heliostats manufactured by MBB and ASINEL.

Figure 15. Aerial view of the experimental SSPS-CRS facility.

The original SSPS-CRS heliostat field was improved several years ago with the conversion of all of its heliostats into completely autonomous units powered by photovoltaic energy, with centralized control communicated by radio using a concept developed and patented by PSA researchers. This first autonomous heliostat field, which does not require the use of channels or cabling, was made possible by financial assistance from the Spanish Ministry of Science and Technology's PROFIT program.

The nominal average reflectivity value of the field is actually 90%, the solar tracking error is 1.2 mrad per axis and the optical reflected beam quality is 3 mrad. Under typical conditions of 950 W/m^2, total field capacity is 2.5 MWth and its peak flux is 2.5 MW/m^2. 99% of the power is collected in a 2.5-m-diameter circumference and 90% in a 1.8-m circumference. The 43-m-high metal tower has three test platforms. The two first are located at 28 and 26 m and are prepared for testing new receivers for thermochemical applications. The third test platform is at the top of the tower at 43 m, and houses an enclosed room with crane and calorimetric test bed for the evaluation of small atmospheric-pressure volumetric receivers, and solar reactors for hydrogen production. The tower infrastructure is completed with a 4-TN-capacity crane and a 1000-kg-capacity rack elevator.

The SSPS-CRS tower is equipped with a large quantity of auxiliary devices that allow the execution of a wide range of tests in the field of solar thermal chemistry. All test levels have access to pressurized air (29 dm^3/s, 8bar), pure nitrogen supplied by cryogenic plant, where liquid N_2 is stored in a liquid tank with a 6 TN capacity (Fig. 10). This installation is safe and efficient to operate and it is extremely versatile to provide all the possible variants. The proposed plant will be able to provide flow rates from 70 kg/hour to 250 kg/hour with autonomy of several days or even weeks. There also steam generators with capacity of 20 and 60kg/h of steam, cooling water with a capacity of up to 700 kW, demineralized water (ASTM type 2) from a 8m^3 buffer tank for use in steam generators or directly in the process, and the data network infrastructure consisting of Ethernet cable and optical fibre.

A hybrid heat flux measurement system to measure the incident solar power that is concentrated by the heliostat field is located at the SSPS-CRS tower. This method comprises two measurement systems, one direct and the other indirect. The direct measurement system consists of several heat flux sensors with a 6.32 mm front-face diameter and a response time in microseconds. These micro sensors are placed on a moving bar, which is mounted in front of the reactor window. The indirect measurement system works optically with a calibrated CCD camera that uses a water-cooled heat flux sensor as a reference for converting grey-scale levels into heat flux values.

2.4 Parabolic DISH Systems

2.4.1 Accelerated ageing test bed and materials durability

This installation consists of 4 parabolic dish units, 3 DISTAL-II type with 50 kW total thermal power and two-axis sun tracking system, and 1 DISTAL-I type with 40 kW total thermal power and one-axis polar solar tracking system. In the 4 dishes, the initial Stirling motors have been replaced by different test platforms to put the materials or prototypes at small scale of high concentration receivers and perform accelerated temperature cycling. With fast focusing and defocusing cycles, the probes placed in the concentrator focus stand a large number of thermal cycles in a short time interval, allowing an accelerated ageing of the material. These platforms can be used for a large variety of applications: materials tests, air-cooled volumetric receivers tests (metal or ceramic), tests of small-size receivers prototypes with or without heat transfer fluid, etc.

Figure 16. An autonomous heliostat in the CRS field.

The DISTAL-I concentrator (Figure 17) is a 7.5 m diameter parabolic dish, able to collect up to 40 kW_{th} energy, which is applied to the probes to obtain the accelerated ageing. The concentrator is made of a stretched membrane, 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. The three parabolic dishes DISTAL-II (Figure 18) were erected at PSA in 1996 and 1997, using the stretched membrane technology. These parabolic dishes have a diameter slightly larger than the DISTAL-1 above described (8.5 m) and the thermal energy delivered in the focus is 50 kW_{th}. The focal distance is 4.1 m and the maximum concentration is 16000 suns at the focus. These concentrators can be used for any experiment requiring a focus with the characteristics above mentioned (50 kW_{th} maximum and 16,000 suns peak concentration at the focus). The tracking consists in a two-axis azimuth-elevation system.

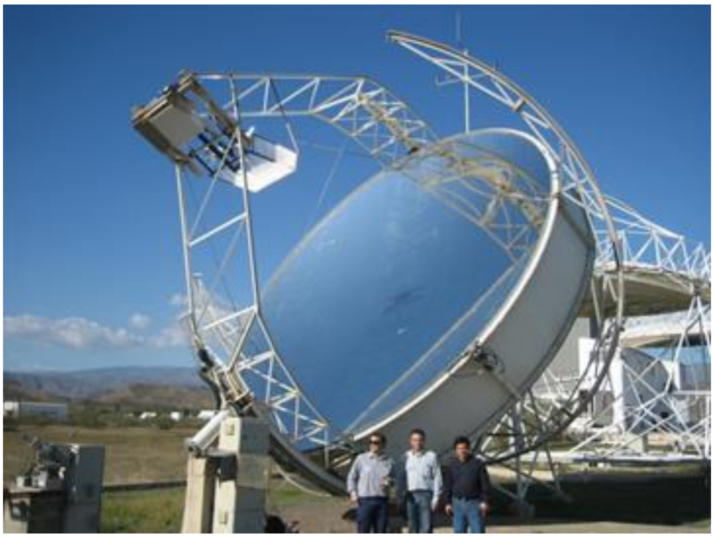


Figure 17. Parabolic-dish DISTAL-I used for accelerated materials ageing at PSA.

Figure 18. View of a parabolic-dish DISTAL- II.

The test bed for durability and accelerated materials ageing is complemented with the laboratory for the assements of the durability and carachterization of materials under concentrated solar radiation existing at PSA, which is described in the laboratories section of this document (section 3.4), and with the durability and accelerated materials ageing laboratory existing at Madrid (section 3.7).

2.4.2 EURODISH

Under the Spanish-German EUROdish Project, two new dish/Stirling prototypes were designed and erected (see Figure 19), discarding the stretched-membrane technology and applying a moulded composite-material system. These parabolic dishes can be used to test new prototypes of Stirling engines, or to perform any other test requiring a focus with 50 kWth maximum and a maximum concentration of 16.000 suns at the focus. The tracking system is azimuth-elevation.

2.5 Installation of Solar Furnaces

2.5.1 SF-60 Solar Furnace

The SF60 consists basically in a 120 m^2 flat heliostat that reflects the solar beam onto a 100 m2 parabolic concentrator which in turn concentrates the incoming rays on the focus of the parabola, where the tested specimens are placed. The incoming light is regulated by a louvered shutter placed between the heliostat and the concentrator. Finally a test table movable on three axis is used to place the specimens in the focus.

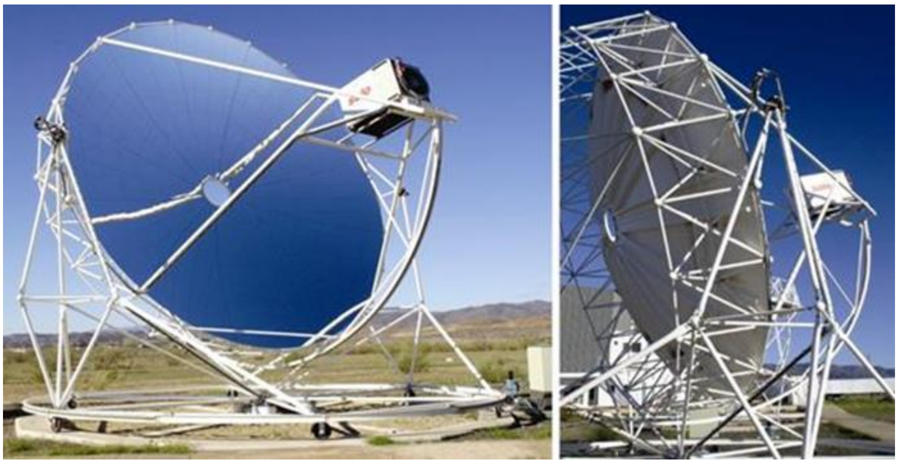


Figure 19. Front and back views of the EURODISH.

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

The only heliostat associated with the SF-60 consists of 120 flat facets, with 1 m^2 reflecting surface each. These facets have been designed, manufactured, assembled and aligned by PSA technicians. Every facet is composed of a 1 m^2 reflecting surface and 3 mm thick Rioglass flat mirror silvered on its back (second surface mirror). Solar Furnace Technicians are also responsible of a new method of fixation of the facet on a frame that minimizes deformation of the reflecting surface. Figure 20 and Figure 21 show the heliostat installed in this solar furnace and a detail of the back side of the facet respectively.

Figure 20. HT120 heliostat with new PSA facets.

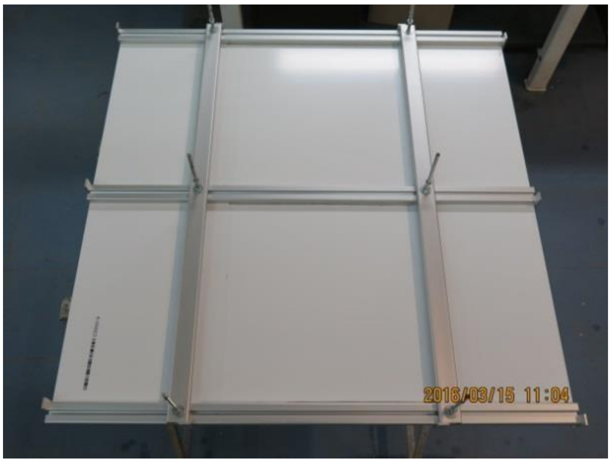


Figure 21. Back side of facet.

The parabolic concentrator is the main feature of this solar furnace. It is made of spherically curved facets distributed along five radii with different curvatures depending on their distance from the focus. It concentrates the incident sunlight from the heliostat, multiplying the radiant energy in the focus.

The shutter (attenuator, see Figure 22) consists of a set of horizontal louvers, which turn on their axis to control the amount of sunlight incident on the concentrator. The total energy in the focus is proportional to the radiation that goes through the shutter.

The test table is a mobile support for the test pieces or prototypes to be tested that is located under the focus of the concentrator. It moves on three axes (X, Y, Z) perpendicular to each other and positions the test sample with great precision in the focal area.

The combination of all of the components described lead to the flux density distribution in the focus which is what characterizes a solar furnace. This distribution usually has a Gaussian geometry and is characterized by a CCD camera hooked up to an image processor and a lambertian target. The characteristics of the focus with 100% aperture and solar radiation of 1000 W/m^2 are: peak flux, 300 W/cm^2, total power, 69 kW, and focal diameter, 26 cm.

Figure 22. HT120 heliostat in tracking.

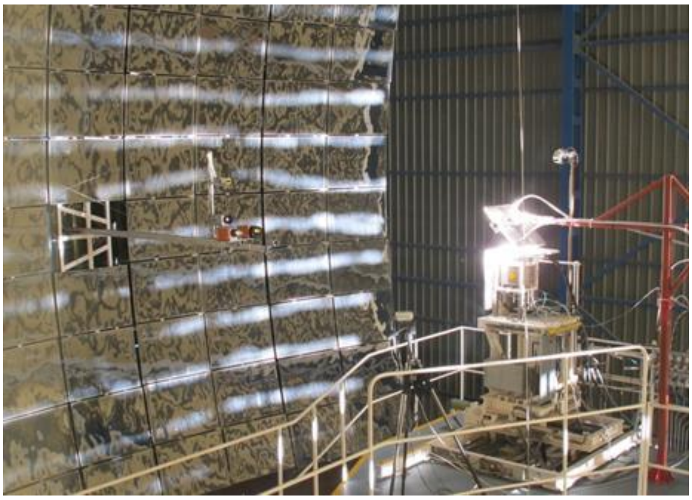


Figure 23. Interior view of the PSA SF-60 Solar Furnace in operation

2.5.2 SF-40 Solar Furnace

The SF-40 furnace consists mainly of an 8.5-m-diameter parabolic-dish, with a focal distance of 4.5 m (see Figure 24). The concentrator surface consists of 12 curved fiberglass petals or sectors covered with 0.8-mm adhesive mirrors on the front. The parabola thus formed is held at the back by a ring spatial structure to give it rigidity and keep it vertical. The new SF40 solar furnace reaches a peak concentration of 5000 suns and has a power of 40 kW, its focus size is 12 cm diameter and rim angle a= 50.3°. Its optical axis is horizontal and it is of the "on-axis" type that is parabolic concentrator, focus and heliostat are aligned on the optical axis of the parabola.

