Grant Agreement number: 281338

Project acronym: OPTS Project title: OPtimization of a Thermal energy Storage system with integrated Steam Generator

Funding Scheme: Collaborative Project

Date of latest version of Annex I against which the assessment will be made: 27/10/2011

Periodic report: 1st ■ 2nd ■

Period covered: from 1 / 12 / 2011 to 1 / 08 / 2014

Name, title and organisation of the scientific representative of the project's coordinator:

Dr. Salvatore Sau

Agenzia per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile – ENEA

Tel: +39 06 30486334

Fax: +39 06 30486779

E-mail: Salvatore.sau@enea.it

Project website address: http://www.opts.enea.it

Declaration by the scientific representative of the project coordinator

I, as scientific representative of the coordinator of this project and in line with the obligations as stated in Article II.2.3 of the Grant Agreement declare that:

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period;
- The project (tick as appropriate):
  - □ has fully achieved its objectives and technical goals for the period;
  - ■ has achieved a significant part of its objectives and technical goals for the period, however, it has not been possible to achieve critical objectivies of the project.
  - □ has failed to achieve critical objectives and/or is not at all on schedule.
- The public website, if applicable
  - ■ is up to date
  - □ is not up to date
- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 3.4) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 3.2.3 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of scientific representative of the Coordinator: Salvatore Sau

Date:

Signature of scientific representative of the Coordinator:

TABLE OF CONTENTS

PUBLISHABLE SUMMARY

Project information

Project acronym: OPTS

Project full title: OPtimization of a Thermal energy Storage system with integrated Steam Generator

EC Program, Theme and Topic: FP7- ENERGY.2011.2.5-1: *Thermal energy storage for CSP plants*

Grant agreement no.: 281338

Participants:

No.	Beneficiary name	Short name	Nationality
1	AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE,L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE ENEA	ENEA	Italy
2	COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES CEA	CEA	France
3	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	CNRS	France
4	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V Fraunhofer	FRAUNHOFER	Germany
5	WEIZMANN INSTITUTE OF SCIENCE Weizmann	WEIZMANN	Israel
6	THE CYPRUS RESEARCH AND EDUCATIONAL FOUNDATION CREF-Cyl	CREF-CYL	Cyprus
7	ANSALDO NUCLEARE SPA ANSALDO	ANSALDO	Italy
8	CENTRO DE INVESTIGACIONES ENERGETICAS, MEDIOAMBIENTALES Y TECNOLOGICAS-CIEMAT CIEMAT	CIEMAT	Spain
9	COBRA INSTALACIONES Y SERVICIOS S.A COBRA	COBRA	Spain
10	Laboratorio Nacional de Energia e Geologia I.P. LNEG	LNEG	Portugal
11	TECNIMONT KT - KINETICS TECHNOLOGYSPA TKT	TKT	Italy

Project logo:

Project Coordinator Contact Details:

Dr. Salvatore Sau

Affiliation: ENEA

Address: via Anguillarese 301, 00123, Rome (Italy)

Phone: +39 06 30486334

Email: salvatore.sau@enea.it

Project Website: www.opts.enea.it

SUMMARY DESCRIPTION OF PROJECT CONTEXT AND OBJECTIVES

The aim of the OPTS project was the development of a new Thermal Energy Storage (TES) system based on a single tank configuration, using stratifying Molten Salts (MS, Sodium/Potassium Nitrates 60/40 w/w) as heat storage material, with 550°C of maximum temperature, and an integrated Steam Generator (SG). The final target is to provide an efficient, reliable and economic energy storage system for the next generation of trough and tower plants.

The experimental program was focused to the full development of the integrated system (TES-SG) up to demonstration level, having as a final target the building of a sufficient relevant scale (at least 12.5 MWth) facility, which maintains the same main thermo-fluid-dynamic parameters as the full scale (125 MWth) system. Unfortunatly, due to the withdrawal of the industrial partner responsible for the test section construction, and given the impossibility to find out a new company available to join the project within the time granted by the EC, it was not possible to finalize the project with the expected facility completion; however the obtained experimental and simulation data, shortly described below, are highly innovative and of great interest for the development of the TES technology related to concentration solar plants (CSP).

Besides the system employing an integrated (immersed) SG, also a thermal energy storage system using a solid filler as heat storage material and molten salts as thermal fluid, coupled with a CSP plant, was investigated. The TES-SG system and the filler based TES was compared.

It was also possible to perform some estimation about the actual cost of an integrated TES SG system, results clearly encourage further investigation on this topic.

PROJECT FINAL RESULTS (RTD)

Here follows a description of the work developed during the project. The activities are described according to the project subdivision in work package (wp) and subtasks.

Basic studies on molten salt mixtures as HSM and HTF and on their compatibility with materials (WP2).

The work package title is "Basic studies on molten salt mixtures as HSM and HTF and on their compatibility with materials". Basically, the wp was dedicated to the study of chemical, physical and fluidodynamics features of the employed heat storage material (HSM), that is, a mixture containing (in weight percentage) 60% of sodium nitrate ($NaNO_3$) and 40% of potassium nitrate (KNO_3); from here on this material will be indicated as "MS" (molten salt).
The MS mixture is one of the most largely used HSM material, for this reason, all the concerned data already present in the scientific literature were to be collected and, where necessary, validated and completed. This work is reported in the "State of Art" report (Task 2.1, deliverable 2.1)
Also the other RTD tasks were completed:

Task 2.2, "Basic heat transfer correlations for a SG tube bundle – MS system"
Task 2.3, "Corrosion aspects of selected materials in contact with nitrites containing MS"
Task 2.4, "Study on MS thermal stratification process"
Task 2.5," Materials and equipment durability"
Task 2.6," Characterization of filler materials and compatibility with MS at high temperature"
Task 2.7," Testing of the reliability of the hydraulic components""

More specifically, the task 2.2 was concerned with both the study of the heat transfer coefficient of the MS/water system and the study of the stractification properties of MS (thermocline), these investigations were carried out at the ENEA PCS and CIEMAT solar facilities; in task 2.3 the compatibility at high temperature (up to 550 °C) of several materials (stainless and carbon steel alloys) is investigated, these alloys are to be employed in the future for the construction of the tank and the immersed SG bundle; regarding task 2.4, the work was mainly dedicated to the fundamental study of MS chemical stability at high temperatures, a crucial point in order to establish the highest possible operating temperatures; task 2.5 was concerned with SG materials resistance under thermal (up to 550°C) and mechanical stresses up to fracture stress in a MS environment.The compatibility between MS and employable filler materials (thermal storage using solid filler materials as HSM is another part of the OPTS project, as described in the previous section) was considered in T2.6.
Finally, T2.7, regards to the reliability and performance of molten salt loop components. Under this task, tests of different immersion electrical heaters, electrical heat tracing systems, valves and insulation materials have been performed at the Plataforma Solar de Almería (CIEMAT).

