DISS-phase I PROJECT

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1 DISS-PHASE I PARTNERSHIP

The project partnership is composed of three Spanish electric utilities (ENDESA, IBERDROLA and UNION ELECTRICA FENOSA), three research centres (the Spanish CIEMAT and the German DLR and ZSW) and three Industries (the Spanish INABENSA and the German PILKSOLAR and SIEMENS).

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2 PROJECT OBJECTIVES AND PLANNING

The DISS (DIrect Solar Steam) Project is a complete R+TD program aimed at developing a new generation of Solar Thermal Power Plants with parabolic trough collectors. This R+TD program has three primary goals:

1. Improve and implement parabolic trough collector components (e.g., absorber pipes with better optical and thermal properties; better-quality mirrors; more accurate tracking systems; etc...).
2. Develop Direct Steam Generation (DSG) in the solar collector absorber pipes, thus eliminating the thermal oil presently used as a heat carrier medium between the solar field and the power block. This would increase system efficiency and reduce investment cost. From a technical stand point, development of the DSG process is the most critical step in the DISS project
3. Optimize overall plant design to improve solar-field power-block integration and O&M to shorten startup and shutdown times.

The final goal of DISS is a 20% increase in performance and 15% reduction in direct investment cost over state-of-the-art parabolic-trough collector solar power plant technology as represented by the SEGS plants currently operating in California. This would lead to a 30% reduction in the cost of electricity generation with this type of solar thermal power plant. Figure 2.1 shows the objectives and expected benefits.

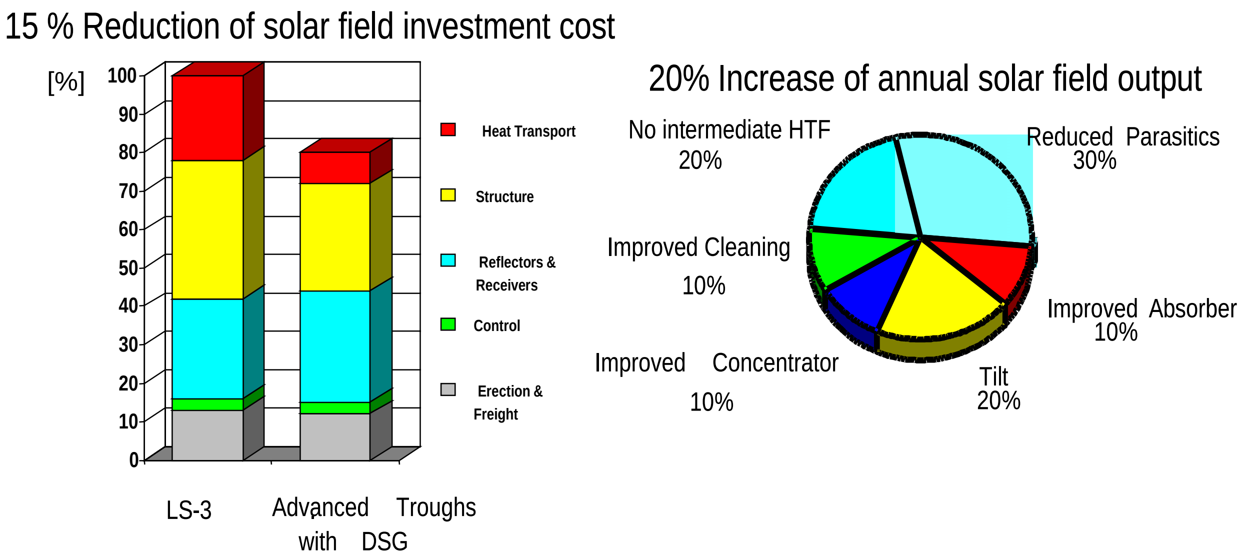


Figure 2.1.- *Expected benefits of DISS*

Due to the extension and complexity of the planned activities, the DISS project plan of work is divided into three consecutive phases. The first phase (the so-called DISS-phase I) was started in January 1996 and ended in November 1998, with the financial contribution of the European Commission within the framework of the JOULE III Programme contract JOR3-CT95-0058.

3 ACTIVITIES PERFORMED IN THE PROJECT

DISS-phase I activities are grouped into three tasks:

1. *Design and implementation of a life-size DSG test facility (the so-called DISS Test Facility) at the Plataforma Solar de Almería (PSA)*: current open questions concerning the DSG processes require a life-size test facility where these processes can be studied under real solar conditions. One of the main project deliverables is the design and implementation of such a test facility at the Plataforma Solar de Almería, a solar research center in Southern Spain owned by CIEMAT. Though the solar field planned for this facility is to have two parallel rows of collectors, only one complete row has been erected and hooked up to a Balance of Plant (BOP) during the first phase. The second row will be designed and implemented in a future phase.
2. *DSG Applied Research* in DSG process thermohydraulics. Results of this task will complement the experiments at the PSA DISS Test Facility.
3. *Collector Improvement:* develop and evaluate better parabolic-trough collector components. A small test loop has been erected at the PSA for testing of improved components under real solar conditions.

3.1 Task "Design and Implementation of the PSA DISS Test Facility"

The project's most critical technical problem is the two-phase flow (liquid water+steam) in the absorber tubes resulting from direct solar steam generation in the solar collectors. The uncertainties involved, such as solar field controllability, process stability, absorber-pipe stress, etc., have to be clarified before the technology can become commercial.

Though lab-scale experiments, either past or planned for the near future, investigate these problems at lab scale, many of them can only be observed under real solar working conditions, which requires a life-size test facility. Therefore, design and implementation of such a test facility at the PSA became an essential objective of DISS-Phase I.

Steam may be produced in the absorber tubes of parabolic-trough collectors in three ways without causing dangerous temperature gradients. These three different options are (See Fig. 3.1):

a) Once-through process
b) Injection process
c) Recirculation process

All of them require that the collector field be composed of long rows of parabolic-troughs connected in series for the complete DSG process of water preheating, evaporation and steam superheating to be performed. Figure 3.1 summarizes the advantages and disadvantages of these three DSG options and points out the needs for experimental research and evaluation.