It basically consists of a 100 m^2 reflecting surface flat heliostat, a 56.5 m^2 projecting area parabolic concentrator, slats attenuator, and test table with three axis movement.

The focus of the SF40 is arranged on the vertical plane. In order to work on the horizontal plane, the beam rays incident in focus is rotated 90°, using a tilted, cooled mirror placed at the focal area, which turn the beam to the horizontal plane. The facility is completed with a gas system and vacuum chamber -MiniVac 2-, which allows tests in controlled atmosphere and vacuum, so that the specimens are not oxidized during tests.

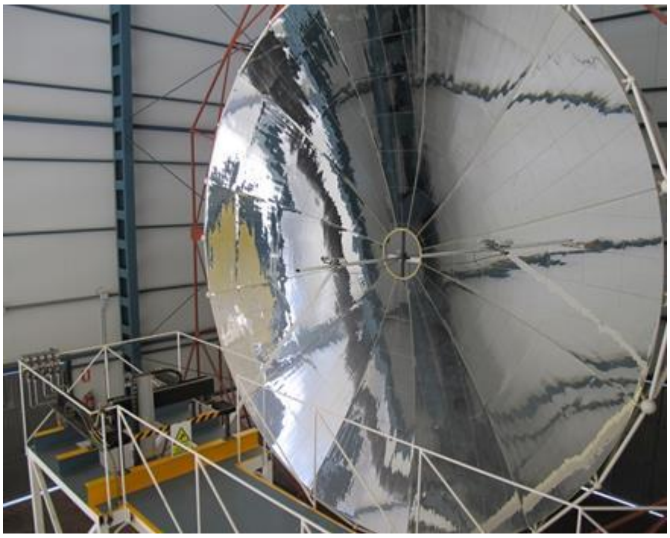


Figure 24. Interior of the SF-40 solar furnace, showing the parabolic concentrator.

2.5.3 SF-5 Solar Furnace

Designed and built at the PSA, this system is in operation from 2012 and is focused to tests that require high radiant flux, strong gradients and very high temperatures.

It is called SF5 -Solar Furnace 5, by its 5 kW power-, reaches concentrations above 7000 suns, its focus diameter is 2.5 cm, and is mainly devoted to heat treatment of materials at high temperature, under vacuum and controlled atmosphere conditions, for which a vacuum chamber, called Spherical Chamber, provided with a gas system are used.

It differs substantially from that existing PSA Solar Furnace SF60 and most operating solar furnaces, as it operates in a vertical axis, i.e., parabolic concentrator and heliostat are vertically aligned on the optical axis of the paraboloid, while that in most existing solar furnaces, are horizontally aligned. The main advantage of vertical axis solar furnaces is that the focus is arranged in a horizontal plane, so that the samples may be treated on a horizontal surface, just placing them directly in the focus, without a holder, avoiding problems of loss of material by gravity in those tests in which the treatment requires surface melting of the specimens.

It basically consists of a 8.7 m^2 concentrator mirror, placed upside-down with the reflecting surface facing the floor, on a 18 m high metallic tower; in the centre of the base of the tower there is a 100 m^2 flat heliostat, whose centre of rotation is aligned with the optical axis of the concentrator. At the top of the tower, in the test room, and 2 m below the vertex of the concentrator, there is a test table. Finally, under the test table and at floor level of the test room, a louver attenuator is placed.

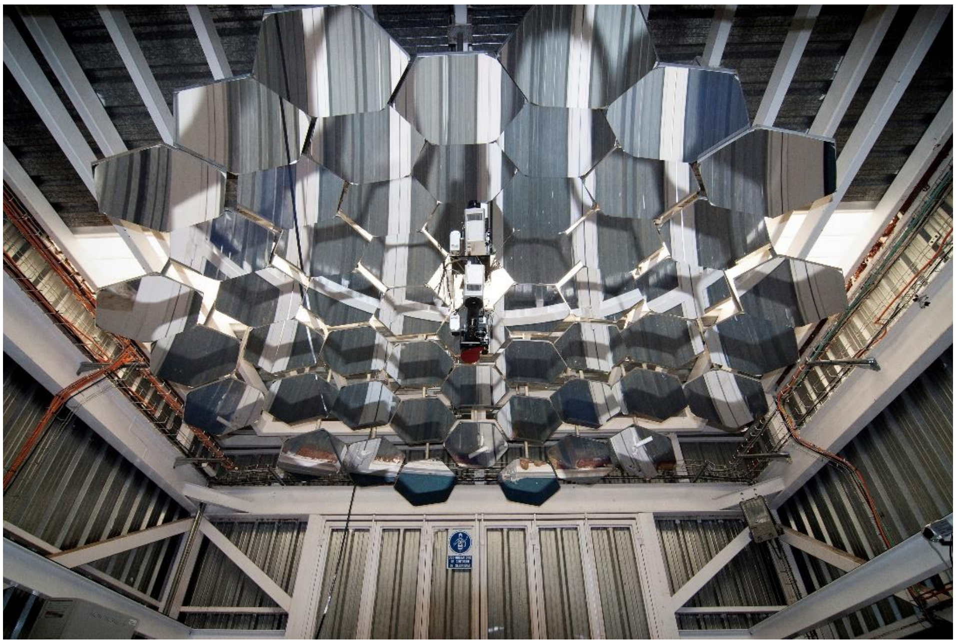


Figure 25. Concentrator of the SF-5 Furnace.

2.6 Thermal Storage Systems

2.6.1 Molten Salt Test Loop for Thermal Energy Systems

This molten salt test loop is a replica of a thermal energy storage system with molten salts and a two-tank configuration. With 40t of molten salts plant, this facility basically consists in:

- Two tanks, one vertical, for hot molten salts, and another horizontal, for cold molten salts.
- A thermal oil loop that can be used for heating the salt up to 380°C and cooling it to 290°C.
- A CO_2-molten salt heat exchanger for heating the salt up to 500°C with CO_2 supplied by parabolic trough collectors.
- Two flanged sections, where different components for this type of loops (e.g. valves, flow meters, heat trace, pumps…) can be tested.

Being a set up which is a reduced scale of a commercial two-tank molten salt storage system, everything related to this type of systems can be tested in this facility. Some applications of this facility are:

- Checking of components (pumps, valves, flowmeters, etc.) for their use in a molten salt medium.

- Optimization of procedures in normal operation for a two-tank system configuration.
- Optimization of procedures in risk situations for a two-tank system configuration. Designing recovery procedures.
- Validation of models and simulation approaches for molten salt thermal systems.
- Characterization of heat exchangers for molten salt/oil.
- Characterization of heat exchangers for molten salt/gas.
- Characterization of thermocline tanks.

Figure 26. Molten Salt Test Loop (MOSA) for Thermal Energy Systems.

2.7 Experimental Solar Desalination Installations

2.7.1 Multi-Effect Distillation Facilities

2.7.1.1 Solar Multi-Effect Distillation Facility

This facility is composed of the following subsystems:

- A 14-stage multi-effect distillation (MED) plant
- A field of stationary large-size flat plate solar collectors
- A water-based solar thermal storage system
- A double effect (LiBr-H_2O) absorption heat pump
- A fire-tube gas boiler

The multi-effect distillation unit is made up of 14 stages or effects, arranged vertically with direct seawater supply to the first effect (forward feed configuration). At a nominal 8 m^3/h feedwater flow rate, the distillate production is 3 m^3/h, and the thermal consumption of the plant is 190 kW_{th}, with a performance ratio (number of kg of distillate produced per 2326 kJ of thermal energy consumed) over 9. The saline concentration of the distillate is around 5 ppm. The nominal temperature gradient between the first cell and the last one is 40°C with a maximum operating temperature of 70°C in the first cell. The system heat transfer fluid is water, which is heated as it flows through the solar collectors and energy collected is then transferred to the storage system. The hot water from this storage system provides the MED plant with the thermal energy required for its operation.

The solar field (AQUASOL-II) is composed of 60 stationary flat plate solar collectors (Wagner LBM 10HTF) with a total aperture area of 606 m^2 and is connected with a thermal storage system (40 m^3) through a heat exchanger (More details about the solar field are supplied within its specific subsection).

The double effect (LiBr-H_2O) absorption heat pump is connected to the last effect of the MED plant. The low-pressure saturated steam (35°C, 56 mbar abs) generated in this last effect supplies the heat pump evaporator with the thermal energy required at low temperature, which would otherwise be discharged to the environment, cutting in half the thermal energy consumption required by a conventional multi-effect distillation process. The fossil backup system is a propane water-tube boiler that ensures the heat pump operating conditions (saturated steam at 180°C, 10 bar abs), as well as operating the MED plant in the absence of solar radiation.

Figure 27. The PSA SOL-14 MED Plant (a), double-effect LiBr-H_2O absorption heat pump (b) and 606-m^2 flat plate solar collector field (c).

2.7.1.2 Test-Bed for Solar Thermal Desalination Applications

The purpose of this facility is the study of the efficiency of large-aperture static solar collectors and its behavior in the coupling with thermal desalination systems minisat 60-90°C temperature levels.

The collector model installed is an LBM 10HTF with an aperture area of 10.1 m^2, manufactured by Wagner & Co. The static solar field is composed of 60 collectors with a total aperture area of 606 m^2 and a total thermal power output of 323 kW_{th} under nominal conditions (efficiency of 59% for 900 W/m^2 global irradiance and 75°C as average collector temperature). It consists of 4 loops with 14 large-aperture flat plate collectors each (two rows connected in series per loop with 7 collectors in parallel per row), and one additional smaller loop with 4 collectors connected in parallel, all of them titled 35° south orientation. Each row has its own filling/emptying system consisting in two water deposits, from which the heat transfer fluid is pumped to the collectors at the beginning of the operation and where all the water volume in the collectors is spilt either at the end of the operation or when a temperature limit is reached (above 100°C). The solar field has flow control valves that allow to have an equal distributed flow rate without further regulation. In addition, the facility has an air cooler that allows the entire energy dissipation from the solar field, which is useful for efficiency tests at different temperature levels. The five loops of collectors are connected with a thermal storage system through a heat exchanger. The thermal storage system consists of two water tanks connected to each other for a total storage capacity of 40 m^3. This volume allows the sufficient operational autonomy for the fossil backup system to reach nominal operating conditions in the desalination plant.

The flexibility of the solar field allows the operation of each loop independently, through their own valves and pumping system. Each loop is connected to an individual heat exchanger that offers the possibility of coupling it with any low-temperature thermal desalination system for testing purposes.

Figure 28. The 606-m^2 large-aperture flat plate solar collector field (AQUASOL-II).

2.7.2 CSP+D test facilities

2.7.2.1 CSP+D Test Bed: Integration of MED Thermal Desalination & Solar Thermal Power Plants

This facility is devoted to the research of the coupling between concentrating solar power (CSP) plants and Desalination (CSP+D). The testing facility is composed of two steam generators (250 kW and 500 kW) fed by thermal oil coming from a parabolic trough solar field able to deliver thermal oil with temperatures up to 400°C and an auxiliary electrical power system that raises the temperature if required. The steam generators are able to produce steam at different pressures, which allow recreating any of the typical intermediate extractions or the exhausted steam available at a turbine of a thermal power plant. The low pressure steam is obtained by making the steam from the generators to flow through two different pipe sections (12-inch diameter) equipped with control valves, which allows achieving saturated steam at two different levels: 0.074 bar/42°C (nominal flow rate of 119 kg/h, maximum flow rate of 360 kg/h) and at 0.16 bar/58°C (nominal flow rate of 195 kg/h, maximum flow rate of 360 kg/h). Both, the high- and low-pressure steam can be used as motive and entrained vapour, respectively, in a train of four steam ejectors coupled to the PSA MED plant, simulating the behaviour of a MED plant working with thermal vapour compression (TVC-MED). The steam ejectors can work in a wide range of pressure conditions for the motive steam (40 - 6 bar; 4 - 2 bar), which also makes this test bed useful for the characterization of such kind of devices. The low-pressure steam can also be condensed through two conventional air condensers without passing by the steam ejectors, with the aim of allowing research in CSP cooling topics. The flexibility of the test facility also allows the on-site evaluation of innovative dry coolers prototypes for their comparison with respect to the conventional air condensers currently available at the market.