WP3

The title is "Full-scale TES-SG system: analysis, modelling, simulation and design", and this wp is dedicated to a theoretical and design study of thermal energy storage (TES) systems presenting a commercial size, namely, 50 MW of electrical power. Two types of TES are considered: the system, representing the main target of the OPTS project, where thermal stratification of MS is used in combination with an immersed SG bundle (TES-SG); and an alternative configuration where different kinds of solid filling materials are employed as HSM; besides, the two TES systems were compared. All the tasks were finalized.

Task 3.1 "Analysis, modelling and simulation of the stratified MS Storage Tank with integrated Steam Generator", was dedicated to a complete thermo fluidodynamic modeling of a 125MWth/50 MWel TES-SG system where five 25 MWth SG units are immersed in the same MS tank.

Task 3.2 "Analysis, modeling and simulation of the thermo-cline Storage Tank with internal filler", was concerned with a thermo fluidoduynamic modeling of a plant presenting the same size of task 3.1, but, in this case, solid materials are proposed to store the thermal energy.

Task 3.3 "Project executive of the stratified MS Storage tank with integrated Steam Generator", was the design, with the production of the final drawings, of the TES-SG system modelled in task 3.1.

Task 3.4 "Implementation of TES models in CSP performance models" involves a simulation of TES models suitable for full year performance of complete solar thermal. The major aim was to study the impact of a TES system over the CSP plant behaviour.

WP4

The WP title is "Reduced scale TES-SG Test Section: scaled modeling, analysis, simulation and design"
In summary, the aim of this wp was the modelling and the design of a test section plant (5MWel) to be constructed and implemented at the COBRA CSP plant in Casablanca (Spain). The plant size was chosen in order to maintain thermo-fluidodynamics features valid also for larger commercial plants (like the one described in WP3). Excluding T4.4, all tasks were finalized.

Task 4.1 "Analysis, modelling and simulation of the Test Section (TS) simulating the integrated Steam Generator inserted in the stratified MS Storage Tank", analogous to Task 3.1, but concerning the modelling of the test section with the presence of just one integrated SG.

Task 4.2 "Design of Test Section", was concerned with the production of the final drawings for the test section.

Task 4.3 "Design of the modifications of existing test facility", it was a design task, regarding the project, with the necessary modifications, to implement the TES-SG system at the COBRA plant in Casablanca.

Task4.4 “Test matrix of experimental tests on the stratified MS Storage Tank with integrated SG”: for the reasons espressed above it was not possible to carry out the task.

WP5, WP6, WP7

For the reasons stated above it was not possible to finalize these wps. Anyway, task T7.2 “Assessment of the cost for up scaling from pilot (or pre – industrial) scale to industrial scale” was addressed and discussed.

WP8

Beside these activities, also a dissemination campaign was carried out, by scientific meeting presentations, publications in peer reviewed journals and by the maintenance of an updated dedicated web-site, where also an e-learning activity was performed.

IMPACT

Substantial worldwide reduction of greenhouse gas emissions is expected by 2020 by exploitation of renewable energy sources. As stated in the European Commission’s SET Plan “reinventing our energy system on a low carbon model is one of the critical challenges of the 21st Century”.
To achieve this objective, the efficient and cost-effective conversion of solar energy to utilizable energy vector is a must.

OPTS impact may be identified in the following domains:
- Lowering the costs of renewable energy and demonstrating solar power applications scalability. By optimizing the technology of basic components, the results of the OPTS project will contribute to make this system cost-effective and competitive, with regard to conventional fossil-fuel based systems. Multipurpose facilities as those that adopt the components developed through OPTS project will efficiently contribute to the objectives as stated in the European Industrial Initiatives (contained in the SET plan), with specific regard to the Solar Initiative, by realizing a plant based on an innovative technology avoiding CO_2 emissions and capable to produce electricity and heating during night time and with rainy weathers and to store/conserve energy for relevant amounts of time. Further, through the implementation of OPTS project, the consortium wanted to show that CSP technologies are not just something confined to the science laboratory, but something efficient and cost-effective enough to be put to use on a much larger, industrial or commercial scale. However it was not possible to build up the 12.5MWth facility, the experimental and modelling results, clearly showed the validity of the CSP-TES systems, and encourage to carry on this direction.
- Contributing to the use and development of renewable energies. OPTS project will demonstrate the technical and economic viability of molten salt solar thermal power technologies to deliver clean, cost-competitive bulk electricity without negative environmental impact. In this process, strong attempts to use local energy sources and to reduce energy transmission losses will be pursued, thus granting sustainability to local territories and communities.

- In particular, the project was particularly focused on the development and validation of new concepts of TES (thermal energy storage) systems for concentrated solar plants, not only by the above described thermocline TES system with integrated steam generator (SG), but also by investigating solid fillers based TES configurations. All the issues concerned with the practical applicability of these technologies, and for which literature data are few or missing, are studied as well (for instance, upper temperature limit of the heat storage material under investigation, that is the "solar salt", construction and equipment material compatibility, and so on).
- Placing EU research organizations and industries in the leading position in solar technologies. OPTS project positively answers to the requirements of the SET plan, with regard to establishing partnering initiatives between public investment and the private sector, as clearly shown in the consortium composition. OPTS develops a new technology in the frame of EERA (European Energy Research Alliance), merging a large part of the on-going Joint Programme on CSP technology and contributing to increase the competitiveness of EU research and industry at world level.

WORK PROGRESS AND ACHIEVEMENTS DURING THE PROJECT PERIOD

In the following paragraphs is described a short summary of the activities carried out in the different tasks; a particular emphasis is put on the description of the accomplishment regarding the expected project objectivies and milestones.
For more information about the technical details, please refer to the submitted deliverables.

WP2: BASIC STUDIES ON MOLTEN SALT MIXTURES AS HSM AND HTF AND ON THEIR COMPATIBILITY WITH MATERIALS

RESUME OF WP2 OBJECTIVES

WP2 was intended to contain all the chemical-physical characterizations strictly necessary in order to validate or complete the data on the following topics:

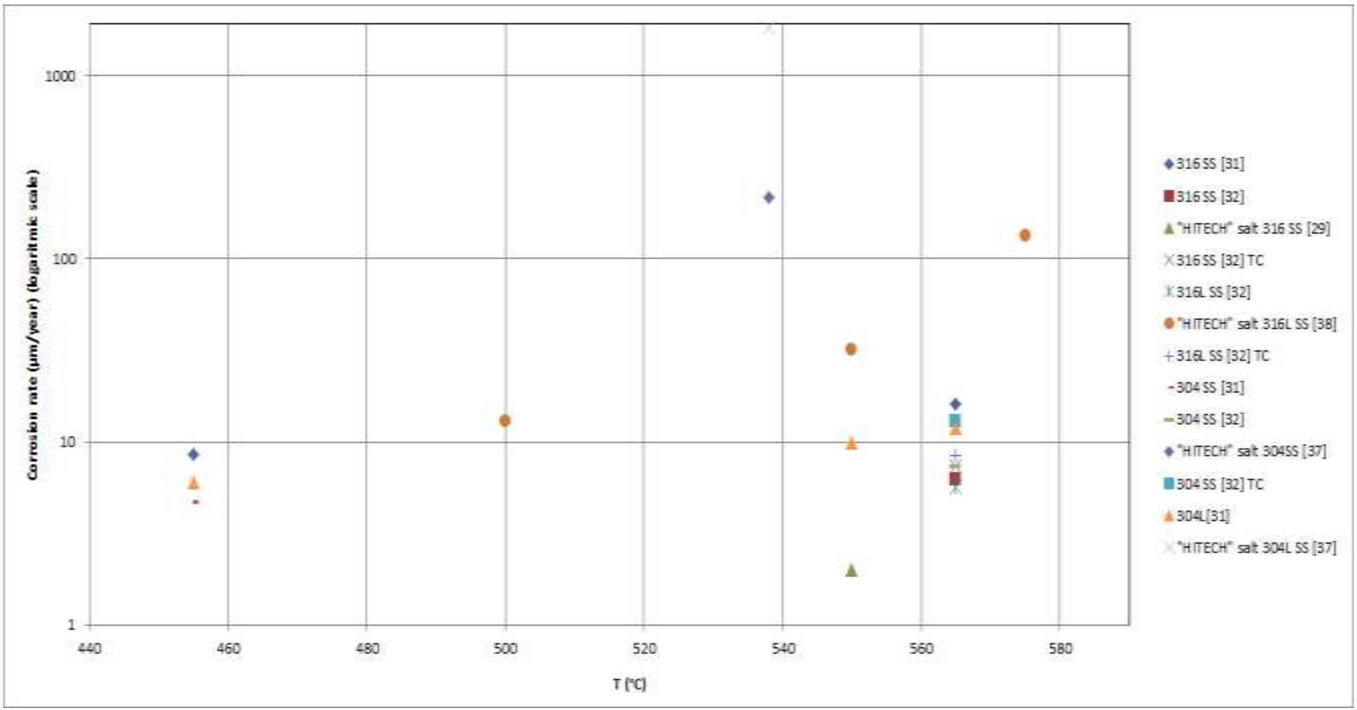
1) Molten salts thermophysical behavior at the operating temperature, with a particular emphasis on heat transfer properties, thermal stratification and thermal stability
2) Compatibility between construction materials or solids used as heat storage systems (filler) with the nitrate binary mixture called “solar salt” ($NaNO_3$/KNO_3 60 :40 in weight percentage)
3) Compatibility between CSP equipment with this mixture at CSP operative temperatures and conditions

Task 2.1: State of the art (deliverable D2.1)

The work was completed by the delivery of D2.1. In particular, an extensive research on the available scientific literature was carried out; the collected data were integrated, when necessary, with ENEA results, and are summarized in the following table:

Thermo-physical property	Equation	Note
Heath capacity - Cp	$C_p = 1.5404 + 3.0924 \cdot 10^{-5} \cdot T$	C_P [J / K gr] T [°C]
Density - ρ	$\rho = A - B \cdot T$	ρ [gr/ml] A=2.1060 gr/ml B=6.6795·10^{-4} gr/ml °C T [°C]
Viscosity - μ	$\mu = e^{\left(A + \frac{B}{T - T_0}\right)}$	μ [cp] (mPa ·sec) respect to 1 cP for water at 25 °C A= -7.71, B=709.8 °C, T0=-59 °C, T in °C
Thermal conductivity - k	$k = 0.3804 + 3.452 \cdot 10^{-4}\, T$	K in W/°C m T [°C]
Thermal diffusivity - α	$\alpha = \frac{k \cdot 10^{-2}}{C_p \rho}$	α [cm^2/sec] K, Cp, ρ from ref. 15

also the available results about corrosion compatibility between molten nitrates and several metals and alloys were collected, they are summarized in the following figure, where is reported a comparison between the effect of the solar salt ($NaNO_3$/KNO_3 60:40 in weight percentage) and a mixture containing nitrites (namely the “Hitech” salt, consisting of 7 wt% for $NaNO_3$, 53 wt% for KNO_3 and 40 wt% for $NaNO_2$) on several stainless steel alloys. Corrosion rate is expressed in µm/year.



Finally, a survey on the available data on molten salts thermal stratification behaviour and heat exchange properties was carried out.

<u>Milestone achieved: MS4.</u>

Task 2.2: Basic heat transfer correlations for a SG tube bundle – MS system (deliverable D2.2)

The work was carried out by Fraunhofer-ISE, ENEA and CIEMAT, and deals with the overall performance and numerical investigation, as well as the experimental determination of the heat transfer coefficient, of an integrated storage sytem (as expected in the OPTS project), where, in particular, helical coils steam generators (HCSG) are used.

Fraunhofer's part gives some general fundamentals of heat transfer which are used in the following section to estimate the heat transfer coefficient in the steam generator. The challenges are highlighted if a multi-phase fluid is used on one side of the heat exchanger. Different correlations for the shell-side heat transfer coeffiecient are compared for the design data of the 300 kW prototype. The experimental methods for heat transfer coefficient determination are explained and the design of a facility to determine the shell-side heat transfer coefficient is described, and the experimental rig constructed for this aim is described. In the last section the experimental data from ENEAs prototype are used to estimate the overall heat transfer coefficient.
ENEA describes the TES-SG system located at the PCS facility in Casaccia and focuses on the stratification behaviour which was originally part of deliverable 2.4 but was moved to this deliverable, 2.2. All the available instruments for temperature, pressure, level and flow are shown and capabilities and limits are presented. Different test have been carried out to investigate e.g. part load or stratification. The results are analysed and recommendations for larger systems are given to improve the performance of the system.
CIEMAT also analyses the heat transfer with a focus on the molten salt heat transfer coefficient. The complete system is simulated by computational fluid dynamics and the numerical methods are presented. Also all the boundary and initial conditions are described. The numerical results are compared to experimental data to validate the simulation. The numerical data are used calculate the shell-side heat transfer coefficient and a heat transfer correlation is obtained. Different already existing correlations for helical coil heat exchangers are investigated and checked if they are suitable for the geometry of the steam generator as well as compared to the obtained correlation.

Fraunhofer's analysis of the prototype SG design data resulted in an OHTC of 635 W m^{-2} K^{-1} which would be necessary to obtain the design power. The precise identification of the primary HTC is difficult due to strongly varying HTC on the secondary side. It was shown that the OHTC is much more sensitive to the primary HTC than to secondary HTC. Optimizing and identifiying the primary HTC is therefore more important. Feeding the SG data into existing correlations for shell-side HTC resulted in a wide range between 831 and 1781 W m^{-2} K^{-1}. The erected molten salt facility at Fraunhofer ISE uses thermal oil and secondary side which would allow an easier identification of the primary HTC. Unfortunately the plant was not ready at the submission of this deliverable. Therefore experimental data from the 300 kW SG prototype in Casaccia have been used to perform a heat transfer analysis. The data show that the SG is even exceeding its design power. A division of the secondary side into three regions allows the determination of UA values and thus also an estimation of the OHTC and primary HTC. The OHTC is around 784 W m^{-2} K^{-1} and the primary HTC depending on the secondary HTC between 950 and 1200 W m^{-2} K^{-1}.