In the *once-through process*, high temperature gradients are avoided by tilting the collectors. Experiments have verified that the two-phase stratified flow pattern occupies a much smaller area in a tilted pipe than in a horizontal one. In the once-through process feed water is preheated, evaporated and converted into super-heated steam as it circulates from the inlet to the outlet of the long collector rows. The main advantage of this process is its simplicity, while the main technical problem is the controllability of the superheated-steam parameters at the field outlet under solar radiation transients.

In the *injection process*, the collectors are horizontal and small quantities of water are injected at several places along the row of collectors. Experiments have shown that steep temperature gradients may be avoided when the mass flow through the absorber pipes is kept above a threshold level. The main advantage of this process is the controllability of the superheated steam parameters at the outlet of the system. On the other hand, the injection system is more complex and costs more.

The third option, the so-called *recirculation process*, is the most conservative one. In this case a water-steam separator is placed at the end of the evaporating section of the collector row. Inlet feed-water flow is much higher than that of the steam to be produced by the system. Only a fraction of this water is converted into steam as it circulates trough the collectors of the evaporating section. The steam is separated from the water by the separator and the remaining water is sent back into the system inlet by a recirculation pump. The excess water in the evaporating section guarantees good wetting of the absorber tubes and makes stratification impossible. This type of system can be controlled well, but the excess water that has to be recirculated and the recirculation pump necessary for it very much increase the system parasitic load.

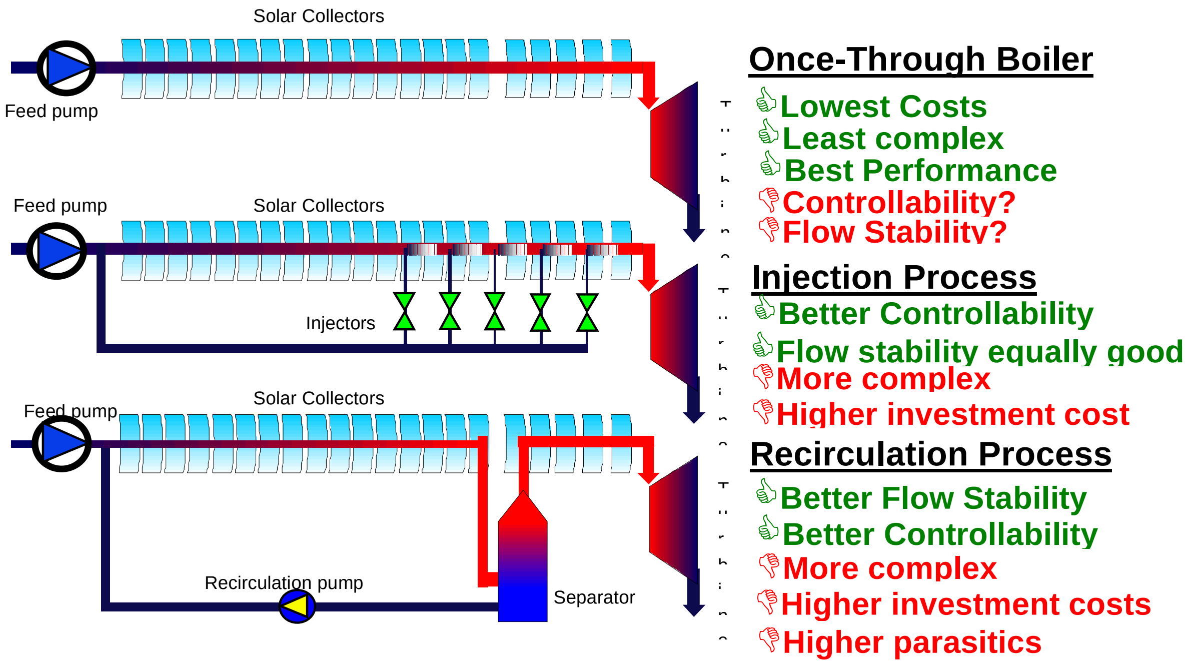


Figure 3.1.- *The three basic DSG options*

There are some technical questions concerning the three DSG processes that must be answered by means of experimental evaluation under real solar conditions in a proper test facility, which must fulfil some requisites (e.g. it must have the flexibility to be operated in the three DSG processes with a wide range of operation loads, and it must be large enough to perform the complete water evaporation and steam superheating)

The test facility required to perform this experimental evaluation has been designed in DISS-phase I. Figure 3.2 shows the configuration of the facility with its two subsystems, the Solar Field and Balance of Plant (BOP), which was designed and implemented at the PSA during DISS-Phase I.

3.1.1 Solar Field

The complete solar field planned for this facility is to be composed of two parallel rows of collectors, however, only one complete row has been designed in detail, erected and hooked up to the BOP during the first phase of the project. The implementation of the second row depends on the success of Phase II testing with the single row system. This strategy delays the investment in a second row until the feasibility of the DSG process is confirmed by the experience with the single row in order to eliminate unnecessary financial risks.

The following table shows the technical data of this first DISS row of collectors implemented at the PSA during the project:

No. of collectors	11
Collector aperture:	5.76 m
Collector length:	25 or 50 m
Inclination of the tracking axis:	0º,2º,4º,6º,8º
Orientation:	North-South
Absorber pipe inner diameter:	50 mm
Absorber pipe outer diameter:	70 mm
Max. pressure at the field outlet:	100 bar
Mass flow per row (once-through configuration)	1 kg/s
Max. recirculation rate:	4
Max. outlet temperature:	400ºC
Max. pressure for water injectors:	140 bar

There are four different collector types:

A) 50-meter collectors with three possible tracking-axis angles: 0º, 2º and 4º. Collectors nº 1, 2,...8 are of this type.