(a)

(b)

Figure 29. View of the outside of the CSP+D test bed building with the air coolers (a) and partial view of the interior of the CSP+D test bench (b).

2.7.2.2 NEP: The facility for Polygeneration Applications

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

The purpose of this facility is the preliminary study of the behaviour of a parabolic trough solar field of small concentration ratio, the determination of its feasibility as a heat source in polygeneration schemes, in particular in CSP+D requiring temperatures around 200°C. The collector selected was the Polytrough 1200 prototype by NEP Solar. It has a production of 15.8 kW per module (0.55 kW/m^2) under nominal conditions, with a mean collector temperature of 200°C, and efficiency over 55% in the range of 120-220°C (for 1000 W/m^2 of direct normal irradiance).

The field is configured with eight collectors placed in 4 parallel rows, with 2 collectors in series within each row. This configuration supplies 125 kW of thermal energy. The temperature of the thermal oil can be up to 220°C, so different schemes for making use of the thermal energy for polygeneration can be evaluated.

Currently the solar field is also being used to generate steam for supplying the double-effect absorption heat pump coupled to the PSA MED plant.

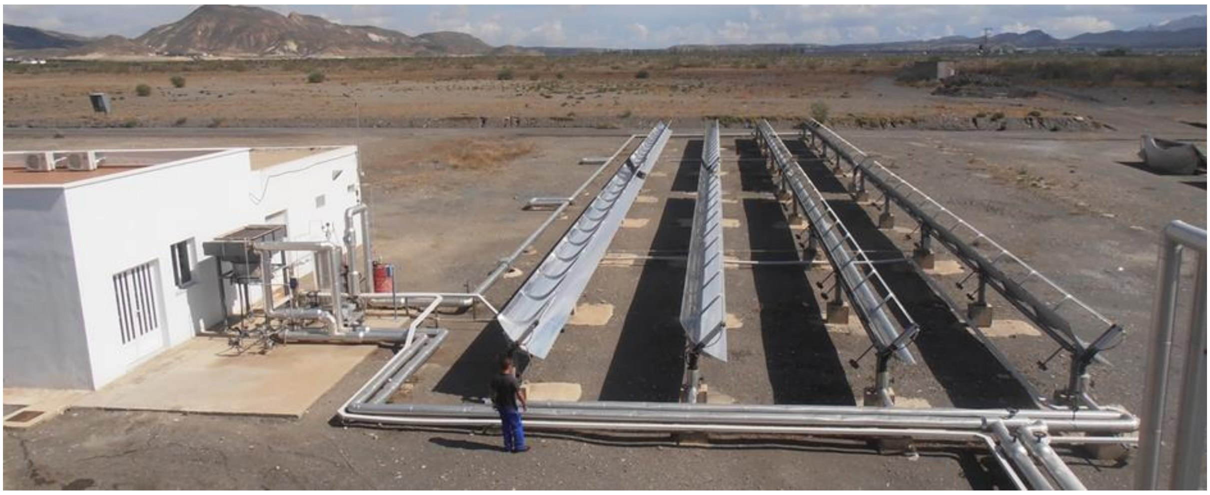


Figure 30. NEP PolyTrough 1200 solar field.

2.7.3 Membrane Desalination Test Facilities

2.7.3.1 Test-Bed for Solar Membrane Distillation Applications at Pilot-Scale

The installation is designed for evaluating solar thermal desalination applications. There are two solar fields of flat-plate collectors available: one of 20 m^2 with two parallel rows of five collectors in series (Solaris CP1 Nova, by Solaris, Spain), and another one of 40 m^2 with four large-aperture collectors in parallel (LBM 10HTF, by Wagner Solar, Spain). Both fields are connected to water storages of 1500 liters acting as heat buffers for thermal regulation and storage, and have a distribution system which enables simultaneous connection of several units. The test-beds allow for a stationary heat supply using the thermal heat storage or for direct supply of solar energy without buffering. The installation is fully automated and monitored (temperatures and flows) and allows for heat flow regulation. The maximum thermal power is 7 kW_{th} in one case and 14 kW_{th} in the other, and hot water can be supplied with temperature up to about 90°C.

The installation has a separate water circuit that can be used for cooling (about 3.5 kW_{th}) in the desalination units and as a device for supplying simulated seawater, with the possibility of working in open or closed loop. In the latter case, both the distillate and brine flows are collected and mixed together to be fed again into the desalination units after passing through a heat dissipation system. The installation currently operates with Membrane Distillation modules and has a wide range of different commercial and pre-commercial units from different commercial manufacturers. The list of MD modules that have been evaluated or are under evaluation is:

1) Plate and frame air-gap (AG) MD commercial modules from Scarab (total membrane area 2.8 m^2).

2) Two plate and frame permeate-gap (PG) MD prototypes from Keppel Seghers (both with total membrane area 9 m^2), a compact one (M33) and another which is split in three separate modules connected in series for higher energy recovery (PT5).

3) Spiral-wound PGMD commercial modules Oryx 150 from Solar Spring (10 m^2).

4) Two spiral-wound AGMD modules from Aquastill with membrane areas of 7 m^2 and 24 m^2 each.

5) WTS-40A and WTS-40B units from Aquaver, based on multi-effect vacuum membrane

distillation technology using modules fabricated by Memsys (5.76 m^2 and 6.4 m^2 total membrane area respectively).

(a) (b)

Figure 31. Internal (a) and external (b) views of the Membrane Distillation experimental test bed within the PSA low-temperature solar thermal desalination facility.

2.7.3.2 Bench-Scale Unit for Testing Membrane Distillation applications in Air-Gap, Permeate-Gap and Direct Contact Configurations

The installation consists of a test-bed with a small plate and frame module (Figure 32)that can be used for evaluating direct-contact, air-gap or permeate-gap membrane distillation. The module is made of polypropylene and designed so that the membrane can be replaced very easily. The module has a condensation plate on the cold side to operate on air-gap configuration, but it can be closed at the bottom to operate on permeate-gap keeping the distillate inside the gap or spared to operate on direct-contact mode. The effective membrane surface is 250 cm^2.

The installation has two separate hydraulic circuits, one on the hot side and another on the cold side. On the hot side, there is a tank of 80 liters equipped with an electric heater (3 kW) controlled by a thermostat (90°C maximum), and circulation is made from the storage and the feed side of the module by a centrifugal pump. On the cold side there is a chiller (800 W at 20°C) controlled by temperature and water is circulated between a cold storage of 80 liters and the module. The circuit is heat insulated and fully monitored for temperature, flow rate and pressure sensors, connected to a SCADA system.

2.7.3.3 Bench-Scale Unit for Flat Sheet Membrane Distillation Testing

The facility is a high precision laboratory grade research equipment (Figure 33) designed for testing fundamental and feasibility test trials on membrane distillation. It possesses the following unique features that are essential for representative and scalable results:

1) Cell format with representative flow distribution. The cell size is sufficient for flow distribution and regime to be applicable to full-scale MD technology.

2) Adjustable MD channel configuration to all channel variants (PGMD, AGMD, DCMD, VMD, VAGMD).

3) Temperature precision of 0.5°C.

4) Driving force temperature difference controllable.

5) Fully automated control system and large range of possible parameter settings by touch screen PLC.

6) Practical A4 format for membrane and condenser foil materials.

Figure 32. Bench-scale unit for testing membranes on isobaric MD.

Figure 33. Bench-scale unit for testing MD with flat-sheet membranes.

2.7.3.4 Bench-Scale Unit for Tests with 2-stage Forward Osmosis and Pressure-Retarded Osmosis

The installation consists of a test-bed with two small plate and frame modules of forward osmosis (FO) which can be connected in series or in parallel. There is, therefore, one pump for the draw solution and two for the feed solution, each with variable flow and flow-rate measurements. The hydraulic circuit has been modified so that the modules can be operated in pressure retarded osmosis (PRO) mode. For that purpose, steel pipes and a high-pressure pump (3 L/min; up to 17 bar) are installed in the draw side, and cells with operational pressure up to 15 bar are used. The cells have each a total effective membrane area of 100 cm^2, and hydraulic channels in zig-zag 4 mm wide and 2 mm deep. The system uses one container for the draw solution and two for the feed solutions, each placed on a balance in order to measure changes in the mass flow rates of the draw solution and the feed solution of each cell. The containers have an automatic dosing system to keep the salinities constant. The system has two conductivity meters for low salinity and one for high salinity, as well as pressure gauges in each line and temperature readings.

2.7.3.5 Pilot Plant for Studying Combinations of Forward Osmosis and Reverse Osmosis

The plant has three different units that can be coupled in different ways between them: (i) a forward osmosis; (ii) reverse osmosis; (iii) microfiltration. The forward osmosis (FO) unit uses a 4” spiral-wound Cellulose Triacetate (CTA) membrane with eleven membrane leaves of 1.5 m^2 surface each, supplied by HTI. The nominal flow rate is 3.6 m^3/h. The reverse osmosis (RO) unit has 4 vessels that can be connected in series or in parallel, each of which hosting 4 membranes. The nominal flow rate is 3 m^3/h, and the pumping system is able to work at different pressures up to a maximum of 80 bar. The unit is designed so that SWRO, BWRO or NF membranes can be used. Finally, there is a MF unit with 3 m^3/h nominal flow rate. The installation is completely monitored with pressure sensors, conductivity- and flow-meters, and is designed in a flexible way regarding the interconnection of the units, so that FO can be used as a pre-treatment for RO, or NF can be used in combination with FO, and even the FO can be used in PRO mode using the pumping system of the RO unit.

Figure 34. Test bed for FO-RO combination research.

2.8 Experimental Solar Detoxification and Disinfection Installations

The main facilities related with solar water purification are listed and described below:

- Solar CPC (compound parabolic collector) pilot plants.
- Solar simulators.
- Pilot plants for biological treatment.
- Ozonation pilot plant.
- Nanofiltration pilot plant.
- UVC-pilot plant.
- Test facility for photocatalytic production of hydrogen based on solar energy.
- Wet Air oxidation pilot plant.
- Experimental culture camera.

2.8.1 Solar CPC pilot plants

Since 1994 several CPC pilot plants have been installed at PSA facilities (Figure 35). Basically, the solar pilot plants are built by modules which can be connected in series. Each module consists of a number of photo-reactors placed on the focus of an anodized aluminum mirror with Compound Parabollic Collector (CPC) shape to optimize solar photons collection in the photo-reactor tube. The modules are place on a platform titled at 37° from the horizontal to maximize the global solar collection of photons through the year. In addition, the pilot plants may be equipped with added systems for different purposes, for example: sedimentation tanks (for catalyst recovery), heating and cooling systems for temperature control during the experiments, coupling with other treatment technologies like bio-treatment, ozonation, etc. A summarize of the already installed solar CPC reactors is shown in Table 1.

Table 1. Summarize of CPC pilot plants at PSA facilities.