ENEA shows all the relevant sensors which can be used for the analysis of the experimental data and explains the operational start-up procedure of the system. During the measurement campaign the steam generator was tested down to 50% part load. The production of superheated steam was possible over the full range even with off-design molten salt inlet temperature which was reduced down to 450 °C. The thermocline zone remained constant when the storage was simultaneously charged with hot molten salt during discharge by the steam generator. Some instabilities arose which are caused by the different tube lengths. An improved system should show a more balanced tube length distribution. An improvement which was identified during the test was the design of inlet pipe to reduce mixing of the inlet stream with cold salt in the tank. Natural circulation could be enhanced by reducing the length of the steam generator compared to the height of the storage tank.

Ciemat's CFD simulation was carried out with Star CCM+, the used geometry has more than 1.6 Mio. cells with refinement in the tube bundle region and close to the walls. The SG outlet temperature, SG power and MS flow rate have been used to validate the simulations with experimental results from the former SG prototype in Casaccia. The difference in SG power between model and experimental results is during steady-state conditions less than 8 kW which less than 5% deviation. During the analysis, the circumferential wall heat flux as well as MS bulk temperature is used to calculate the heat transfer coefficient. As expected, the HTC varies locally and is in a range between 600 and 1200 W m^{-2} K^{-1}. The highest HTC values are on left and right side of the tubes where the gap is the smallest and the velocity, thus, the highest. The surfaced averaged HTC of the individual tubes is between 775 und 950 W m^{-2} K^{-1}. The highest values arise in the upper section of the steam generator. The obtained correlation from the CFD results is compared with correlations from literature. It shows a good agreement with one correlation which was obtained experimentally. The new correlation can be used for the design of future system of this kind.

Together with other wp2 activities described below, the results obtained in this task contributes to the achievement of MS5 and MS7

Task 2.3: Corrosion aspects of selected materials in contact with nitrites containing (deliverable D2.3)

This work was carried out by ENEA and LNEG laboratories.

To date, the most conservative option for systems working at temperatures above 500 °C, is the employment of SS alloys such as 321H and 347H; however some results are already present in the scientific literature, mainly derived from the Solar Two experience, it is necessary a completion of the data regarding these materials, especially considering that they represent the first choice for the construction of the OPTS TES/SG (Thermal Energy Storage/Steam Generator) like systems. It is also very interesting to investigate the compatibility behavior of materials like carbon steels.

Considering all these issues, the work of ENEA and LNEG was organized in this way: 347H (LNEG) and 321 (ENEA, practically equivalent, for the study purpose, to 321H) compatibility was investigated in a temperature range of 550-560 °C; both tests were performed for a significant contact time (4100 h at LNEG and 2000 h at ENEA) and in static conditions.

Moreover T91 was tested at ENEA laboratories, in the same static conditions of SS 321.

Results can be summarized as following:

- A stable oxide surface layer, some microns of width, is formed both on 347H and 321 surfaces. Two different sample handling methods were employed by ENEA and LNEG. ENEA kept the oxides over the specimens and followed the weight increase while LNEG removed all the oxide coating formed and followed the weight of metal that was lost to form those oxides. LNEG did a calculation of the average oxide thickness based on the area of samples and the density for hematite and magnetite, and values are in good agreement with the thickness measured micrographsby microscopy. Corrosion rates were quite significant initially and then reduced after long-hour immersion and was explained by the occurred depletion of chromium on the layers nearby the surface that creates difficulties to diffusion. In summary, a weight increase due to oxide layer formation was present both for SS347H and SS321 (in this case, only the initial and final weight was checked).

- The resistance of SS 347H and 321 in contact with alkaline molten nitrates at 550 °C can be confirmed.

- Clearly, considering the higher oxidation tendency, and the evident presence of descaling processes, T91 showed, as expected, a minor resistance to nitrate aggression. However, no internal corrosion phenomena were detectable. Tests at longer exposition periods are certainly necessary to confirm or not the compatibility of this material. Given the relatively high oxidation rate, also the molten salt degradation (for instance, accumulation of chromate and molybdate) should be checked. In case, a proper material thickness can be calculated for long period employments. Anyhow, the employment of carbon steels could be useful in systems presenting a lower upper temperature limit (below 500 °C), in this case the increase of molten salt amount (necessary to keep constant the energy stored as sensible heat), could be compensate by the decrease of the tank and SG costs; evidently, also lower temperature will be employed in the next future for T91 compatibility tests.

- In a TES system presenting an integrated SG bundle, the components (tank and heat exchanger) are exposed to daily temperature gradients, from about 550 °C to 290 °C. Thermal stresses could affect the material resilience, thus, more corrosion tests are to be implemented in the next future including thermal cycles procedures

- As a final remark, it is necessary to stress the fact that the use of SS 347H and 321H is mainly due to the plant handling during maintenance in shutdown conditions, where the equipment can be exposed to atmospheric agents (see report D2.1, par. 4, for more explanations about this behavior). In general, an integrated TES/SG system could be subjected to those kinds of procedures, for instance, an immersed SG could present the necessity to be extracted for reparation. It is clear that, the possibility to employ cheaper alloys is also related to the improvement of these procedures.

<u>T2.3 results are a contribution for MS5 achievement and are concerned with the reaching of MS5.</u>

<u>Task 2.4:</u> Study on MS thermal stratification process (deliverable D2.4)

The task work is concerned with the development of a bench scale experimental set-up for static condition tests on thermal stratification of MS.

Considering that thermal stratification properties are also being investigated, on a scale larger than the laboratory one, in T2.2, and that both ENEA and the task beneficiary, CREF-Cyl, considered extremely important, for the completion of the molten salts experimental data, the study of the kinetics and thermodynamics behaviour concerning the nitrates thermal degradation:

$MNO_3 \rightleftarrows MNO_2 + \frac{1}{2} O_2$ (M = Na,K)

$5MNO_2 \rightarrow M_2O + 3MNO_3 + N_2$ (M = Na,K)

ENEA and CREF proposed to change the task topic from thermal stratification into thermal degradation investigation. However, CREF-Cyl also performed laboratory scale thermal stractification tests.

The work was organized in this way:

ENEA studied chemical degradation of molten salt mixture named “solar salt” and consisting of $NaNO_3/KNO_3$ with a weight percentage composition of 60/40. Experiments were carried out in a temperature range from 575 °C to 675 °C; both evolved gases and the molten bulk were sampled and analyzed.

Cyprus Institute investigated, in parallel with ENEA, “solar salt” thermal decomposition, by employing a very similar experimental setup. Furthermore stratification experiments were performed aiming to study natural convection in a regular geometry, at Rayleigh numbers encountered within molten salt tanks.

Both organizations approached the chemical decomposition problem with the same strategy, e.g. creating a small reactor vessel and sampling the produced gas and liquid to determine produced species. Although the strategy was similar, several differences are present in the implementation and the experimental procedure.

One major difference of this work with respect to previously published works is the sample size used in the decomposition experiments, which is on the order of a few kg versus a few milligrams in the literature studies. This was done for two reasons, firstly that the larger sample size is more representative of stagnant molten salt occurring in a thermocline thermal energy storage tank and also to verify the belief that the decomposition reaction is catalyzed through the presence of oxygen, and hence occurs on the melt mixture and not throughout the melt volume. Preliminary data supports this postulation; however, further experiments are necessary to definitively answer this question.