B) 50-meter horizontal collector (collector nº 11)

C) 25-meter horizontal collector (collector nº 10)

D) 25-meter collector with five possible tracking-axis angles, 0º, 2º, 4º,6º and 8º. This is the so-called Special Test Collector (collector nº 9)

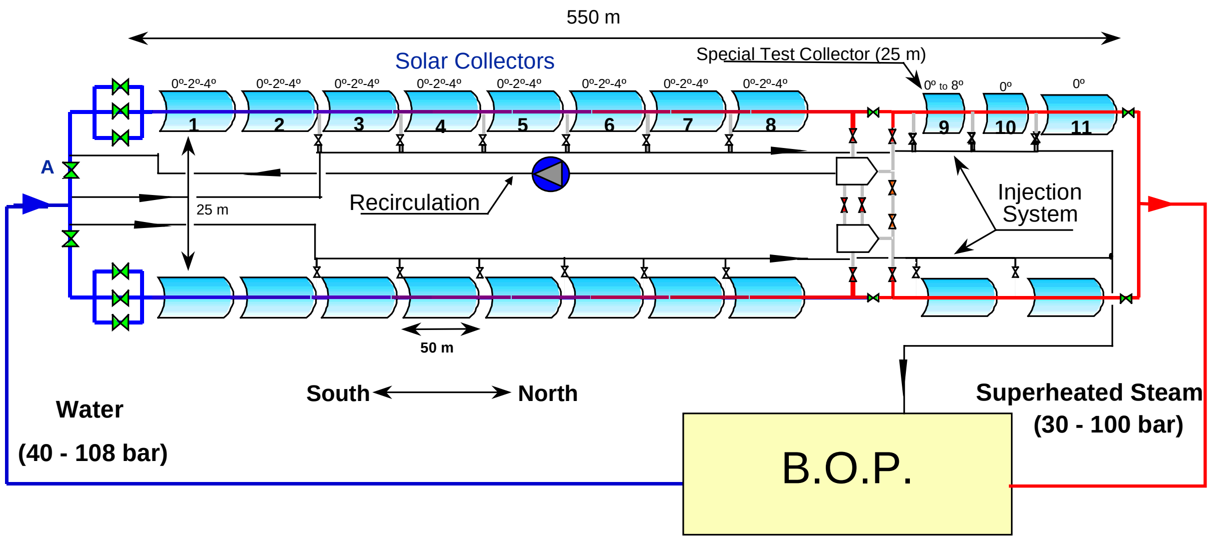


***Figure 3.2.-** Schematic diagram of the DISS solar field*

Figure 3.3 shows the basic dimensions of one type A collector when its tracking axis is 4º tilted. Collector types A and B are made up of four 11.98-meter-long parabolic-trough modules. Collector types C and D have only two modules.

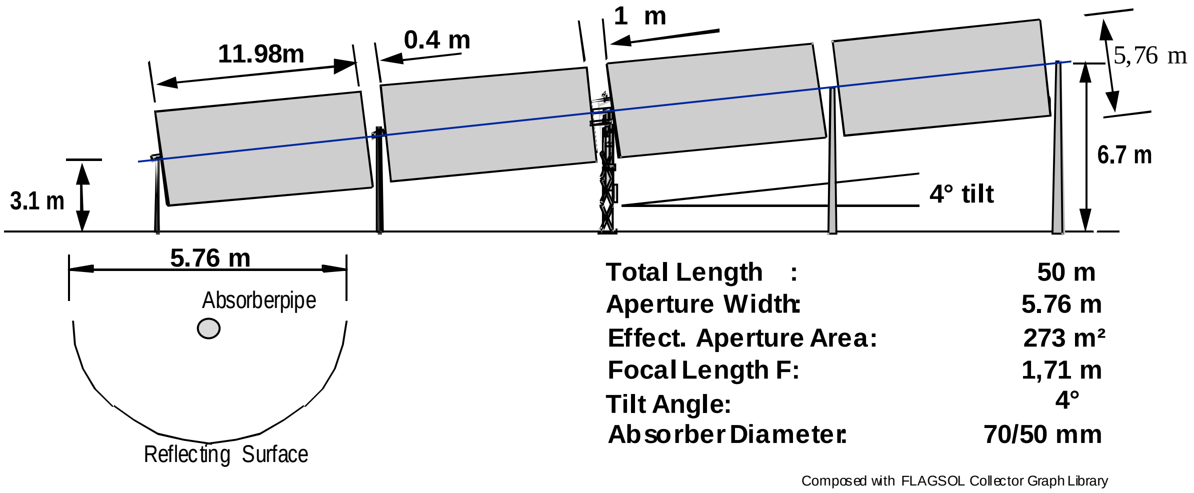


***Figure 3.3.-** Basic dimensions of a 50-meter collector with a 4º tilt (collector type* A)

There are two different types of absorber tubes in the DISS collectors. The difference is a set of eight thermocouples (the so-called *"Test Cross Sections")*. installed in the steel tube wall. This will be used during testing to monitor the temperature profile around the steel absorber tube where the set is installed. 44 such absorber tubes have been installed at the end of Collector Type A, B and C parabolic-trough modules, while all six absorber tubes of collector Type D (the so-called "Special Test Collector) are provided with test cross sections.

Though the solar field will be operated over a wide temperature/pressure range, the three main operating modes will be:

Solar field conditions	inlet	-	outlet
• **Mode 1**::	40bar/210ºC		30bar/300ºC
• **Mode 2**:	68bar/270ºC		60bar/350ºC
• **Mode 3**:	108bar/300ºC		100bar/375ºC

3.1.2 Balance of Plant (BOP)

In the BOP the superheated steam produced by the solar field is condensed and converted into feed water that is pumped back to the field inlet and the water injection system. This allows closed-loop facility operation, thus saving water and energy.

The steam produced in the solar collectors enters a water/steam separator in the BOP where the pressure is between 30 and 100 bar. Solar field outlet pressure is controlled by a pressure control valve and a pressure reduction valve. The 25-bar (approx.) steam delivered by the pressure reduction valve is condensed in an air-cooled heat exchanger (steam condenser). The condensate this delivers flows into a feed-water tank.

The main feed pump sends water through the preheater to the solar field inlet. Three valves installed in parallel at the collector row inlet control the flow rate by means of the pressure drop across the valve. It is impossible to use a single valve at the inlet to control the flow of water for all three due to their different parameters, so each of the three valves has had to be specially designed for use with the particular operating parameters of a different DSG process.

The recirculation system is composed of a water/steam separator and a recirculation pump. The water entering the separator between the boiler and superheater sections of the solar field is recirculated to the solar field inlet by the pump.

The water injection system is fed by the main water pump. Injection valves are used to control individually the water flow through the corresponding injection nozzle. A relief valve connected to the BOP flash tank continuously maintains a minimum flow through the main injection pipe to avoid injection system restartup delays. Valve A in Fig. 3.2 ensures that water pressure at the injection circuit inlet is higher than at the collector row inlet.

The BOP also has a deaerator tank to release, in combination with three chemical dosing units that inject hydrazine and ammonia at three different locations, any air that could exist in the demineralized water fed to the system.