Year	CPC (m^2)	Total/illuminated volume (L)	Flow or static	Tube diameter (mm)	Added systems/Characteristics
1994	3x3	250/108	Flow	50	
2002	15	300	Flow	32	
2004 (CADOX)	4	75/40	Flow	50	- 50L ozonation system - Biological water treatment system - Monitoring (pH, T, ORP, O_2, flow rate, H_2O_2, O_3), control (pH, T, flow rate)
2007 (SOLEX)	3.08(x2)	40/22	Flow	32	- Twin prototypes - Plexiglass screen - Monitoring dissolved O_2 and temperature - Specially developed for photo-Fenton applications
2008 (FIT)	4.5	60/45	Flow	50	- Monitoring (pH, T, O_2, flow rate) and control (T (20-55°C), flow rate). - 100 L sedimentation tank for catalyst separation
2010 (FIT-2)	4.5	60/45	Flow	50	- -Monitoring (pH, T, O_2, flow rate) and control (T (20-55°C), O_2, flow rate) - -Sedimentation tank
2011 (HIDRO-CPC)	2.1	25/14.24	Flow	32	- -Coupled with H_2 generation pilot plant
2011 (CPC25)	1	25/11.25	Flow	50	
2013 (ELECTROX)	2	40/25	Flow	50	- Coupled with electro-photo-Fenton plant
2013 (NOVO75)	2	74/68.2	Flow	75	- Monitoring (pH, T, O_2, flow rate) and control (T, O_2, flow rate)
2013 (CPC25)	1	25/11.25	Flow or static	50	- Variable volume, versatile for different volume of water
2013 (SODIS-CPC)	0.58(x2)	25/25	static	200	- Low cost, no recirculation system
2016 (NOVO 75 V1.0)	2.03 (x2)	34 or 53	Flow or static	75	- Two module of collectors: CPC versus U-mirror type alternatively used - Tubes installed in vertical position - Air injection in tubes - Monitoring (pH, T, O_2, flow rate) and control (T, O_2, flow rate) - - Automatic control system for filling the system accordingly to incident energy - - Solar panel for water heating

As mentioned in table 1, CADOX photoreactor was hooked up to a 50L-ozonation system with an ozone production of up to 15 g O_3/h. It is completely monitored (pH, T, ORP, O_2, flow rate, H_2O_2, O_3) and controlled (pH, T, flow rate) by computer. Besides, and connected to this photo-reactor, there is a biological water treatment system consisting of three tanks: a 165 L conical tank for wastewater conditioning before treatment, a 100 L conical recirculation tank and a 170 L flat-bottom fixed-bed aerobic biological reactor. The fixed-bed reactor is filled with Pall®Ring polypropylene supports that take up 90-95 L and can be colonized by active sludge from a MWWTP.

Figure 35. View of several CPC photo-reactors for purification of water.

A 2m² CPC collector with 10 borosilicate glass tubes (50 mm diameter), illuminated volume of 25 L and a total volume of 40 L is connected to four electrocells for experimental research on electro-photo-Fenton processes for decontamination and disinfection of water.

In 2016, a new pilot plant with two modules of 2 m²-collectors with different mirror shape (CPC and U mirror type) has been installed at PSA (Figure 37). It is composed by a feeding polypropylene tank of 192 L of total volume and a preparation tank of 92.5 L, connected by gravity to the CPC and U type photoreactors. The last presents 1.98 m² of irradiated surface with a recommended operating volume of 53 L. The whole pilot plant is equipped and automatically controlled by a UVA solar sensor. In addition, the pilot plant is equipped with a solar water heating panel which permits to increase the temperature of water prior to discharge it in the photoreactors.

Figure 36. Electro-Fenton pilot plant coupled with a 2 m² CPC (ELECTROX).

Figure 37. View of new CPC and U-type photoreactors (NOVA 75 V 1.0).

2.8.2 Solar simulators

Along with these pilot-plant facilities, there are two solar simulators provided with xenon lamps for small-scale water decontamination and disinfection experiments. In both systems, the radiation intensity can be modified and monitored. One of the solar simulator XLS+ contains a UV filter (Suprax) with wavelength limitation to 290 nm simulating external solar radiation. Temperature can be also modified and controlled in both systems by a cooling system (SUNCOOL) (Figure 38).

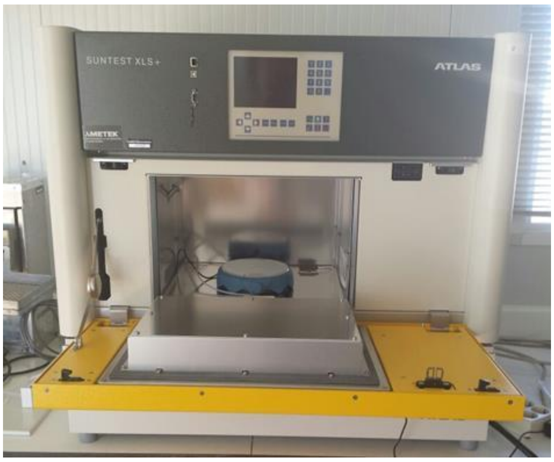


Figure 38. Solar simulator SUNTEST XLS+.

2.8.3 Ozonation pilot plant

The ozonation system has a contact column reactor with total volume of 20L (minimum operation volume of 8L), reagents dosing system and pH automatic control. The pilot plant is equipped with pH and redox sensors, inserted in the recirculation line. In 2016, new instrumentation has been added to the ozonation pilot plant: (i) equipment for humidity elimination in the ozone gas outlet (Figure 39.a); (ii) Thermo-catalytic ozone destructor (Figure 39.b); (iii) dissolved ozone sensor (Figure 39.c). This ozonation system works in batch mode allowing its combination with other technologies such as CPC photoreactors and the UV pilot plant.

(a) (b) (c)

Figure 39. a) Equipment for humidity elimination in ozone gas outlet; b) Thermo-catalytic ozone destructor; (c) Dissolved ozone sensor.

2.8.4 Nanofiltration pilot plant

The nanofiltration (NF) system has two working modes, in series and in parallel. The basic system consisted of two FILMTEC NF90-2540 membranes, connected in parallel, with a total surface area of 5.2 m^2. These polyamide thin-film composite membranes work at a maximum temperature of 45°C, a maximum pressure of 41 bar and a maximum flow rate of 1.4 m^3 h^{-1}, whereas operation pH range is 2-11. A third membrane was installed later and so the filtration total surface area was increased to 7.8 m^2. pH control permits the cleanings and to evaluate the separation of different compounds in the membranes depending on the pH value. A dosing pump is also included for studying the effect of biocide addition. It has a feeding tank of 400 L (Figure 40.a). In 2016 the nanofiltration system has been automatized by including electro-valves and automatic acquisition of the signals from the different instruments (flow, pressure, temperature, etc.) with the final aim of controlling by a computer (software Labview was employed, Figure 40.b) the generation of permeate and concentrate flow rates.

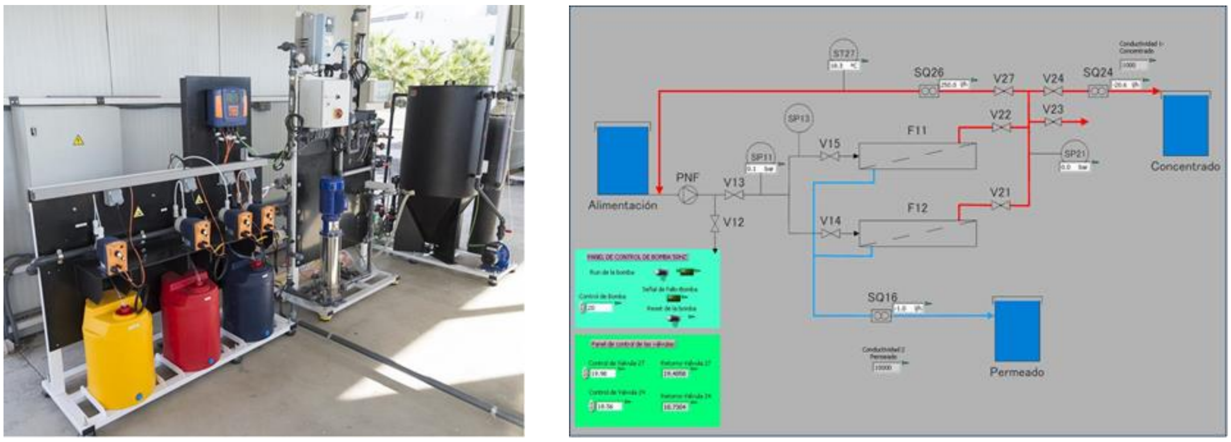


Figure 40. a) Nanofiltration pilot plant photo; b) New lavbiew interface for control and automatic operation of the pilot plant.

2.8.5 UVC-H_2O_2 pilot plant

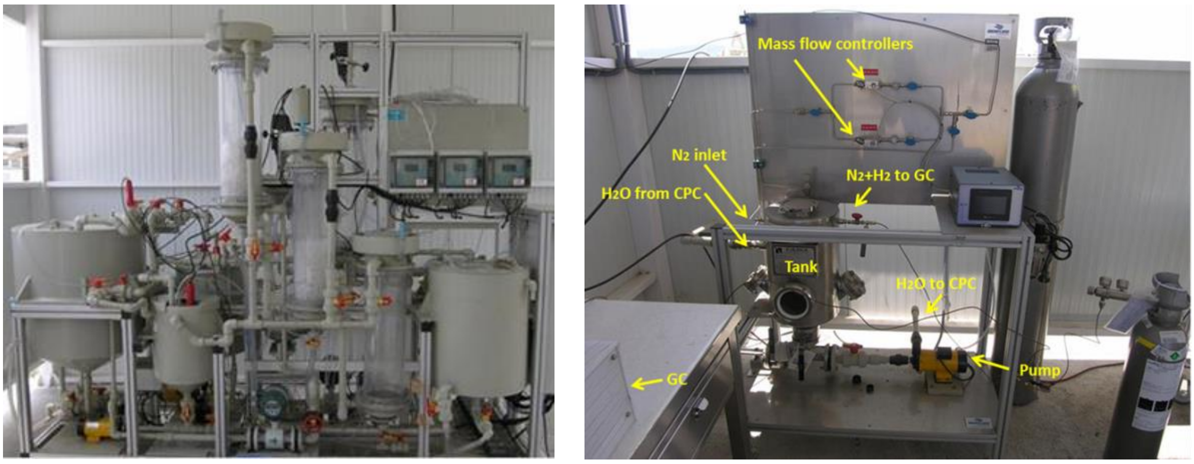
Ultraviolet (UV) pilot plant was designed to treat and disinfect water for purposes and research and comparison with the solar technologies. This plant consists of three UV-C lamps (max. flow rate 25 m^3 h^{-1}, 254 nm peak wavelength, 400 Jm^{-2} max. power) connected in series, with the flexible configurations for single lamp, two or three lamps in recirculating batch mode or continuous flow mode. Lamps power and flow rate can be regulated according to the needs of the water. Furthermore, the plant is equipped with a dosage system of reactants (acid, base and hydrogen peroxide). The total volume per batch of this plant is 200-250 L, with illuminated volume of 5.5 L per lamp module. The system is equipped with pH and dissolved oxygen sensors in-line and connected to a PROMINENT controller for automatic data acquisition of both parameters (**¡Error! No se encuentra el origen de la referencia.**).

2.8.6 Biological pilot plant

A biological pilot plant with a double depuration system (Figure 41.a) has an Immobilized Biomass Reactor (IBR) system with a total volume of 60-L: three IBRs of 20-L each one; and a Sequencing Batch Reactor (SBR) system: two SBRs 20-L each one. These modules use the same reception tank (200L) as well as the pH and oxygen dissolved control systems and electronic equipment. In addition, this plant can be operated in continuous or in batch mode. For the batch operation, two conical decantation tanks (40-L) are used. Data acquisition of three MULTIMETERS (M44 CRISON) is done by means of programmable relays and the main parameters are monitored by a SCADA system

2.8.7 Photocatalytic generation of hydrogen pilot plant

This plant is connected to a CPC photo-reactor for the simultaneous removal of organic contaminants contained in aqueous solutions and hydrogen generation. The pilot plant consists on a stainless steel tank with a total volume of 22 L, fitted with gas and liquid inlet and outlet and a sampling port. Two parallel mass flow controllers are used to control the desired N_2 gas flow into the reactor headspace during the filling step. The CPC photo-reactor coupled with this system was described above in table 1 (Figure 41.b).



(a) (b)

Figure 41. a) Biological pilot plant installed at PSA facilities. b) Solar pilot plant for photocatalytic generation of hydrogen.

2.8.8 Wet Air Oxidation pilot plant

A pilot plant designed and installed in 2016 as a harsh pre-treatment to reduce the complexity of industrial effluents and reaction time of a subsequent solar advanced oxidation process (AOP). This pilot plant operation allows different combinations of temperature and pressure, various proportions of oxygen and nitrogen, oxidants as peroxide and peroxymonosulfate before heating and/or pressurized the system, and the use of different metallic salts as catalyst. The Wet Air Oxidation pilot plant consists of a stainless steel reactor with a total volume of 1000 mL, a magnetic stirrer, a breakup disk, liquid reagents injector prepared to operate under 200 bar and a maximum temperature of 300°C, thermo-probe, pressure sensor (until 250 bar) and a cooling-heating jacket, all made of stainless steel. The Wet Air Oxidation pilot plant includes an automatic system of control and data acquisition of diverse parameters such as pressure, temperature, reagents dosses and mixture.