Unfortunately, it was not possible to exactly predict the temperature inhomogeneity present in a batch reactor like the one used in the here reported experimental campaign. Temperature gradients were very high during the tests and for this main reason the obtained kinetics data can be considered with a semi-quantitative precision. The time and resources limitation of the project did not give the opportunity to upgrade the experimental facility in order to fix these problems. However, when possible, another experimental investigation will be carried out by using the same equipment integrated with a stirring system for the molten salt decomposer.

The most significant obtained information can be summarized as following:

1. Thermal degradation of nitrates mixtures takes at least one week of time to reach the equilibrium value of nitrites concentration;
2. Oxides are detectable in the liquid melt only above 625 °C, but nitrogen evolution is present from 600 °C on. Apparently, gas measurement looks like a better method to qualitatively

estimate the onset for alkaline oxides / super oxides formation. It is also interesting to note that this onset corresponds to the one reported in the scientific literature [1];

3. Even after one week time, oxides percentage is in any case very low. The obtained values were always below 0,03% (wt% considering hydroxides), which can not affect in any way the physical/chemical properties of the nitrates mixture. When possible, it will be necessary to follow oxide formation during far longer periods of time, in order to determine the real life time of the binary mixture at temperature above 600°C;
4. Concerning the back reaction, it appears to be very slow at temperature when thermodynamics favours it. This behavior would make difficult an eventual molten salts upgrading if nitrites have to be rapidly reconverted to nitrates;
5. The obtained equilibrium or quasi-equilibrium (a very slow oxygen evolution was present even after one week time at temperatures below 650°C) values for nitrites formation can be considered realistic by comparing them with calculated literature values.

<u>These task activities contribute to the achievement of MS7.</u>

<u>Task 2.5:</u> Materials and equipment durability (deliverable D2.5)

Task 2.5 focused on investigating possible damages of metal components of the heat exchanger evaporator due to combined thermal (up to 560°C) and mechanical stresses. Whereas studies on the effect of pure corrosion by several different salt mixtures on metals are already published the combined effect of both mechanical loads and high temperature corrosion are rarely available.
The reason for this is the insufficient availability of testing equipment for mechanical testing of materials in a molten salt environment.
Thus the objectives of Task 2.5 can be summarized as following:
(i) Developing a test rig to investigate the possible damage of metallic materials under a combined mechanical and corrosive loading situation
(ii) Performing comparative strength investigations to assess the additional effect of molten salts on high temperature strength properties of metallic materials used in the heat exchangerevaporator

CERT (combined mechanical and corrosive loading) tests in salt are difficult to conduct due to the corrosive attack of the salt also on the test setup. The CERT setup in salt could be realized and tests could be conducted successfully.
The results of the CERT tests were unexpected. For example for the short term tests the sample tested in salt bears higher forces than the sample tested in air.
The interpretation of test results is complex, as multiple effects influence the samples during the CERT test:

- the samples need to endure corrosive attack from the salt and also at air at 550°C
- the microstructure changes during the test due to nucleation and coarsening of carbides
- nitrogen diffuses into the samples tested in salt which changes the surface properties

Comparison of the hardness after each test shows that the effect of precipitation of carbides on the mechanical properties are significant. The effect of nitrogen on the overall material properties may be small as only a small surface area is affected.
It can be concluded that the effect of precipitation hardening on the samples during the test may be greater than the effect of the corrosive salt media on the CERT test.

The work of this task is as well concerned with MS6.

Task 2.6: Characterization of filler materials and compatibility with MS at high temperature (deliverable D2.6)

As a major advance towards a sustainable and low cost TES system, one interesting way is to use filler materials made of recycled industrial waste. Recent achievements have been done in the production of 100% recycled ceramics from industrial waste. Those refractory ceramics are elaborated by melting and subsequent crystallization of asbestos containing wastes (Cofalit) or municipal solid waste incinerator fly ash, coal fly ash and steel slags. Up to 1000°C, they present good thermo physical and high thermo mechanical strength. Those refractory ceramics are potentially suitable for structured thermoclinestorage. Some of them can be obtained as a molten form during their industrial production and directly shaped at the outlet of the furnace without any additional energy consumption. This is particularly interesting since it allows to shape some complex and optimized geometries in order to intensify the external convective heat transfer between the HTF and the filler material by increasing the exchange area or creating obstacles in the fluid channels. Considering that the corrosion by molten salts is animportant parameter, it is essential to study, in the range of the operating temperature (300–500 C), the relative compatibility of the considered ceramics to validate the approach. Indeed, in the packed-bed TES system, the ceramic will be always in direct contact with the molten salt. The risk is that the salt reacts with the ceramic and destroys it partially or even entirely.

The aim of task T2.6 is to evaluate the feasibility of using ceramics from industrial wastes as filler materials in a direct storage configuration. A direct molten salt thermocline storage system using these low-cost ceramics as filler material is considered. Thus, the chemical and structural behaviors of ceramics made of: asbestos containing waste, coal fly ashes and metallurgical slags were investigated for a direct contact with the conventional solar salt. The tests were performed during 500 h at 500°C which is the potential maximum working temperature of parabolic troughs. Post-mortem analyses after the corrosion test were performed using X-ray diffraction (XRD) and Environmental Scanning Electron Microscopy (ESEM).

Results can be summarized as following: Three different ceramics, corresponding to different kinds of inorganic wastes (asbestos containing waste, Coal Fly Ashes, Converter steel slag) have been investigated. The samples were immersed for 500 h at 500°C in Solar Salt, the binary sodium-potassium nitrate. The post-treatment microstructure analysis had permitted to conclude that: the Cofalit, the CFA can be used in direct contact with the conventional solar salt. The converter steel slag is not appropriate to be used in a direct molten salt storage configuration. The limiting factor appears to be the high iron concentration in certain crystallographic phases. One explanation may be that the iron containing phases are dissolved in the molten salt at low temperature. This assessment needs to be pushed forward in order to get a better comprehension of the corrosion process occurring within the iron containing phases as this ceramics is investigated to be used in direct contact with molten salt as thermal storage material. In any cases, the Cofalit and the CFA ceramics represents good candidate for TES application.

Also the work of this task is concerned with MS6.

Task 2.7: Testing of the reliability of the hydraulic components (deliverable D2.7)

According to the MS8 objectives, the following hydraulic components have been tested:

Component	Tests to be performed
Immersion electrical resistance (from two different companies)	Performance test
Electrical Heat Tracing (from two different companies)	Performance test
Control valve with special packing (Φ=3”)	Leak test Validity at nominal working conditions Cold zones tests Gasket test Control hysteresis test
Thermal Insulation (from two different companies)	Performance test
Immersion Electrical Heaters (IEH) (from two different companies)	Performance test

Two immersion electrical resistance types, coming from different manufacturers (COMPANY D and COMPANY E), have been tested. Both IEH have been tested under normal working conditions comparing the behaviour in time:

- Under normal operating conditions (e.g. normal temperatures in the tank and without molten salt’s movement in the tank) check if the cut-off temperature (300ºC) is reached without overtaking the 350ºC at the middle sensor.
- Corrosion: According to bibliography the constituent materials will not suffer any corrosion in the experimental temperature range. Despite this, there is the possibility that the heat is not uniformly distributed and, in some specific areas, higher temperatures are reached that could lead to the development of corrosion areas.
- Comparison of the possible breakage.