The nominal steam flow at the collector row outlet is 1 Kg/s, with a maximum of 1.5-2 Kg/s. Since the BOP must be able to work with a single row and with two rows, some BOP elements have two identical sections so that one of the sections could remain out of operation when only one row of collectors is operating.

3.2 Task “DSG Applied Research”

Previous DSG projects have contributed significantly to the understanding of two-phase flow in horizontal tubes. It could be shown, for instance, that stratified flow does not necessarily lead to unacceptably high azimuth temperature differences and minimum mass flow densities required to keep thermal stress down in the tube wall material have been found.

Such experimental research performed at existing laboratory facilities, as well as the development and application of numerical simulation tools, have provided scientific support for the design and implementation of the PSA DISS test facility and permitted the preparation of a detailed test plan incorporating the latest knowledge on direct steam generation. Moreover, general research has permitted thermohydraulic issues, definition of potential alert situations, and corresponding control requirements to be dealt with.

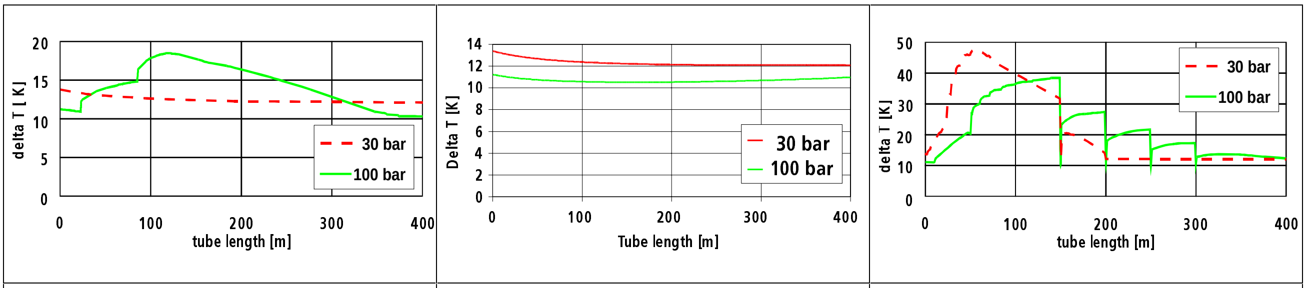
3.2.1 Thermohydraulic aspects

A) Heat transfer and temperature gradients

It was found during the research performed in DISS-phase I that the mass flow density (MFD) has the most impact on the flow pattern, steam quality and pressure. Heat flux density has a significant impact on the tube wall temperatures and also a perceptible influence on the flow pattern.

Tube heating can cause extreme azimuth temperature differences if the circumference is only partially wet. A typical trough collector heats only half the absorber tube circumference, the most critical situations being in the morning and evening when the tube is heated from the side.

A simulation program has demonstrated excellent agreement with the GUDE project experiment results and is now available as a tool for the design of DSG absorber tubes. Figures 3.3 a) to c) show the maximum azimuth temperature differences for the three DSG concepts. The inner tube diameter is 50 mm and heating is applied from the side with a heat flux density of 46 kW/m².



a) once through	b) recirculation	c) injection

Figure 3.3 *Azimuth temperature difference along a 400-m-long absorber tube.*

Once through mode: Due to the larger region of stratified flow at 100 bar, temperature is affected by azimuth in a larger part of the tube than with annular flow. The whole circumference is wet from the inlet to 25 m, but from 25 to 80 m, due to sluggish flow, the circumference is only partially wet. From 80 m onward, stratified flow leads to increasing azimuth temperature differences up to a maximum at 125 m. After that, continuously increased wetting by droplets causes it to decrease again steadily. At 30 bar the entire tube wall is always wet, because droplet wetting starts before wetting from the wave tips fades, thus avoiding an area of stratified flow. These simulation results were obtained using a mass flow of 0.71 kg/s at 30bar and 0.84 kg/s at 100 bar in horizontal absorber pipes.

Recirculation mode: The simulation shown in Figure 3.3.b) was performed with a recirculation rate of 3. At both pressures the whole tube wall is always wet.

Injection mode: The simulation shown in Figure 3.3.c) was performed with injection at 0, 150, 200, 250 and 300 m. The mass flow of injection is set to provide water for 200 m of evaporation in the first nozzle and 50 m in all the rest. In comparison to the once-through mode, the whole circumference is completely wet at an earlier axial position. This is due to the lower water inventory in the tube in the injection mode. After a region of partial wetting, pure stratification occurs at axial positions of 25 and 48 m for 30 and 100 bar respectively.

B) Pressure drop

The pressure drop in water/steam two-phase flow has been investigated in detail at the HIPRESS test facility of ZSW. The pressure drop along the test section was measured by a differential pressure device. The measurements were then compared to several theoretical models.

The pressure drop in one-phase flow can be calculated as dependent on the friction factor. The best results were obtained with the common Colebrook and White equation.

In two-phase flow, the flow rates are different for each phase. This causes additional friction at the phase boundary between water and steam, thus resulting in higher pressure losses. These additional pressure losses can be taken into account by using a two-phase multiplier R. The two-phase multiplier is the ratio between the pressure drop in the two phases and the pressure lost by the total mass flow in liquid phase. Several, mostly empirical models are available to find R. Results of the Thom, Friedel and Taitel models were compared to measurement of a complete evaporation process. The best correspondence with measurement was obtained with the Friedel mode. Analyses of this model show that the impacts of mass flow and diameter are very small and can be neglected. The effects of pressure and steam quality are therefore very strong. Consequently, a correlation for mean mass flow densities and pipe diameters which gives the two-phase multiplier only as a function of pressure can be found.

3.2.2 Enhanced heat transfer

The results of the GUDE project showed that excessive stress from uneven insolation can be avoided by keeping the mass flow over a threshold level. Nevertheless, within this task, enhancement of heat transfer by improved wetting of the inner pipe surface have been investigated. The reason is that these techniques may contribute later to optimizing the DSG process in the first absorber tube section.

A) Enhancement of heat transfer by displacers

It has been observed that heat transfer can be improved and stratified flow avoided in the injection concept by installing a displacer inside the absorber steel tube. The flow pattern is strongly influenced and the transition to annular flow occurs earlier. Moreover, the steam heat transfer coefficient is higher due to faster flow of steam. The heat transfer depends directly on the flow pattern in the pipe. Flow patterns that create a closed water film on the inner pipe wall guarantee satisfactory heat transfer.