2.8.9 Solar UVA monitoring equipment

UV and global solar radiation data monitoring and storage system is composed by different pyranometers (**¡Error! No se encuentra el origen de la referencia.**), including global solar radiation in the range of 310 – 2800 nm (Kipp and Zonen CMP-6 with sensitivity 5 – 20 V W^{-1} m^{-2}, max. value: 2000 W m^{-2}), and the global UVA radiation in the range 300 – 400 nm (Kipp and Zonen CUV-5 with sensitivity 1 mV W^{-1} m^{-2}, max. value: 100 W m^{-2}). Besides this, a spectral photometer with double channel was installed to monitor the solar spectral irradiance at the location of the solar tests. This equipment (AVANTES) has UVA sensors and filters to measure in the whole spectral range of 200 – 1100 nm.

2.8.10 Cultivation chamber

The culture crop chamber of 30 m^2 is used for treated wastewater re-use experience since 2014 (Figure 42). This controlled chamber is made of polycarbonate of 10 mm thick to avoid ultraviolet radiation supported by white rolled steel (Sendzimir). The shoulder height is 2.5 m with a roof slope of 40%. The camera consists of 4 individual areas of 3x2.5 m^2. Each area is equipped with temperature and humidity sensors, and a cooling and heating system. The crop camera is equipped with a global solar radiometer for measuring the incident solar radiation. So, through this probe an opaque plastic cover located on the top of the camera can be automatically fold and re-fold to reduce the incidence of irradiance inside the crop camera. Finally, the roof slope of each area acts as windows which can be automatically opened and closed to favour the airflow inside each area and enhance the efficiency of the temperature control. The measured of sensors (temperature, humidity and solar radiation) and temperature control of each individually area (by the cooling and heating system, windows and top plastic cover) is made using the Ambitrol® software which permits to keep a comfortable temperature for crops approximately to 25°C during the different seasons.

Figure 42. Cultivation chamber for wastewater crops irrigation reuse at PSA facilities.

2.9 Experimental Installations for the Evaluation of the Energy Efficiency in Building

The Building Component Energy Test Laboratory (LECE), one of the facilities at the *Plataforma Solar de Almería* (PSA), is part of the Energy Efficiency in Building R&D Unit (UiE3) in the CIEMAT Energy Department's Renewable Energies Division. The UiE3 carries out R&D in integral energy analysis of buildings, integrating passive and active solar thermal systems to reduce the heating and cooling demand. This unit is organised in two lines of research focusing on Energy Analysis in Urban Environments, and Experimental Energy Analysis of Buildings and Building Components. The test facilities described are under the last of these. They integrate several devices with different capabilities as summarised below:

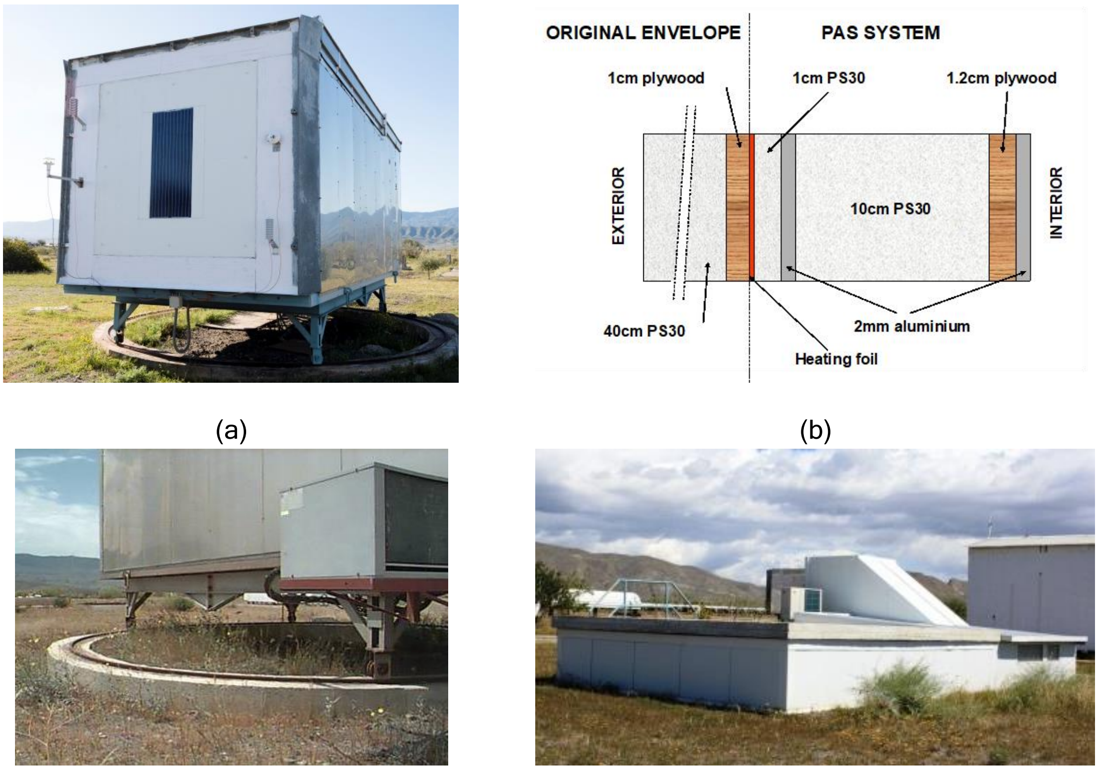
1) Test cells: The LECE has five test cells, each of them made up of a high-thermal-insulation test room and an auxiliary room. The test room's original south wall can be exchanged for a new wall to be tested. This makes experimental characterisation of any conventional or new building envelope possible.

2) PASLINK Test cell: The Spanish PASLINK test cell incorporates the Pseudo-Adiabatic Shell

(PAS) Concept. This system detects heat flux through the test cell envelope by means of a thermopile system, and compensates it by a heating foil device. The inner surface in the test room consists of an aluminium sheet which makes it uniform to avoid thermal bridging. It also has a removable roof that enables horizontal components to be tested. The cell is installed on a rotating device for testing in different orientations.

3) CETeB Test cell: This is a new test cell for roofs. The design of this test cell solves some practical aspects related to roof testing, such as accessibility and structural resistance. An underground test room allowing easy access to the test component is used for this.

4) Solar Chimney: This was constructed for empirical modelling experiments and validating theoretical models. Its absorber wall is 4.5 m high, 1.0 m wide and 0.15 m thick, with a 0.3-m-deep air channel and 0.004-m-thick glass cover. A louvered panel in the chimney air outlet protects it from rodents and birds. The air inlet is protected by a plywood box to avoid high turbulences from wind. The inlet air flow is collimated by a laminated array so that the speed component is in the x-direction only.



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

Figure 43. (a) CIEMAT's PASLINK test cell carrying out a thermal test of a PV module, (b) Schematic drawing of the PAS system, (c) Detail of the rotating device, (d) Exterior of the CETeB Test cell.

5) Single-zone building: This is a small 31.83 m^2 by 3.65 m high simple single-zone building built in an area free of other buildings or obstacles around it that could shade it except for a twin building located 2 m from its east wall. Its simplicity facilitates detailed, exhaustive monitoring and setting specific air conditioning sequences that simplify its analysis for in-depth development and improving energy evaluation methodologies for experimental buildings.

6) The PSE ARFRISOL C-DdIs are fully instrumented Energy Research Demonstrator Office Building Prototypes which are in use and monitored continuously by a data acquisition system. The CIEMAT owns 3 of 5 of these "Contenedores Demostradores de Investigación, C-DdIs"

(Research Energy Demonstrators Building Prototypes), built under the ARFRISOL Project. Each of them is an office building with approximately 1000 m^2 built area. One of them is also at the PSA and the others in different locations representative of Spanish climates. These C-DdIs are designed to minimize energy consumption by heating and air-conditioning, whilst maintaining optimal comfort levels. They therefore include passive energy saving strategies based on architectural and construction design, have active solar systems that supply most of the energy demand (already low), and finally, conventional auxiliary systems to supply the very low demand that cannot be supplied with solar energy, using renewable energy resources, such as biomass insofar as possible.

These prototypes were built for high-quality measurements recorded during monitoring to support research activities on thermal comfort, building energy evaluation and both active and passive systems integrated in the buildings.

(a) (b) (c)

Figure 44. (a) Solar Chimney. Configuration including Phase Change Material tiles, (b) Reference single-zone building, (c) ARFRISOL Building Prototype in use.

3 Laboratories

3.1 Laboratory for the geometrical characterization of solar concentrators - GeoLab

The concentrators used in solar thermal systems (heliostats, parabolic-trough collectors, parabolic dishes, Fresnel lenses, etc.) require high precision concentration of the solar radiation for it to be suitable and most of it incident on the receiver component (receiver tubes in parabolic-trough collectors, receivers in tower systems, parabolic dishes, Fresnel lenses, etc.). The laboratory of the Concentrating Solar Systems Unit has a specific activity line for the geometric characterization of these concentrators. Photogrammetry is used to quantify the optical quality of:

- Parabolic-trough collector facets
- Parabolic-trough collector modules
- Heliostat facets
- Heliostats
- Fresnel lenses and reflectors
- Parabolic dishes
- Structural frames
- …

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

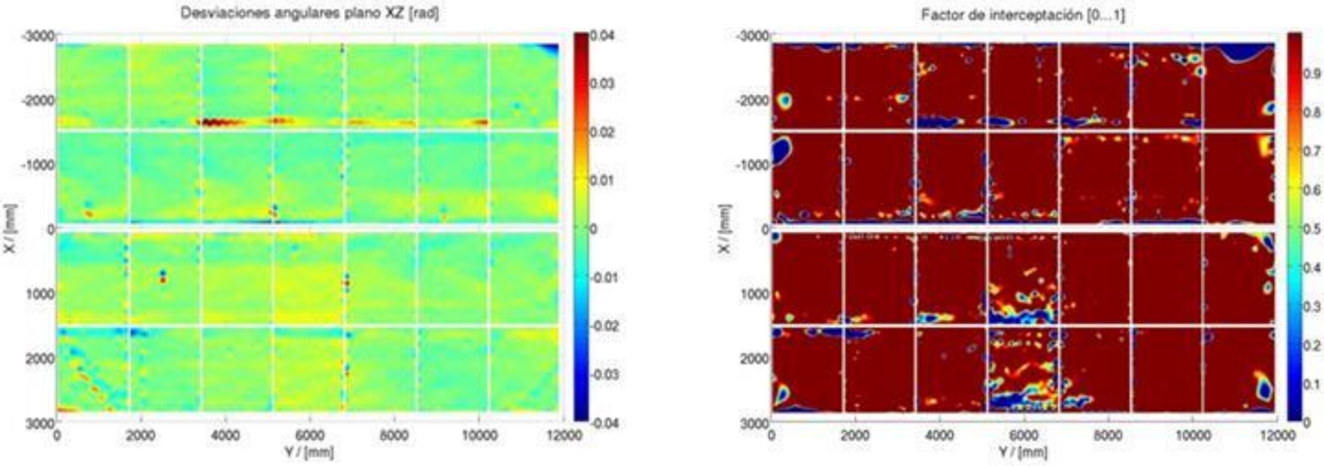
The equipment allocated to this activity at PSA is composed of:

- CANON EOS5D MarkII 22-Mpixel Camera.
- CANON EF 20mm f/2.8 USM and CANON EF 24mm f/2.8 USM lenses.
- Photomodeler Scanner 2017 photogrammetry software.
- LEYCA P20 laser scanner

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

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

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



(a) (b)

Figure 45. Angular deviations (a) and intercept factor (b) of a parabolic-trough collector module analysed by photogrammetry.