The main conclusion of the 2 years operation test is that no failure has occurred in any of the two IEHs. The surface load concentration could range for stainless steel between 1.2 and 1.4 W/cm2 without problems of overheating any part of the IEHs.
The IEHs’ design has to be taken into account the possibility of removing it from the tank under security conditions. This affect the baffles design that should include draining channels and have a smaller radio as the internal radio of the flange and inserting pipe.
Whereas no corrosion has been observed in the internal materials of the IEHs, the parts exposed to the atmospheric conditions have suffered the normal and expected corrosion processes.
In order to avoid overheating of electronic elements in connexion boxes both solutions, longer connecting bars and dissipating fins, have resulted to be equally effective.

- Electrical Heat Tracing System (EHTS)

Two EHTS (from company B and C) have been tested along 3 years.
In general terms we can say that the electrical heat tracing system from company B was not installed properly by this firma, and so many failures occurred. Once it was installed properly, many other failures occurred due to the technical characteristics of this EHT. In the case of EHT

from company C, it was installed properly and, when the cold ends were welded at factory, they presented a very low breakage percentage. When the cold ends were welded at the facility, a higher percentage occurred depending this on the welder and on the weather conditions of the day the welding was made. Rainy or very humid days resulted in a very high percentage of cold ends that broke after a short operation time.
The following general recommendations are given according to the experience gained when testing these two EHTS:

- Some problems occur if the heat tracing cable length does not match the pipe length or the type of valve or fitting in the salt circuit, so this is something that must be well defined during design phase. The specific heat dissipation (W/m) of the heat trace cable and the mass of the elements to be heated must be taken into account, as well as the expected duration of the warming-up period. Since the mass, and therefore the thermal inertia, is greater in the valves than in the piping, different electrical heat tracing circuits should be used for valves and adjacent piping. The heat tracing of the valves is then controlled independently from the ones of the piping. This means that valves and adjacent piping must be electrically heated by independent heat tracing circuits and controlled by different temperature sensors.
- In order to have a good temperature distribution in the molten salt system, the heating cable has to be carefully installed, thus running parallel and well attached to the piping.
- The temperature sensors for the control of the EHT should be placed where the lowest temperature is expected and so that no other heat source leads to a false temperature measurement.
- The cold ends have shown to be the weakest part of the EHT. Here, the heating wire is welded with the part of the wire that does not heat. Cold ends are normally filled up with a dielectric material (e.g. magnesium oxide) between the wires and the housing. Because of the high hygroscopicity of magnesium oxide, if moisture enters the cold ends the dielectric rupture can happen. Direct contact with piping or equipment can result in overheating of the welding thus producing pores through which moisture can enter. Separating the cold ends from the equipment has proved to be a good option. The cold ends should be installed in the outer part of the insulating material but weather protected (e.g. under the aluminium protection). A cold end with a higher distance between the wires and the housing can also be used in order to make more difficult the dielectric rupture.
- Regular measurement of the insulation resistance of EHT can help in predicting when the EHT is about to break down.

- Valves

CIEMAT-PSA has designed a device to test flanged components with solar salt. This device can be used for testing valves with molten salts and has been designed for perform tests in stationary conditions up to 400 °C and 22bar. Although it was initially planned to test valves from two different companies, only it was possible to arrange an agreement with just one company, so just a globe valve has been tested at 350ºC and 15 barg.
The test consisted in continuously open and close the valve in a special device for testing valves with molten salt (60%w $NaNO_3$ and 40%w KNO_3).
After 6 hours of testing the valve packing presented a small leak that left some gas passing through. This leak was so small that no salt was released to the atmosphere.
One hour later, the leak was big enough to release salt to the atmosphere through the threaded bushing (between the stem/bushing connection).
The packing provided by the company GARLOCK is made of graphite with a special coating. It is

well known that in the moment that some salt contact graphite, a chemical reaction occurs. The packing composition or the valve design must be changed in order to avoid leaks.

- Thermal insulation

  Rock wool and Microtherm® thermal insulation are two of the most installed insulating materials in concentrated solar power plants, so they are the ones tested at this task2.7. These insulating materials have been tested in normal operation conditions comparing their behaviour in time, and comparing the cooling time of the corresponding pipe section or valve they wrap.
  The main conclusion of the work could be the importance of a good installed insulation to avoid the presence of solid molten salt in pipes and valves together with a good installed electrical heat tracing.
  From the two insulation materials tested, rock wool and microtherm®, prices and evolution along the time have been compared. Rock wool is much cheaper than microtherm®. On the other hand, rock wool degradation along the time is higher than the one suffered by the microtherm®. Besides this, microtherm® can be used to insulate small components and narrow places, something quite usual in molten salt facilities due to the tendency to make the pipes as short as possible to save money in electricity.

  The work on this task accomplishes the milestone MS8.

DEVIATIONS FROM ANNEX I, REASONS AND THEIR IMPACT ON OTHER TASKS AS WELL AS ON AVAILABLE RESOURCES AND PLANNING

The performed wp work is fully compliant to the expected objectivies, and all the wp milestones have been achieved. Moreover, molten nitrates thermal stability tests, not specifically indicated in the DoW document, have been carried out and the study of molten salts stratification properties (essential to establish the scientific feasibility of the proposed thermal storage method) has been performed by the PCS facility, and hence on a larger scale than the laboratory one originally planned, thus producing data more reliable for pilot and industrial scale applications. Some task was completed late, the motivation and justification for the delays are reported in the first period project report.

MILESTONES ACHIEVMENT DURING THE PROJECT PERIOD

The following table summarizes the expected milestones and the related deliverables.

Milestone		Associated deliverables	Status
MS4	Assessment of the State of the Art on MS mixtures as Heat Storage Medium and Heat Transfer Fluid	D2.1	Accomplished
MS5	Report on materials behaviour and thermal exchange properties	D2.2, D2.6	Accomplished
MS6	Full characterization of construction materials in the respect of MSs	D2.3, D2.5	Accomplished
MS7	Full characterization of MS mixture phenomena and thermal exchange properties	D2.2, D2.4	Accomplished
MS8	Election of first hydraulic components to be tested and definition of testing procedures	D2.7	Accomplished

WP3: FULL-SCALE TES-SG SYSTEM: ANALYSIS, MODELLING, SIMULATION AND DESIGN

RESUME OF WP3 OBJECTIVES

The purpose of WP3 is to support the final design of the one-tank Molten Salt (MS) Thermal Energy Storage (TES) concepts (stratified MS Storage Tank (ST)) with integrated Steam Generator (SG), or with a storage consisting of a filler/MS system and an external steam generator. WP3 was intended to contain all the simulations and engineering necessary in order to validate or complete the data on the following topics:

1) Modeling and engineering of the "full scale" system, that is, a TES/SG system presenting the minimum thermal and electrical power (125 MWth, corresponding to about 50 MWel) to be employed in an industrial scale, as defined in the dow document. This configuration is based on the thermal stratification properties of the molten nitrates and presents an immersed (integrated) steam generator
2) Analysis, modeling and simulation of the thermo-cline Storage Tank with internal filler, M/S as thermal fluid and an external steam generator (CNRS will also study the possibility for an internal steam generator configuration). The plant scale (120 MWth) is comparable with the one of the MS/TES/SG system.
3) Based on the modeling results, a comparison between the two system is performed
4) Based on TES models and the simulation results described in points 1 (T3.1) and 2 (T3.2), TES models suitable for full year performance models of complete solar thermal power plants will be developed and implemented. Such models, comprising the simulation of the different blocks of the CSP plant (Solar field, thermal storage and power block), will enable both a TES impact assessment over the CSP plant behaviour and an optimization analysis for different CSP plant operation modes.