The DISS experimental research was therefore intended to detect flow patterns in the pipe with and without a displacer. Without a displacer, flow is dominated by stratification when mass flow density is not high enough. The flow pattern in a heated pipe can be found based on the circumferential temperature profiles. By evaluating all the temperature profiles measured, a complete flow regime map can be obtained. On this map, the annular, stratified and wavy flow regions are separated. By comparing pipe transition curves with and without the displacer, it becomes apparent that the minimum mass flow density necessary to avoid stratified flow is significantly reduced by the installation of a displacer. With high steam quality, dry-out arises earlier in the pipe with a displacer than without it because the displacer suppresses deposit of droplets.

B) Enhancement of heat transfer by capillary structures

Increase in wet area by capillary pressure has been widely used for heat pipe collectors in solar energy. Capillary pressure lifts up a thin film of liquid over the base water that cools the pipe, reducing thermal gradients. For development of capillary pressures, porous-coated or micro-grooved pipes are necessary.

The theoretical influence of capillary system characteristics has been studied by CIEMAT for water-steam flow in a 70/50-mm pipe. It was shown that at least 83% of the absorber pipe perimeter can be rewetted with a microgroove radius of less than 0.33 mm, while the results for the various porous coatings with different layer thicknesses, porosities and permeabilities showed that they would not be able to respond to the required wetting capacity forecast. As their behavior depends on the temperature, the need to measure the capillary behavior under working conditions is obvious. An experimental setup has been designed and manufactured by CIEMAT for measuring the capacity for wetting of pipe samples under DSG conditions.

The applicability of porous coated and micro-grooved pipes depends on their long-term fouling characteristics because fouling from magnetite corrosion is possible under DSG conditions.

3.2.3 Control, downtime and alert

Potential alert situations need to be identified in order to provide for them in the DSG process. Hardware requirements for detection and recovery procedures from such situations have been specified and implemented at the PSA DISS test facility.

3.2.4 Instrumentation

The experience gained in laboratory experiments led to the design of instrumentation implemented in the DISS test loop. Nevertheless, with regard to the future implementation of a commercial DSG plant, some questions remain unsolved. The most important of these questions are:

- Influence of transient conditions on flow pattern and heat transfer
- Influence of pipe diameter on flow pattern and heat transfer coefficients
- Influence of tilt on flow pattern and heat transfer coefficients in large pipes

The instrumentation of the test loop has been chosen so that these questions can be answered in the second phase of the project. The measurement of wall temperatures will provide information on flow pattern and heat transfer. Because the absorber tubes move during the day, the position of the highest wall temperature on the circumference is not always the same, but varies with the time of day. It also varies if the area of wetted inner pipe wall changes.

Therefore, a set of eight thermocouples installed around the absorber pipe is necessary to ensure that the highest wall temperature or at least one close to it is measured at any given time.

For control of the injection process, nine capacitance void-meters are inserted into the absorber tube. These void-meters measure the local void fraction over time.

3.2.5 Test Plan for DSG-process

A first DISS test plan has been defined. This test plan includes all the necessary loop and component calorimetric and static tests as well as the experiments in all three basic DSG processes with horizontal absorber modes. It is not a fixed test matrix, because previous DSG projects have shown that single experiments have to be changed as lessons are learned from earlier experiments.

3.3 Task "Collector Improvements"

Activities carried out in this Task are summarized in the following paragraphs, grouped in accordance with the work packages defined for this Task.

3.3.1 Set up of the LS-3 Test Loop

At an early stage of the project the opportunity arose to purchase at low cost from the company SOLEL a used prototype of the LS-3 technology, which could be converted into a test facility on the PSA to allow the investigation of improved components without any interference with testing to be performed at the DISS Testloop. At the same time, the early implementation of this collector could provide valuable hands-on experience for the DISS Test loop construction, as well as providing a reference "bench mark" against which improvements can be measured.

For experimental reasons, the collector axis is oriented east-west This arrangement allows testing without any cosine- and end-losses at noon, and also investigation of the influence of different incident angles during the course of the day. The collector was provided with a prototype unit of the new local control system developed by the PSA for both parabolic trough collectors and heliostats.

3.3.2 Improvement of DISS Test Loop

A) Prepare procedure definition for improvement process

The primary objective of this task was to identify and define improvements for a future test loop based on first test loop experience. Following this, the secondary objective was to evaluate improvements within the context of a commercial, mass-produced system.

Three steps were to be implemented in this process:

A. Track component characteristics and parameters
B. Review and evaluate design for 1st loop
C. Postulate improvements for 2nd loop

There are a number of areas in which improvements can be postulated, dictated in the end by the cost/benefit ratio of any given approach. The collector is comprised of a series of systems and subsystems, all of which should be considered. Furthermore, manufacturing methods and material selection will strongly influence costs, and certain component designs will lend themselves to lower costs.

B) Review and evaluate design of the first loop

During the implementation of the DISS test loop at the PSA, the design of the test loop was evaluated. Some possible improvements were identified which should be considered for the implementation of more collectors in the future. These are e.g.:

- The mixture of different standards like DIN, ASME, ISO and different units like inch and centimetre must be avoided in technical specifications.
- All drawings and equipment specifications should be released in the mother language of the manufacturer to avoid misunderstandings.
- A very important point is the implementation of a good Quality Control from the beginning and during the fabrication and assembly.

C) Record cost and resource utilization for the set up of the first loop

The objective of this work package was to gather information on the cost presently associated with the production and installation of the components needed to accomplish the DSG process. These data served as the primary input for the cost calculation carried out within the next working package, the extrapolation of this data to mass fabrication level (see below).

D) Extrapolate and scale-up gained data to mass fabrication

With the findings of the DISS project an increased overall system efficiency and better cost competitiveness of Solar Thermal Power Plants are expected. A possible reduction in the Levelized Electricity Cost (LEC) of about 30% was anticipated in the project proposal. The main objective of this working package was to estimate the commercial costs of Solar Thermal Power Plants with DSG process to review this assumption. The revision of initial performance and cost assumptions for both, HTF and DSG technology, as well as the evaluation of new performance and cost data, were performed in order to fulfil this objective.