3.2 Laboratory of optical characterization and solar reflector durability analysis - OPAC

The PSA optical characterization and solar reflector durability analysis laboratory, which is the result of a joint collaborative project between CIEMAT and DLR, has the necessary equipment to completely characterize the materials used as reflectors in solar concentrating systems. This laboratory allow the characteristic optical parameters of solar reflectors and their possible deterioration to be determined. The following equipment is available in the laboratory of optical characterization of solar reflectors (see Figure 46 a):

- Three portable specular reflectometers, Devices and Services Model 15R-USB, for measuring specular reflectance at 660 nm at different aperture angles (3.5, 7.5, 12.5 and 23 mrad).
- One portable specular reflectometer, Devices and Services model MWR, for measuring specular reflectance at 460, 550, 650 and 720 nm and at different aperture angles (2.3, 3.5, 7.5, 12.5 and 23 mrad).
- Reflectometer prototype for measuring specular reflectance in a 5 cm diameter with spatial resolution of 10 pixel/mm, which measures at various wavelengths and aperture angles (model SR^2, designed and patented by DLR).
- Perkin Elmer Lambda 1050 spectrophotometer, with 150-mm integrating sphere and specular reflectance accessory with 0 to 68° incidence angles (URA).
- Nikon D3 camera and 90 cm Cubalite kit for photos of specular surfaces without parasitic reflections.
- Zeiss Axio microscope model CSM 700 (with magnifications of 5, 10, 20, 50 and 100) for finding the profiles and roughness of highly reflective surfaces.
- Hitachi S3400 electronic scan microscope (SEM) with EDX analysis.
- Parstat 4000 impedance system to analyse the corrosion of reflector materials.
- General Purpose Optical bench as accessory for the Perkin Elmer Lambda 1050 spectrophotometer with advanced features for mounting optical devices for the development of new measurement instruments.

- Attension Theta 200 Basic tensiometer for static and dynamic contact angle assessment, which is a key parameter to study the performance of the anti-soiling coatings applied to solar reflectors and receiver tubes.

The solar reflector durability analysis laboratory is designed for accelerated ageing tests of these materials with the purpose of predicting in a short time, the behaviour of these materials during their useful lifetime (see Figure 46 b). To do this, the environmental variables producing degradation of solar reflectors when they are exposed to outdoor conditions are applied in a controlled manner, both separately and in combination. The following equipment is available for these accelerated ageing tests:

- ATLAS SC340MH weathering chamber for temperature (from -40 to+120°C), humidity (from 10 to 90%), solar radiation (from 280 to 3000 nm) and rainfall of 340L.
- Vötsch VSC450 salt spray chamber with temperatures from 10 to 50°C (450L).
- Erichsen 608/1000L salt spray chamber with temperatures from 10 to 50°C.
- Two ATLAS UV-Test radiation chambers where UV light (with a peak at 340°nm), condensation and temperature can be applied. One of the chambers also includes rain simulation.
- Hönle UVA Cube Ultraviolet radiation chamber.
- KÖHLER HK300M acid rain chamber, 300 L and temperatures up to 70ºC and humidity up to 100%, to apply the Kesternich test.
- SC100 heatable water bath, to perform the Machu test, according to the Qualitest guideline.
- Vöstch VCC3 0034 weathering chamber to test the material resistance against corrosive gasses (335L, see Fig. X2).
- Ineltec CKEST 300 test chamber for humidity and condensation testing with temperatures up to 70°C (300L).
- Memmert HCP108 weathering chamber to apply humidity (20-95 %) and temperature (20-90°C with humidity and 20-160 °C without humidity).
- Two Nabertherm LT 24/12 and LT 40/12 Muffle Furnaces.
- Control Técnica/ITS GmbH sandstorm chamber with wind speeds up to 30 m/s and dust concentrations up to 2.5 g/m³.
- Erichsen 494 cleaning abrasion device to test the degradation due to the cleaning brushes, with several cleaning accessories.
- Taber 5750 linear abraser to check the materials resistance against the abrasion.
- Lumakin A-29 cross-cut tester to analyze the possible detachment of the paint layers.
- Several devices for thermal cycles specially designed at the PSA.

Along with the equipment installed indoor in the Lab, there are a series of outdoor test benches for exposing materials to outdoor weather conditions and comparing their degradation with those found in the accelerated ageing tests, to study the effectiveness of special coatings, to optimize the cleaning strategy and to analyse the soiling rate. In addition, two heliostat test benches were recently installed, one to test the influence of blocking on the coatings lifetime and another one to accelerate the reflectors degradation due to UV radiation under outdoor weather conditions. Finally, the laboratory is equipped with accessories necessary for their proper use, such as precision scales, thermo magnetic stirrer, drier, ultrasonic bath for sample cleaning, tools for reflector samples preparation (cutting and polishing), safety cabinets, instrumentation for measuring pH, conductivity, oxygen, etc.

(a) (b)

Figure 46. OPAC solar reflector optical characterization lab (a) and durability analysis lab (b)

3.3 Radiometry laboratory – RadLab

The activity line devoted to Radiometry came up of the need to verify measurement of highly important radiometric magnitudes associated with solar concentration. These magnitudes are solar irradiance ("flux" in the jargon of solar concentration) and surface temperature of materials (detection by IR). At the PSA different systems are used to measure high solar irradiances on large surfaces. The basic element in these systems is the radiometer, whose measurement of the power of solar radiation incident on the solar receiver aperture depends on its proper use. The measurement of this magnitude is fundamental for determining the efficiency of receiver prototypes evaluated at the PSA and for defining the design of future central receiver solar power plants. Calibration of radiometers is performed in a specific furnace for this purpose.

Figure 47. View of the PSA Radiometry equipment.

The calibration of the reference radiometer is radiant calibration referenced to blackbody simulators as source standards. The calibration of the reference radiometer is transferred to the commercial sensors by comparison in a calibration furnace that uses a graphite plate that radiates homogenously and symmetrically when an electrical current passes through it. The calibration constant obtained with this method translates voltage to irradiance on the front face of the sensor. The accuracy of gages calibrated in this way is within ±3% with repeatability of ±1%. A black body can be used as a source of thermal radiation for reference and calibration of IR devices (infrared cameras and pyrometers) that use thermal radiation as the means of determining the temperature of a certain surface.

The equipment associated to this activity also includes three black bodies used as references for calibrating IR sensors devoted to temperature measurement with guaranteed traceability between 0 and 1700°C:

- The MIKRON 330 black body is a cylindrical cavity which can provide any temperature from 300 to 1700°C accurate to ±0.25% and a resolution of 1°C. Its emissivity is 0.99 in a 25-mm-diameter aperture.
- The MIKRON M305 black body is a spherical cavity that can supply any temperature between 100 and 1000°C accurate to ±0.25% and with a resolution of 1°C. Its emissivity is 0.995 in a 25-mm-dia. aperture.
- The MIKRON M340 black body is a flat cavity and can provide any temperature from 0 to 150°C accurate to ±0.2°C and a resolution of 0.1°C. Its emissivity is 0.99 in a 51-mm-aperture.

These black bodies have a built-in PID control system and the temperature is checked by a high-precision platinum thermocouple.

Figure 48. IR sensor calibration using a black body.

3.4 Laboratory for the assessment of the durability and characterization of materials under concentrated solar radiation - MaterLab

This activity line of the laboratory is focused on the study and evaluation of how the concentrated solar radiation affects the performance and durability of materials. This is especially important for materials used for central receivers, thus requiring an accelerated ageing to study the durability of the most critical components of solar thermal power plants, not only absorbent materials, but also surface treatment and coatings that increase their absorptance. It is therefore necessary to find out and study the mechanisms of the physical degradation, fatigue and breakage of these materials at high temperatures under concentrated solar radiation.

The equipment associated to this activity is composed of devices located both indoor and outdoor. The indoor devices are devoted to the metallographic preparation and the analysis of test pieces treated with concentrated solar radiation and eventually thermal cycling for accelerated aging, and characterization of solar test by thermogravimetry. These devices are inside the Solar Furnaces control building and located in four rooms, every one of them dedicated to different kind of analyses:

- The Metallography Room
- The Microscopy Room

- The Thermogravimetry Room
- The Thermal Cycling Room

The lab's equipment located in these rooms is listed below:

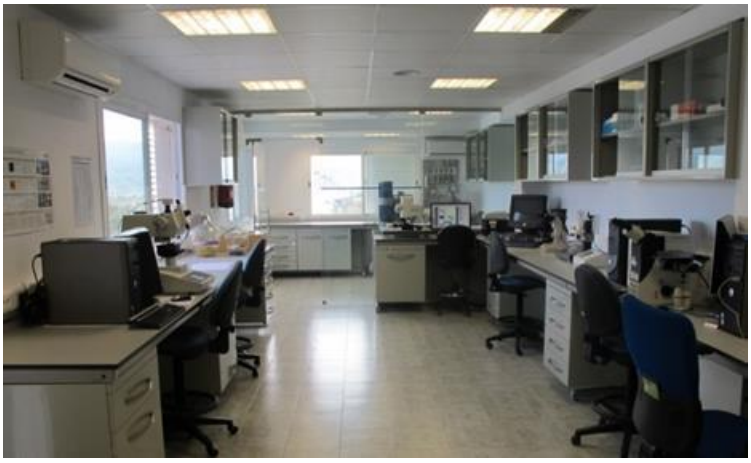
3.4.1 Metallography Room

- Automatic cut-off machine: Struers Secotom
- Manual cut-off machine: Remet TR60
- Mounting press: Struers Labopres-3
- Vacuum impregnation unit: Struers Epovac
- Polisher: Tegrapol-15 automatic with Tegradoser-5 dosing system
- Metallographic polisher 2 plates: LS1/LS2 (Remet)
- Grinder: Remet SM1000
- Ultrasonic bath: Selecta Ultrasons-H 75°C with heater
- Fume cupboards: Flores Valles VA 120 960 M-010-02
- Power Source programmable: Iso-Tech IPS 405 for electrochemical attack
- Analytical sieve shaker: Retsch AS 200 Control (Sieves: 20, 10, 5, 2.5 y 1.25 mm and 710, 630, 425, 315, 250, 160, 150, 90, 53 y 32 µm)
- Digital Camera with reproduction table

Figure 49. View of the Metallography Room in the Solar Furnaces building

3.4.2 Microscopy Room

- 3D Optical Surface Metrology System: Leica DCM 3D
- Leica DMI 5000 optical microscope with Leyca-IM50 image acquisition system and motorized table.
- Olympus optical microscope Union MC 85647.
- Struers micro hardness tester Duramin HMV-2 with visualization system and software micro Vickers hardness tester HMV-AD 3.12.
- Manual hardness tester
- Surface Finish Measuring Unit ZEISS Surfcom 480 with data processor
- Balance: Mettler E2001/MC max 60 kg
- Balance: Mettler Toledo classic max 320g / min 10mg



(a) (b)

Figure 50. View of a) the Microscopy Room, b) Thermogravimetric balance inside of its Room.

3.4.3 Thermogravimetry Room

- The thermogravimetric Balance SETSYS Evolution18 TGA, DTA, DSC (Temperature range ambient to 1750°C) equipped with a compact recirculating cooler (Julabo FC1600T) and a thermostatic line to 200°C, with a security box for tests in presence of H_2, and adapted to connect a controlled evaporator mixer and a MicroGC simultaneously to the equipment. This thermogravimetic Balance has different possibilities of tests:
    - Tests under pure Hydrogen atmosphere up to 1750°C
    - Tests under pure Oxygen atmosphere
    - Tests under H_2O steam with other gases simultaneously.
    - Tests under corrosive atmosphere up to 1000°C
- CEM System (Controlled evaporator mixer system) for steam supply.
- Fixed Gas Detector: Dräger Polytron SE Ex, with a control system Regard 1.

3.4.4 Thermal Cycling Room

It includes the instrumentation necessary for thermal cycling:

- two muffle furnaces,
- a high-temperature kilns,
- a weathering chamber,
- an air-cooled volumetric receiver test loop and associated instrumentation;
- optical and electronic microscopes,

The indoor devices located in the four rooms described above are complemented by an electronic microscope installed in its own room, which is shared by the AMES and SCS units, and with the following specifications.

- Scanning electronic microscope (SEM) - Hitachi, model S-3400N II, high/low vacuum, secondary electron image, backscattered electron image, cooling stage and magnification 5x to 300.000x.
- Energy dispersive x-ray spectrometer (EDS) Quantax 400

Besides, the SEM room also has environmental secondary electron detector (ESED), a critical point dryer and sputterer.