Task 3.1: Analysis, modeling and simulation of the stratified MS Storage Tank with integrated Steam Generator (deliverable D3.1)

Deliverable 3.1 corresponds to Task 3.1, regarding the analysis, modelling and simulation of the stratified MS Storage Tank with integrated steam generator. The partners involved in this work package are CyI, CEA, Fraunhofer ISE, Ansaldo, ENEA and COBRA.
This task includes all the activities necessary to develop the software instruments to perform and to improve modelling, simulation and analysis of the stratified MS Storage Tank with integrated Steam Generator:

- Heat transfer modelling and simulation of the SG tube bundle, since heat transfer coefficients and exchange correlations in real working conditions for the fluids involved in these heat transfer geometries are not available in literature. Use of computational fluid dynamics models based on high-resolution and very high-order methods to predict the heat-transfer coefficients.
- Integration of heat exchange studies both for Pool type or Loop type heat exchangers, to evaluate the different working behaviour, advantages and costs in the two possible configurations.
- Modelling of presence of multiple SGs in big TES tanks for large power plants.
- Simulation models for dynamic charging/discharging with steam/water interface.

This report also includes a comparison, carried out by the Weizmann Institute, between the TES systems with and without filler. This activity was expected to be included in task T3.2 (deliverable D3.3) but is instead inserted here because previously not all the necessary data were available.

Various approaches were used by the different partners involved, leading to concrete guidelines to evaluate the performance of the proposed design. The full scale steam generator design has been given in D. 3.2 and was summarized herein for completeness (see deliverable Sec. 1).
The following broad questions regarding aspects of the integrated unit were investigated:

- How to best integrate the steam generator in a stratified molten salt tank?
- How does the steam generator perform?
- How efficient is the stratified tank?

Various ways of integrating the steam generator with the stratified molten salt tank were devised an analyzed, whether internal or external to the tank. Each option has its distinct advantages but also disadvantages, as summarized in Table 2.6 present in the report. Additionally, for steam generators internal to the molten salt storage tank, various mechanisms leading to loss of efficiency where analyzed (e.g. convective currents through originating from thermal losses through tank walls), and a design to mitigate such effects was proposed.
The performance of the steam generator was also investigated. Detailed numerical simulations allowed for the calculation of heat transfer coefficients over tube bundles, where fair agreement with correlations obtained in the literature were found (c.f. Fig. 3.8 in the report). Additionally, more the performance of the whole steam generator was modeled after validation with experimental results and compared favorably with the design case (c.f. Fig. 2.6 in the deliverable)
The system operation from the point of view of discharge conditions was simulated. Due to the high Reynolds number expected from the operating conditions of the steam generator, preliminary results indicate that the extent of the thermocline becomes too large before the end of the discharge operation, therefore not all the energy stored within the tank can be directly used for steam production at nominal conditions (Fig. 4.6 in the deliverable). However these results have been obtained on a simplified geometry and a sensitivity analysis must be performed before drawing final conclusions. In addition, further studies on the influence of the diffuser geometry and tank partitioning should be performed in order to complete the system assessment for large plant applications.

Concerning the comparison between systems with and without filler a computational model for a thermocline TES tank was developed in the study and compared to available experimental and other numerical results of un-filled and filled tanks, the results show that using a cheap solid filler can keep the TES performance practically identical, whereas the tank cost is substantially reduced. Few obstacles were identified on the way.
The ICs in the experimental literature data used by most of the reviewed studies, are unspecified, but are required for a successful comparison. This seems the major difficulty. Various approaches were used in the reviewed models, but not all details were given in most of them.
Missing or inconsistent data in the reviewed sources is the second important factor. This includes large variations of the data used by various authors (e.g., the flow rate, the particle size and the materials properties) and missing or inconsistent definitions (e.g., of non-dimensional variables).
Other, less important, contributors to the challenge were the various suggested correlations for the HTC and the effective conductivities and the different assumptions and approaches used by the reviewed studies.

<u>These activities fulfill the achievement of MS9</u>

<u>Task 3.2:</u> Analysis, modeling and simulation of the thermo-cline Storage Tank with internal filler (deliverable D3.3 and D3.5)

This task includes the development of numerical models for simulating and analyzing the thermo-fluid-dynamics of thermocline storage tanks with internal filler, with the goal of comparing this concept with the stratified molten salt storage tank with integrated steam generator. Deliverable D3.3 contains the contributions of all Task 3.2 participants: LNEG, Weizmann, CREF-CyI, CEA, CIEMAT, Fraunhofer ISE and CNRS-PROMES (the last ones are described in D3.5). The activities of the different participants have been ordered according to the Task 3.2 description included in the DoW.

- LNEG contribution

The approach pertained by LNEG for the Task 3.2 included the development of 1D, 2D and 3D models. The 1D model should be able to give us a rough representation of the thermocline behavior inside the tank, the 2D model was developed aiming to a more thorough knowledge of the thermocline behavior as well as to find if the simpler models could neglect the changes in the radial direction. Finally, the 3D model would be able to show if the acentric position of the tank inlet(s) and outlet(s) could influence the flow and the thermal behavior of the thermocline.
Although the 1D model works very well, it may have room to some improvement, mainly the influence of gravity in the convective term and velocity to be considered inside the tank.
The 2D model was validated and it was possible to simulate the prototype tank with thermocline. Some results were presented.
3D model must be improved in order to match experimental data and a model of OPTS tank prototype with filler must be developed.
Since the 3D model uses the same computational fluid dynamics software package as the 2D model, the next step can be to compare both model summaries and try to reproduce the 2D results in the 3D model. In the first approach a quartzite rock/sand can be used and afterwards the filler will be replaced for Cofalit and Plasmalit as proposed.