Due to the early stage of this 3-phase project, only limited new information was available for the evaluation of the benefits of the DSG process. Therefore, the results of this evaluation include a relatively high level of uncertainty. Hence these results are clearly preliminary, to be refined during the course of the project. The IEA (International Energy Agency) economic analysis method for renewable energy sources was used in this analysis to calculate the LEC. In general, levelized life-cycle cost is the present value of a resource's cost (including capital, financing and operating cost) converted into a stream of equal annual payments. By levelizing costs, resources with different lifetimes and generating capacities can be compared.

E) Possible improvement measures

Potential improvement measures must take into account factors of performance gain, operating characteristics, initial cost and maintenance cost. The purpose of this work packages was to identify such measures based on field experience with parabolic trough collectors, new prototype developments and ongoing R&D in Europe and elsewhere. Component improvements were identified based on ongoing work in this task, on technical developments carried out in the U.S. at Kramer Junction as part of the KJCOC/Sandia National Laboratories cost-shared program, and from a variety of other sources and work relevant to parabolic trough technology. Additional improvements were identified as a result of the construction and operation of the first DISS loop.

3.3.3 Improvement of Mirrors, Structure and Tracking System of the LS-3 Test Loop

A) Front surface mirrors

Optimization of mirror reflectance and durability is necessary in order to improve the thermal efficiency of solar concentrators. Now, the R&D efforts to improve the mirrors for solar applications are focused on the so-called *Front Surface Mirrors*.

In CIEMAT, a conventional technique to produce dielectric coatings such as sol-gel, has been introduced in the production of front surface solar reflectors.

B) Hydraulics, drives and tracking system

These components have a significant effect on performance, as all have an effect on tracking accuracy. The impact on cost is small compared to other components in a parabolic trough collector. Based on available information, and largely influenced by the operation of the LS-3 system at the SEGS plants in California, PilkSolar concluded that no significant improvements were possible in these components. CIEMAT, however, developed an open-loop tracking system based on a calculated position of the sun (as opposed to active closed-loop sun sensor tracking of the sun) which has been implemented in the first DISS loop. Performance of this system will be observed during first loop testing.

C) Membrane collector manufacturing and testing

The substrate of the mirror has to play the role of a structural element to better use the advantages of front surface mirrors. CIEMAT is analyzing a quite interesting possibility of simultaneously improving collector efficiency and reducing cost: the parabolic trough with a thin metallic membrane as the substrate of a front surface mirror. For such objective theoretical analysis, using ANSYS code, have been carried out. Additionally, a small prototype has been designed, and construction was started in 1998, to test the accuracy of the simulation results and to search for practical solution to fix the membrane to the main steel structure.

3.3.4 Heat Collection Element Improvement

A) Review of ongoing development world-wide

The solar radiation is absorbed by the selective coating on the absorber surface. Due to the high temperature of the absorber tube from 300°C up to 400°C, the absorber itself is radiating in the infrared wavelength range. The predominant factor of the absorber heat losses is the radiation losses. Therefore good selective coatings for absorber tubes need a high solar absorptivity in the UV and visible wavelength range and low thermal emissivity in the IR wavelength range. Within the first phase of the project, a review of ongoing developments of selective coatings was conducted, to provide bench marking information for project partners developing their own coatings, and to identify possible duplications of effort or co-operation opportunities.

B) Stress analysis in the absorber tube

Parabolic trough absorber tubes are subject to thermomecanical stresses caused by the non-uniform and unsteady heating by the concentrated solar radiation. This causes circumferential temperature gradients in the tube walls, which consequently lead to deformation of the tube or strains and stresses. For steam generating systems it is expected that the non-uniform heat transfer at the inner tube wall, caused by the two phase flow, may aggravate the problem. Finite Elements Methods have been adopted and applied to simulate the loads for specific configurations and boundary conditions.

However, a user-friendly interface for the integration of different designs, heating profiles or flow parameters is yet to be developed. Such methods shall be applied first to define operational limits of the DISS test facility. Further investigations shall be carried out to study the influence of strains and stresses on the optical and thermal performance of the collector, and to evaluate and optimise different HCE designs.

C) Selective coatings

During this project, an innovative technique has been employed by CIEMAT to produce solar materials such as selective absorbers and antireflective coatings. This technique, called sol-gel, is a simple and inexpensive method to produce thin dielectric layers with better mechanical and structural properties than PVD techniques. The initial investment required is low because only mechanical devices and a oven are necessary to carry out the whole manufacturing process.

D) Summary review of new geometries

A lot of individual thermal loss effects are responsible for the low energy conversion of solar radiation into process heat. Thermal losses of the absorber pipess contribute with their lowest single efficiency to the annual average value of SEGS IX plant of 52%.

The absorber itself is radiating in the infrared wavelength range due to its high temperature. This IR radiation is almost completely absorbed by glass. Therefore the glass envelop and the steel tube are in radiation exchange. On the outer surface of the glass envelope conduction and convection are the dominant heat loss mechanism. They are influenced by ambient conditions like wind speed, wind direction and ambient temperature. The predominant factor of these loss mechanisms is the radiation between absorber tube and glass envelope.

On the top of the absorber the heat losses are higher than the energy supply by the not concentrated radiation. The energy balance in this region is negative. We have called this section: "Region of losses". In direct steam generating systems, this effect may be even more pronounced. Therefore, alternative geometries for the HCE must be reviewed, and options for further development shall be selected.

E) Evaluation of selected options

As a result of the previous work pachages, technical solutions for improved HCE have been investigated experimentally. As far as possible the results of small scale prototype testing performed in other projects outside the scope of DISS are taken as a basis for tests of full scale HCEs on the LS-3 Testloop at the PSA. The focus of development shall be on improved geometries, but the integration of new selective coatings and other features are also considered.

F) Absorber final design

On the basis of the evaluation of improvement options, the detailed engineering of improved absorbers for future DISS collectors was started and it will continue in DISS-phase II. The PSA DISS Special Test Collector can be used for this purpose.

4 CONCLUSIONS

The main conclusions and lessons learned during the project are summarized in the following paragraphs, on a task-per-task basis.