The outdoor equipment is composed of several solar-dish concentrators located close to the PSA solar furnaces building. These solar dishes are used for thermal cycling under real solar conditions, with very high solar flux (up to 1200 kW/m^2) and high temperatures (from 200°C to 1200°C) and are equipped with different test benches for volumetric and tube configuration testing.

3.5 Receivers testing and characterization for concentrating solar thermal systems - SRTLab

This activity line comprises both linear tube-type receivers and volumetric air receivers. The equipment associated to linear receivers is located at PSA and the two main test devices are: a) a test bench called HEATREC (see Figure 51, a), for measuring heat loss of single receiver tubes under indoor laboratory conditions, and b) an outdoor test bench called RESOL (see Figure 51, b), for measuring optical efficiency of single receiver tubes under natural solar radiation. Heat loss measurements can be done under vacuum conditions to avoid convection outside the glass tube, thus obtaining a more uniform temperature along the receiver section and looking for the heat loss by radiation. In addition, is possible to determine heat loss at different vacuum levels in the space between the metallic absorber tube and the glass envelope. The emissivity of the selective coating can be then inferred from these measures. The optical efficiency test is done by evaluating the slope of the temperature of a fluid (water) circulating inside the receiver tube vs the time during an interval of steady state solar radiation when heat losses are null. The optical efficiency is calculated from an energy balance of the system. The test provides in one measurement the receiver optical efficiency, i.e. the combned value of the absorptance and transmittance of the receiver tube.

(a)

(b)

Figure 51. View of the HEATREC test chamber to measure heat losses in solar receiver tubes (a) and RESOL test bench to measure receiver's optical efficiency (b).

HEATREC device lets to characterize heat losses of receiver tubes with inner diameter greater than 62 mm and tube length lower than 4.5 m. Measurements can be performed for absorber temperature ranging from 100°C to 500°C. The vacuum in the test chamber can be set up to around 10^{-2} mbar. RESOL is currently configured to measure standard receiver tubes for parabolic troughs, i.e. tubes 4060 mm-long and with absorber tube diameter of 70 mm.

Besides HEATREC and RESOL, the activity line devoted to linear receivers is equipped with tools and devices for proper manipulation and monitoring of receiver tubes.

3.6 Advanced Optical Coatings Laboratory - OCTALAB

This laboratory line is devoted to the development and complete study of new selective coatings for absorbent materials used in solar concentrating systems at medium and high temperature (up to

700°C), as well as for anti-reflective treatments for glass covers used in some receiver designs, such as receiver tubes in parabolic-trough collectors. The equipment devoted to this activity line is sufficient to characterize and evaluate coating developments, and to evaluate the behaviour of other treatments available on the market or developed by other public or private institutions. The equipment associated to this line may be also used for optical characterization of solar reflectors, thus complementing the equipment specifically devoted to the activity line devoted to testing and characterization of solar reflectors.

A summary of the equipment available for advanced optical coatings is given below:

- Perkin Elmer LAMBDA 950 Spectrophotometer (**¡Error! No se encuentra el origen de la referencia.**.a).
- Perkin-Elmer Frontier FTIR spectrophotometer equipped with a gold-coated integrated sphere manufactured by Pike (**¡Error! No se encuentra el origen de la referencia.**.b)
- *Portable Optosol absorber characterization equipment*: This equipment measures solar absorptance and thermal emittance of selective absorbers at 70°C, both on flat substrates and absorber tubes. The device for measuring absorptance has an integrating sphere with two detectors. For measuring emissivity, it has a semi-cylindrical tunnel which emits infrared radiation at 70°C.
- LEICA DM4 M optical microscopy with image acquisition system and software for image analysis (**¡Error! No se encuentra el origen de la referencia.**.c).
- QUV weathering chamber, Q-PANEL, for accelerated ageing tests (**¡Error! No se encuentra el origen de la referencia.**.d).
- BROOKFIELD LVDV-I+ Viscometer.
- BRUKER DektakXT stylus profilometer with optical camera and software for surface analysis (**¡Error! No se encuentra el origen de la referencia.**.e).
- KSV CAM200 goniometer for measuring contact angles (**¡Error! No se encuentra el origen de la referencia.**.f).
- Kilns. There are three kilns for thermal treatment:
  - 120x100x300 mm kiln with a maximal temperature of 1200°C.
  - Controlled atmosphere kiln with a maximal temperature of 800°C.
  - 500x400x600 mm forced convection kiln with a maximal temperature of 550°C.

3.7 Porous media laboratory for solar concentrating systems - POMELAB

The porous media laboratory located in CIEMAT-Moncloa (Madrid) comprises three main facilities, and some other techniques for the characterization of porous materials used for central receiver systems with air as heat transfer fluid.

1) Thermal characterization of volumetric absorbers

Its main component is a test bench designed for the thermal test of new volumetric absorbers and configurations and its ageing in steady and dynamic conditions. The main components installed in this test bench (Figure 52) are:

- A 4 kWe solar simulator made up of a Xenon lamp and a parabolic concentrator that can reach fluxes of up to 1500 kW/m^2;
- Receiver sub-system: with 24 K-type thermocouples, 2 surface thermocouples and an infrared camera;

- Helicoidal Air-Water Heat Exchanger sub-system: with 4 PT100 sensors, a water mass flow-rate measurement, a water pump and 2 surface thermocouples; and
- Extraction system: with 1 k-type thermocouple, 1 PT100 sensor, an air mass flow-rate measurement, and an air blower.

This test bench has the flexibility to study the extinction coefficient of different mediums, which can be used as a tool to approximate radiation analysis in semi-transparent mediums following the Bouger's law.

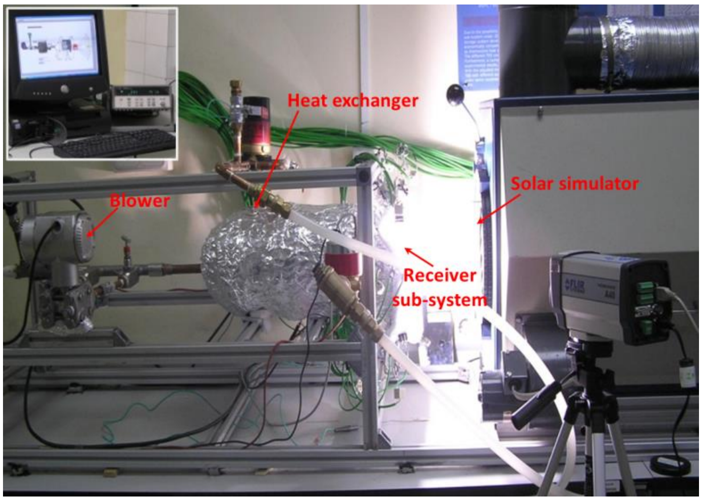


Figure 52. Test bench for volumetric receiver testing.

2) Thermal evaluation of porous beds in regenerative systems

Previous facility is complemented by an indoor facility to study thermal storage materials for high temperature using air as heat transfer fluid. This facility is composed of a thermocline storage test bench of about 0.1 m^3 as experimental loop for static and dynamic thermal characterization of porous beds. The system consists of:

- Six power heating resistor with a total power of 15000 watts electric energy able to heat air up to a target temperature (maximum temperature limited by the resistor is 1000°C) by means of a temperature controller.
- 35 K-type thermocouples units of 400 mm long are used to measure the material temperature. The behaviour of the tank is measured at 7 levels with 5 measurement each level.
- 35 T-type thermocouples units are used to measure the vessel outlet temperature in order to calculate thermal losses to the environment.
- The total power consumption is recorded, with a three-phase electrical measurement, to match the energy balances and the heat losses.

Moreover, the external surface temperature mapping is registered by a thermograph camera, which offers a complete image of the external chassis of the tank.

The two possible configurations of this test bench are (Figure 53):

- Static configuration: the experimental loop allows the characterization of effective thermo-physical parameters of the bed; material thermal conductivity, thermal losses, stored energy, etc. for different filler materials.

- Dynamic configuration: the experimental loop allows an agile characterization of the global storage at different working temperatures, filler materials, charges and discharges strategies, etc.

(a) (b)

Figure 53. Test bench for porous material characterization. Static configuration (a), dynamic configuration (b).

3) Measurement of the pressure drop up to 300°C

This facility measures the pressure difference across porous materials, such as volumetric absorbers or filler materials, for different fluid velocities. Moreover, it is able to measure the pressure difference at ambient temperature and for air temperatures up to 300°C.

Then the main properties described by the Forchheimer extension to Darcy's law are derived: viscous permeability coefficient and, inertial permeability coefficient. The main components are:

- Sodeca Blower with velocity control
- Hastinik ball valve of 1 ½".
- Airflow anemometer
- Nabertherm heating resistor
- Honeywell pressure difference-meter

Moreover, different techniques have been developed for the evaluation and measurement of several important geometric parameters of porous materials such as the porosity and specific surface area.

3.8 Laboratory for evaluation of materials and components for molten salt circuits - BES

Molten salts are becoming not only a standard thermal storage medium, but also a working fluid for central receiver solar plants. However, there are still open questions regarding the durability of components and materials currently available at the market for molten salt circuits. Keeping this in mind, a specific activity line was implemented in the laboratory of Concentrating Solar System Unit for this purpose. The equipment associated to this activity is installed indoor at PSA and it is composed of two test benches, BES-I and BES-II (Figure 54) especially designed and manufactured for:

1) The validation and checking of different types of valves for their use in molten salt loops. Various tests can be offered, such as leak test, validity for design conditions test, cold zone test, and packing life test.

2) The validation and checking of different types of pressure transmitters for their use in molten salt loops. Various tests can be offered, such as constant pressure test, and pressure variation test.

3) The validation of other components and auxiliary equipment (heat tracing, insulation, etc.) for their use in molten salt loops. Components with a nominal diameter from 2” up to 6” can be evaluated in these test benches.

These tests are carried out under real working conditions up to 600°C and 40 bar.

(a) (b)

Figure 54. Test benches BES-I (a) and BES-II (b) for evaluation of molten salt components.

3.9 Laboratory for the assessment of materials for thermal storage systems ATYCOS

The performance of phase change materials (PCM) for latent storage is usually evaluated with differential scanning calorimetry (DSC) or T-history techniques. Nevertheless, it is important to check their behaviour under service conditions in order to assure their feasibility as storage media. For this purpose, this laboratory has three set ups: HDR and AgH devices, where the PCM is tested in atmospheric air, and SUBMA where the PCM is tested in inert atmospheres. The main features of these devices are the following:

HDR:

- Small furnace under ambient air atmosphere
- Accurate control of heating/cooling rates
- Sample temperature monitoring
- Allows melting/freezing cycles up to 500ºC
- Subsequent cycles or cycles with stand-by periods
- Sample size: 2-5 g

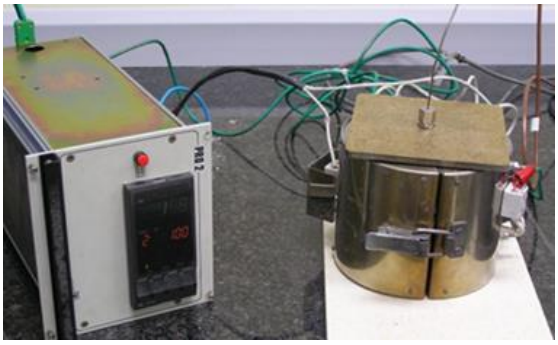


Figure 55. The HDR device.

SUBMA:

- Small closed device inside a furnace
- Allows tests under inert atmosphere (N2, Ar)
- Furnace temperature and gas flow control
- Sample temperature monitoring
- Allows melting/freezing cycles up to 500ºC
- Subsequent cycles or cycles with stand-by periods
- Sample size: 30-40 g

Figure 56. The SUBMA device.

AgH:

Furnace under ambient air atmosphere
Accurate control of heating and cooling
Allows melting/freezing cycles up to 350ºC
Subsequent cycles or cycles with stand-by periods
Sample size: 10-20g

Figure 57. The AgH device.

3.10 Laboratory for the characterization of materials for solar fuel production

Some specific activities are studied at the laboratory of the Solar Fuels Group to support at lab scale the PSA R&D activities related to solar hydrogen. These activities include the following topics: (1) Exploring new materials as candidates for thermochemical cycles and (2) Development of innovative solar reactors as fluidised bed reactors.