4.1 Task "Design and Implementation of the PSA DISS Test Facility"

The flexibility demanded to this facility to investigate the three DSG processes over a wide range of parameters (e.g., pressure, temperature and flow rate) has required special equipment that is not usual in standard industrial processes at present, so that some key elements had to be specially designed for the facility (e.g. water recirculation pump and absorber pipes), making it significantly more expensive and causing delays in the project. Nevertheless, the suppliers have remarked that the commercial DSG plant equipment would not be so unique and, therefore, their delivery and price would not be an obstacle.

In spite of these problems, the main objective of this task (i.e., implementation of a large test facility suitable to investigate the three DSG processes under real solar conditions) has been achieved and the test facility erected at the PSA will be invaluable in the next phases of the project for improving current solar power plant technology and increasing their penetration in the power market.

Another lesson learnt during the project is the importance of the materials used in piping and vessels to avoid unnecessary extra cost and problems. After having used four different types of steel piping and fittings, carbon steel (ASME A106 Grade B (St45.8) and Grade C), as well as low-alloy steel (A-335 P11 and P22), it was found that the use of low-alloy steel pipes and fittings must be limited to those places where carbon steel is not possible. Increased wall thickness is preferable to changing from carbon steel grade B to grade C or low alloy steel.

ZSW and SIEMENS have analyzed the technical requirements for the piping of a commercial DSG system, taking into account nominal subsystem pressures and temperatures and have come to the conclusion that carbon steel is suitable in most cases. Only the collector absorber pipes should be manufactured with low-alloy steel.

The review of the current state-of-the-art and availability of information on the LUZ LS-3 SEGS plant collectors at this stage of the project has also been very useful. It was learned, for instance, that some improvements should be included in the original technical specifications issued by SOLEL in order to be able to take advantage of European market availability for manufacture of the solar collector. Some possible manufacturing and assembly improvements have also been identified.

As engineering companies from several countries were involved in the detailed design of the facility, some problems came up with regard to the use of different standards, like DIN, ASME and ISO and different units such as *inch* and *centimeter*, which should have been avoided in the technical specifications and drawings.

Drawings should include only the standards of the manufacturing country. Furthermore, all drawings and equipment specifications should be released only in the language of the manufacturer to avoid misunderstandings.

Good quality control from the very beginning and during fabrication and assembly is essential to assure a quality product. The solar field acceptance tests showed excellent accuracy during mechanical assembly, thus meeting the low margin of tolerance required to achieve good optical efficiency.

4.2 Task "DSG Applied Research"

This task has provided scientific support for the design and implementation of the PSA DISS test facility and the preparation of a detailed test plan incorporating the latest knowledge on direct steam generation.

The applied DSG research projects performed in recent years have contributed significantly to understanding two-phase flow in horizontal tubes. It could be shown, that stratified flow does not necessarily lead to unacceptably high azimuth temperature differences which are decreased by droplets distributed in the steam phase (entrainment) and the tangential heat flux along the tube circumference. The minimum mass flux densities required to maintain thermal stress in the tube wall material below certain levels have been found. The most important conclusion that can be derived from these studies is the certainty that direct solar steam generation is possible in parabolic trough collectors with horizontal absorber tubes. No critical thermohydraulic situations, such as sluggish flow or excessive temperature gradients, occur under static conditions in any of the three basic concepts provided that mass flux density is kept above a minimum value. Therefore, the DISS tests will begin with horizontal absorbers. If any problem arise, the absorbers can be tilted.

The pressure drop in two-phase flow has been investigated in numerous experiments. It is usually described by the pressure drop in one-phase flow with a two-phase multiplier. It was found that the impact of pressure on the two-phase multiplier is very strong, whereas the effects of pipe diameter and mass flow are negligible. Consequently, a correlation can be found between mean mass flow density and pipe diameter, which gives the two-phase multiplier versus the pressure.

As additional possibilities for enhancing heat transfer in the HCEs, the influence of displacers and capillary structures have been investigated. Insertion of displacers can improve heat transfer significantly during the first 200m of the absorber tube by causing closed annular flow to occur earlier. After this initial section, the steam flow rate is high enough to cool the pipe and create annular flow with a closed water film and the installation of displacers is not required. These flow patterns were detected by the typical temperature profiles in the tube cross section and two-phase flow maps for several pressures, thus optimizing the absorber pipe design and DSG process.

The use of capillary structures is an option for future absorber tubes that improves the capacity for rewetting due to integrated capillary systems, such as porous coatings and internal micro-grooves, in horizontal absorber tubes.

Theoretical models have been built to study the behavior and optimize the characteristic property ranges of porous coated and micro-grooved pipes. An experimental setup for checking sample behavior under DSG conditions has been built by CIEMAT for further experiments and optimization of capillary heat transfer.

Based on such experimental research, several numerical simulation tools were developed and tested. Such static simulation programs that determine the pressure drop and heat transfer coefficients of two-phase flow and the temperature distribution over the tube wall were used for the detailed engineering of the DISS test loop.

The dynamic simulation programs developed in DISS have been used to investigate the behavior of the test loop under transient conditions as startup and shutdown. First simulation studies have shown that strong mass flow fluctuation may occur in the once-through and injection concepts. Based on these results, modified startup processes must be found to reduce the increase in flow rates when boiling begins. An optimized general startup procedure must be found that considers the time needed for safe startup and the safety requirements of the solar field. In the following DISS phase, the control strategies for the three DSG modes will be investigated and optimized with these programs to minimize risk to the absorber tubes during experiments.

Besides the general investigation of thermohydraulic aspects, potential alert situations and corresponding control requirements have been identified. As a result of all these studies a first test plan for the experiments at the DISS test facility have been defined. This test plan includes all necessary calorimetric and static tests of the test loop and its components as well as experiments in the three DSG modes in horizontal absorber tubes under solar conditions.

4.3 Task “Collector Improvements”

4.3.1 Set up of LS-3 Test Loop

The optical analysis performed at the half LS-3 collector pointed out the great importance of an accurate mechanical assembly of the space frames in order to meet small tolerances regarding the position of the parabolic mirror supports. Another conclusion from the assembly and preliminary testing of the LS-3 test loop is the necessity of an experimental comparison between the traditional local tracking control designed by LUZ and the advanced local control developed by the PSA (based on a calculation of the sun position by means of theoretical algorithms).