In the first category, some specific activities are foreseen, that include new materials that improve kinetics and reduce working temperatures of current materials used in thermochemical cycles. These materials are synthesized in the laboratory (or purchased on the market) and assayed for the thermochemical cycles under different reaction conditions.

For material characterization, a versatile electric furnace loop is available at CIEMAT's Solar Hydrogen Laboratory shown in Figure 58. The laboratory is equipped with the instrumentation necessary for evaluation of innovative processes for hydrogen production. Horizontal tubular furnace: high-temperature kiln with maximum operating temperature of 1600°C suitable for a variety of laboratory and pilot applications; coupled with a gas chromatograph (Varian CP4900) equipped with a molecular sieve column and a TCD detector, etc

Furthermore, in order to qualify these materials, it is of upmost importance to assess the damage induced by thermal shock on consecutive cycles. For this purpose, materials are subjected to cycling heating under well-controlled conditions. Several important physical-thermal, mechanical, and chemical properties of the relevant materials can be identified when assessing the influence of treatments onto a solid substrate.

Figure 58. Indoor Solar Simulation Loop for evaluation of materials for thermochemical cycles.

For special purposes, some other equipments are available to complete the characterization of these materials: A Thermogravimetric Equipment STA 449 F1 for simultaneous TGA-DSC analysis. This equipment has two exchangeable furnaces: a SiC for high temperature reaction (1600°C) and water vapour kiln up to 1200°C. Finally, a temperature furnace perfectly suited for cycling candidate's materials is available. This furnace has special heating elements made of molybdenum disilicide providing temperatures of about 1650°C with a precise temperature control, also in the lower temperature range (**¡Error! No se encuentra el origen de la referencia.**).

3.11 Laboratory for qualification of industrial endothermic processes using concentrating solar technologies

For qualification of industrial endothermic processes, a research bench has been designed and assembled. The reactor was designed for operation in the 60kW Solar Furnace at the *Plataforma Solar de Almería* (PSA). Tests are performed pursuing to advance in novel solar reactor concepts through the development of innovative solar reactors as fluidized bed reactors. As the only way to introduce concentrated solar radiation into a low expansion fluidized bed is from the top, a vertical beam must be provided. For the testing device, see Figure 59, this is done with a 45°-tilted, water cooled mirror located close to the focus.

Fluidized beds as chemical reactors present several advantages that include a high rate of heat and mass transfer, low pressure drops, and uniform temperature distribution. This concept is being applied for development and testing of a solar powered fluidized bed reactor for the extraction of oxygen from lunar regolith. This is done by the reduction of one constituent of lunar soil, ilmenite ($FeTiO_3$), with hydrogen, and the subsequent electrolysis of the obtained water.

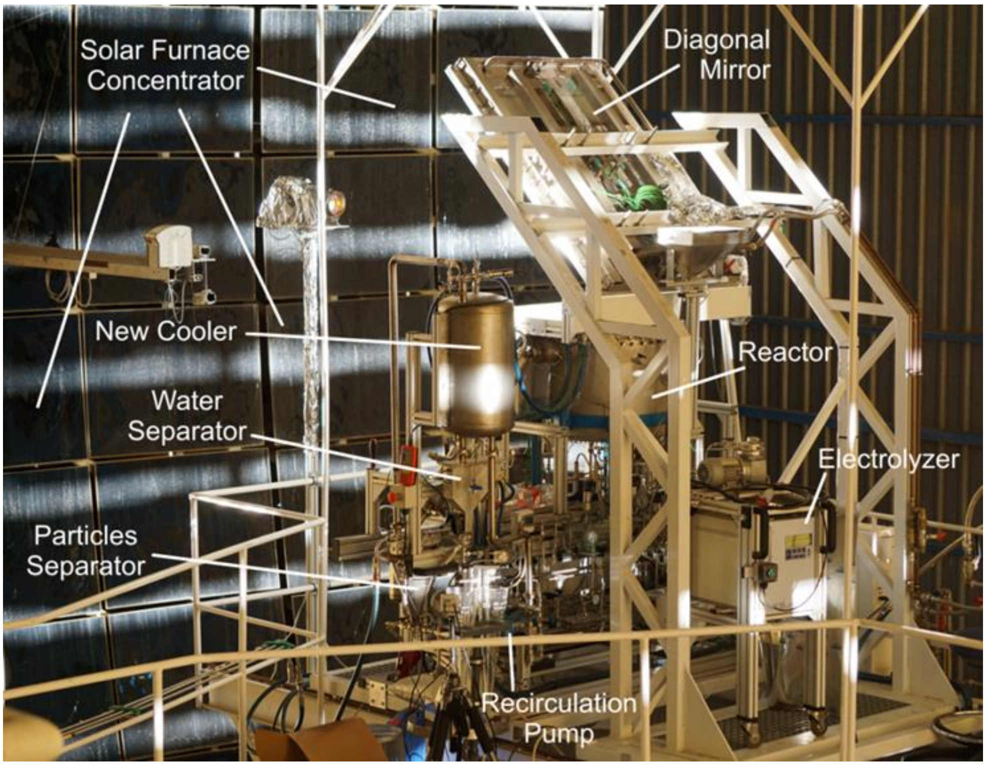


Figure 59. Testing of Alchemist plant in a solar furnace to produce oxygen form regolite.

The general goal for these tests is to improve the understanding of fluidized bed hydrodynamics by completing the following objectives:

- Identify the gas flow demand of the main fluidized bed in the reactor as a function of the temperature.
- Operate the reactor at 900°C solely heated with concentrated solar power.
- Demonstrate water production from the reaction of the ilmenite with hydrogen.

3.12 PSA Water Technologies Laboratory - WATLAB

Within the scope of the SolarNova Project funded by the Ministry of Science and Innovation within the Special State Fund for Dynamization of Economy and Employment (*Fondo Especial del Estado para la Dinamización de la Economía y el Empleo – Plan E*) a new laboratory was built in 2009. Since them, acquisitions of new instrumentation have been done within the SolarNova Project. The PSA water technologies laboratory consists of 200 m^2 distributed in six rooms: two rooms for chemicals and other consumables storage. It is a 30-m^2 storeroom. It is organized on numbered and labelled stainless steel shelving with refrigerators and freezers for samples and standards keeping; ii) A 17-m^2 office with three workstations where visiting researchers can analyse the data from the experiments carried out at the PSA. In addition, 4 technical rooms are also part of the laboratory and are listed and described below:

- General lab
- Chromatography lab
- Microbiology lab
- Microscopy lab

3.12.1 General laboratory

The main laboratory is 94 m^2 (Figure 60). It is equipped with four large work benches, two gas extraction hoods, a heater, a kiln, ultrasonic bath, three centrifuges, two UV/visible spectrometers, a vacuum distillation system, ultrapure water system, pH gauge and conductivity-meter, and precision-scale table. In addition, it has a centralized gas distribution system, UPS, three-pin plugs connection and safety systems (extinguishers, shower, eyewash, etc.). The laboratory is also equipped with *Vibrio fischeri* and activated sludge respirometry toxicity measurement devices, biodegradability measurement by two respirometers for suspended activated sludge and for immobilized activated sludge, and equipment for the analysis of BOD and COD. Jar-Test system for the optimization of separation of solids for water treatment.

Figure 60. General view of the new PSA Water Technologies Lab.

3.12.2 Chromatography laboratory

This lab (**¡Error! No se encuentra el origen de la referencia.**.a) is equipped with three high performance liquid chromatographs with diode array detector (HPLC-DAD and two UPLC-DAD) with quaternary pump and automatic injection; an Automatic Solid Phase Extraction (ASPEC) which permits working with low concentration of pollutants and two ion chromatographs (**¡Error! No se encuentra el origen de la referencia.**.b): one configured for isocratic analysis of amines and cations (Metrohm 850 Professional IC), and another for gradient analysis of anions and carboxylic acids (Metrohm 872 Extension Module 1 and 2) with conductivity detectors (Methrom 850 Professional IC detector). Two total organic carbon (TOC) analyzers by catalytic combustion at 670°C and total nitrogen (TN) analyzer with autosampler are also included. In addition, an AB SCIEX TripleTOF 5600+ was acquired to detect and identify non-targeted or unknown contaminants present in wastewater or generated (transformation products) during the water treatments: Triple TOF by a DuoSpray Source combining Turbo Ion Spray and APCI (Atmospheric Pressure Chemical Ionization) modes. Besides, the system includes metabolomics statistical package to analyze multiple samples from multiple experiments and identified possible chemical and biological markers (**¡Error! No se encuentra el origen de la referencia.**.c).

3.12.3 Microbiology laboratory

A 47-m^2 microbiology laboratory with biosafety level 2 (**¡Error! No se encuentra el origen de la referencia.**) is equipped with four microbiological laminar flow (class-II) cabinets, two autoclaves, three incubators, a fluorescence and phase contrast combination optical microscope with digital camera attachment. Besides, automatic grow media preparer and plaque filler and a filtration ramp with three positions are available. This lab is also equipped with ultra-fast real-time quantitative PCR (Polymerase Chain Reaction) equipment, fluorospectrometer and spectrophotometer NanoDrop for genetic quantification of micro-volumes. A 'Fast Prep 24' was also acquired, it is a high-speed benchtop homogenizer for lysis of biological samples, needed for further analyses of genetic material samples. Homogenizer stomacher 400 Comecta equipment was acquired to blend food samples, stirring and storage is a reproducible way without any risk of cross contamination between samples.

3.12.4 Microscopy laboratory

The microscopy laboratory is 11 m^2 room (Figure 61.a). A Scanning Electron Microscope (SEM) is located in this room. For the preparation of microbiological samples and catalysts to be analyzed in the SEM, the system is completed with a metal coater and critical point dryer. In this room it is also located two optical microscopes: i) A fluorescence and phase contrast combination optical microscope and ii) FISH microscope (Leyca) with fluorescence module to develop the FISH (Fluorescent in situ hybridation) technique for visualization of DNA hibrydation with specific probes in live cells used for monitoring of key microorganisms within a heterogeneous population (Figure 61.b). In addition, the system is completed by a station for photographic documentation, consisted in UV-trans-illuminator to detect and visualize DNA, RNA and proteins. It also includes a documentation station with a camera to take images of DNA, RNA and proteins.

3.13 PSA radiometric net

The PSA has had a meteorological station since 1988, primarily for measuring integral solar radiation (global, direct and diffuse radiation), but also for other generic meteorological variables (temperature, wind speed and direction, relative humidity and atmospheric pressure, accumulated precipitation, etc.). The old station was completely remodelled in 2005 following the strictest requirements of quality and precision in the measurement of solar radiation according to the Baseline Surface Radiation Network guidelines. This station is called METAS station since 2012 (Figure 62).

(a)

(b)

Figure 61. a) SEM (Scanning Electron Microscope). b) Optical microscope for FISH technique.

Figure 62. General view of the new PSA radiometric station.

The METAS station instruments are in the highest range of solar radiation measurement. All the radiation sensors are ventilated-heated and have a temperature measurement sensor. This equipment provides the best information on solar radiation and more general atmospheric variables, and can be used for filtering input data and validating spectral models. They are used for:.

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

Additionally, a set of complementary structures for the calibration of radiometers has been installed near to this meteorological station following the standardized international procedures (ISO-9059 and ISO-9846). On the one hand a high performance tracker with the possibility of carrying 2 reference pyreheliometers (absolute cavity radiometer PMOD PMO6-CC) and a total of 19 field pyreheliometers has been installed close to METAS; on the other hand 3 calibration benchs with capacity to carry 20 pyranometers each one have been placed at 50 meters of METAS (Figure 63). These facilities are operated in collaboration with the Instrumentation Unit.

Figure 63. Calibration facilities.

Since the beginning of 2018 there are seven new radiometric stations fully operational all around the PSA area. These stations are equipped with first-class pyranometers and pyrheliometers, 2-axis solar trackers and have data acquisition systems Campbell CR1000 (METAS has a CR3000).

These eight stations, which constitute the radiometric network of the PSA (Figure 64), register synchronously at 1 second and 1 minute. All recorded data are stored in a relational database management system that will allow access to solar radiation data registered through a web platform (under construction). Thus, the homogenization of procedures as measure, data acquisition, quality control, storage and treatment are included in the objectives.

Figure 64. PSA radiometric stations.