4.3.2 Improvement of DISS Test Loop

A procedure was defined to aid in the process of improving the collector and loop design for future prototype systems. This consisted of an analytic evaluation of the cost-effectiveness of potential improvements, noting development status, technical characteristics now and with improvements, and estimates of cost and performance change

Although the fact that the experimental character of the DISS test facility added complexity to the design, it may be concluded that tilt leads to significant cost increases for LS-3 like designs, which will be difficult to compensate by increased performance. Main problems are the higher wind loads and the resulting forces on the elevated north ends of the collectors, and the expected complications for O&M of such systems (e.g. the cleaning procedure).

The economic comparison of selected HTF and DSG systems show that a LEC reduction in the order of 25% seems to be possible by introducing a DSG system. The original projection of a 30% LEC reduction was slightly higher. However, additional improvements stipulated in the original proposal but not yet included in the comparison (e.g., tilt, other collector design improvements and larger plant size) could lead to further projected benefits.

Additional benefits of the DSG process are the possible reduction of fire hazards and environmental risks as well as a most likely higher efficiency (than HTF systems) by integrating this process into combined cycle plants. Quantification of these benefits, however, is not possible on the basis of present knowledge.

On the basis of the evaluation of the most promising improvements and experience with operation of the first loop, a preliminary selection of improvements to be implemented in the second loop was made. However, operating experience with the first DISS loop is a prerequisite before final selection.

4.3.3 Improvement of Structure and Tracking System of the LS-3 Test Loop

Silver and aluminium front surface reflectors have been produced by CIEMAT with very good optical properties and specular reflectances from 0.94 to 0.965. Durability has been studied in a weathering chamber. Extrapolated to outdoor conditions the durability obtained up to now is 5 years.

As stated earlier, no improvements in the tracking system (hydraulics, drives and tracking software) components are currently recommended, though the open-loop tracking system in the first DSG collector loop will continue to be observed.

4.3.4 Heat Collection Element Improvement

A review of the ongoing development regarding selective coatings was performed and mainly two production methods for commercial selective coatings are known. Selective coatings like black chrome and Sunstrip (colored aluminum by cobalt), are produced by a electrochemical method. With PVD methods, like evaporation and sputtering, selective coatings with high performance are produced. A Cermet with very good optical properties seems to be the combination of SiO_2 and Cu. However, such selective coatings are not commercially available yet and have considerable durability problems at 400°C in air. A protection and antireflective coating on the top of the selective coating can be a possibility to solve this problem. Cermets based on SiO_2 and Cu or Pt are currently produced by applying the sol-gel technique.

Regarding the stress analysis in the absorber tube, calculations showed 70K to be an acceptable circumferencial temperature difference in the steel pipes. Therefore, this value was defined as an operating limit for the single row system, and the development of the complex FEM model postponed.

With the results achieved by CIEMAT by applying the innovative sol-gel technique also in the field of absorbers and AR coatings it is possible to conclude that sol-gel opens an important way in the production of solar materials, with the advantage of using a unique deposition technique.

Concepts of new absorber geometries are under discussion with industrial partners. The emphasis is on simplicity of design and production, as opposed to highest concentration. After first tests of such prototypes at the new PAREX test facility at the DLR research centre at Köln-Porz, promising concepts will be designed in LS-3 size to be tested at the PSA LS-3 test loop during the second phase of the DISS project.

Evaluating selected options, a LS-3 size design was developed and manufactured within the PAREX project (because the associated costs exceeded the resources allocated to this task within DISS). The prototypes were tested on the PSA in October 1998. Unfortunately, the evaluation of these experiments was marred by the performance problems of the LS-3 test facility. Nevertheless, some design shortfalls could be identified, and an improved design is underway and will be tested during summer 1999.

5 EXPLOITATION PLANS AND BENEFITS

The partners of DISS belong to the main sectors involved in a future commercialisation of the technology to be developed within this project (i.e. Industries and Electric Utilities), thus guaranteeing a proper exploitation of results in the future. The progress in using the solar energy for power generation will be a synthesis and melting together of the know-how brought in by all the partners from the solar field side, the conventional power plant side and from the laboratory and field test responsibles as well. The results gained during the DISS project will be the basis for further activities based on practical results.

Solar thermal electric parabolic trough technology must seek ways to reduce costs at higher performance levels, compared to current levels, to be more competitive in the power market. The DISS project is a valuable chance in that direction because it is aimed at developing the DSG technology and those potential improvements that could lead to a new generation of solar thermal power plants, thus reducing 30% the current electricity generation cost. This reduction is the result of a 15% reduction in direct investment costs and a 20% increase in efficiency.

Recent studies have shown the high potential for solar thermal electricity generation in the Mediterranean area: 3.5 GW until year 2005; 23.2 GW until 2025 for particular countries; 60 GW in the case of Mediterranean-wide interconnecting grids. These values can double if the electricity demand is higher than expected. In the southern Mediterranean area, the available potential is practically unlimited. It has also been pointed out by these studies that the introduction of solar thermal installations in the Mediterranean must be accelerated to play a pilot function because this area represents only a fraction of the earth's sunbelt.

As the electricity generation cost is still high when using the available solar thermal electric parabolic trough technology, development and implementation of improved components and a more efficient technology will allow the installation of solar thermal power plants all over the sun-belt of the earth, thus opening a very attractive market not only for industries located in these area, but also for industries located in countries where the technology could be exported from.

Many recent studies performed by European and non European countries have concluded that implementation of Solar Thermal Power Plants is technically feasible, economically affordable and, due to environmental reasons, necessary in order to reduce the CO_2 emissions:

- A solar thermal plant saves about 2000 Tons of CO_2 emissions per year and MW of power. This means that a 80 MW plant would save 160000 Tons of CO_2 per year.
- Each GWh produced with solar energy reduces the CO_2 emissions in 800 Tons (approx.).

These data show the positive social impact of solar thermal technology, improving the living conditions and protecting the environment from the pollution caused by the conventional fuels. Since the main objective of the DISS project is the improvement of the competitiveness of this technology by means of a reduction of the levelized electricity generation cost, its social and economic benefits seems to be clear.

Nevertheless, it must be pointed out here that commercial development of the DSG process and solar collector improvements will be useful not only for solar thermal power plants, but also for the implementation of any other solar thermal energy application at medium and high temperatures (e.g. Seawater Desalination, Industrial Process Heat applications, etc..) where a more efficient heat transfer between the solar field and the industrial process will improve their competitiveness against conventional systems powered by fossil fuels.