- Weizmann contribution

This task includes the development of the numerical models for simulating and analyzing the thermo-fluid-dynamics of Thermocline storage tanks with internal filler, with the goal of comparing this concept with the stratified MS storage tank; however, given the lack of the necessary technical information at the moment of the delivery of the present report; that activity is included in D3.1.
The major part of the report is devoted to study alternative cycle involving the molten salt Thermocline as a superheater. The study was focussing on a PCM storage unit with innovative features of charging/discharging mechanism as will be described in the first part of the Weizmann section.
The purpose of this activity of Weizmann during the first period is to explore alternative scheme of storage suitable specifically for upgrading existing technology of parabolic trough (PT) with oil or molten salt or direct steam that does not include storage unit to supply saturated steam at high pressure with possible extension of molten salt (MS) section with Thermocline and integrated steam generator (SG) for the superheating. This

scheme can be considered for those plants where the power block (PB) can be also adjusted to the new conditions of the steam (higher pressure and temperatures than typically characteristic of the oil technology). In the case that such upgrading cannot be retrofitted into existing PT plant a new plant integrating both the e.g. oil or future direct steam and the MS technologies as proposed e.g. in WP7 can be conceived. A schematic layout of this configuration can be seen in figure 1. The component studied in this work is the reflux heat transfer storage (RHTS) which will be based on phase change material (PCM) to provide the boiling and the saturated steam to the Thermocline unit for further superheating.
The results of testing the 3Ca-Diphyl composition (as PCM/HTF pair) using chemical reactors of various mass scales, from a few mg in the DSC analysis to about 1 kg in the lab set-up, are clearly be positively interpreted in terms of chemical stability up to a temperature of 410^{o}C.
However, for guaranteeing longer chemical stability of Diphyl the recommended operational temperature should be maintained around 400-405^{o}C.
The concept has been proved on the lab scale and its further development is out of the scope of the OPTS project.

- CREF Cyl contribution

Thermal energy storage is a key technology towards enabling concentrating solar power (CSP) systems to be deployed on a wide scale, as the plant has the ability to dispatch electricity without fossil fuel backup. Current research focuses on the reduction of the cost of the thermal energy storage systems.
Thermocline heat storage is considered a viable and relatively cost effective technique for providing heat in extended operation of CSP systems. Single-tank storage systems have been proposed over two-tank systems to reduce cost. An additional cost-savings can be achieved by replacing some of the heat storage fluid with a lower-cost solid filler material. Typically filler materials with a porosity of $\varepsilon \sim 0.25$ are used, implying that the cost of thermal storage fluid will decrease by a factor of 4.
In a thermocline heat storage charging process, hot fluid from a solar field is introduced into a tank from the top, which forces the existing cold fluid in the tank out from the bottom to return to the solar field. In a heat discharge process, hot fluid is discharged from the top of the tank, runs through the energy extraction cycle, and returns to the bottom of the tank as a cold fluid. A stratification of hot and cold fluids in a thermocline tank prevents convective mixing, which allows the maximum utilization of a single tank.
In order to capture the transient temperature profiles occurring during the charging and discharging process, the energy equations for the liquid and solid filler material are considered separately, forming a two-phase model. Such models take into account convection and diffusion of temperature in both phases, as well as heat transfer between the two phases. However, in most engineering applications, assumptions and simplifications can be made allowing for a lumped heat capacitance model to be written.
Molten “solar salt” (40%-60% by weight KNO_3-$NaNO_3$) have been assumed as heat transfer fluid and as filler material a mixture of quartzite rock and sand has been considered. Results are reported and discussed in the deliverable.

- CEA contribution

The numerical model developed to simulate the thermocline storage tank is based on Schumann's one-dimensional model.

The following assumptions have been made:
❑ The fluid flow is considered only along the tank axial direction and a uniform transversal velocity and temperature profile is assumed over the whole tank height
❑ The rock bed temperature is also assumed to be transversally uniform and therefore the transient governing equations are only solved in the axial direction (one-dimensional approach)
❑ The transversal heat transfer between the molten salt and the rock bed has been taken into account by a simple convective equation.
❑ The inlet and outlet flow manifolds are not included in the analysis and uniform velocity and temperature distributions are assumed at the inlet of the storage tank. The rock bed is considered as a continuous, homogeneous and isotropic porous medium.
❑ The properties of the rock bed are assumed to be constants.
❑ The heat losses from the storage to the external ambient are neglected considering the high volume to outer surface ratio of the tank, and the tank wall axial conduction is not taken into account.

The model has been validated with respect to the results obtained by the Sandia laboratory (see the cited references) on a molten salt and packed-bed of quartzite sand and rock thermocline. The data and the conditions are issued from [3] (see Table 2), and the profile at 0.4h is taken as the initial conditions.
Simulations were carried out with a tank capacity equal to the injected heat and also considering different tank capacities; then, a storage cycling case was simulated. To characterize the storage performance against cycling, the storage efficiency as well as the capacity factor (see definitions in the report) have been calculated for each cycle.
The capacity factor indicates the effective use of the tank capacity.
It can be seen that the storage efficiency and the capacity factor improve with cycling, and that in steady state conditions almost all the energy injected is used since the efficiency reaches 98 %, and the capacity factor 91 %.
This results show that in order to get a correct understanding of the behaviour of the storagesystem and to properly assess its performance it is important to carry out the analysis over a certain number of charge/discharge cycles allowing reaching steady state conditions.
Finally it must be taken into account that the preliminary conclusions drawn by the present analysis regarding a stand-alone storage system must be validated against a more global analysis carried out at the overall solar plant level.

- CIEMAT contribution

From a practical point of view, one way to have a good picture of thermocline tank behavior, is to simulate the annual performance of a solar thermal power plant (STPP) in which this kind of storage has been implemented. Several simulation models for parabolic trough plants that include thermal storage systems have been already developed by different organizations but all of them only consider the conventional molten-salt two-tank storage system for which outlet/inlet temperatures are fixed by design and the power supplied/extracted is easily calculated through the molten salt mass flow rate.
In contrast, in a thermocline storage tank, the available thermal energy at maximum temperature is

expected to decrease with subsequent charging/discharging cycles due to a continuous increase of thermocline thickness. Moreover, thermocline thickness also increases during idle periods due to thermal diffusion, which decreases storage system exergy and hence the potential useful power that can be extracted.

CIEMAT activities in OPTS Task 3.2 have been focused in the development of an analytical function which provides outlet temperature with time for a thermocline storage tank that is going to be implemented in the simulation of a Solar Thermal Power Plant (STPP). This function will be used for optimizing control strategies of thermocline storage systems (activity displaced to task3.4). In this way we have proposed the Logistic Cumulative Distribution Function (CDF) expressed in dimensionless coordinates for describing thermocline tank behavior not only during dynamic processes of charge/discharge but also during stand-by periods. Comparing withother analytical functions already reported for thermocline tanks (i. e. error function, Normal CDF or polynomial approximations), Logistic-CDF is accurate and simple enough to be included in any kind of solar thermal power plant simulation model. The dependence of function parameters withworking conditions and tank features has been obtained by fitting the Logistic-CDF to the resultsof a numerical model already validated with experimental results. The Logistic-CDF has beingexpressed in dimensionless coordinates, which makes it valid for any thermocline storage tank containing any kind of storage medium.

To summarize the results (for the meaning of the used symbol, see nomencalture at pags. 68-69 of the report): CIEMAT contribution to OPTS Task 3.2 consists on introducing a Logistic-CDF as analytical function for describing thermocline tank behavior in dimensionless coordinates not only during dynamic processes of charge and discharge but also during stand-by periods. The dependence of the Logistic-CDF parameter, *S*, with the working conditions has been obtained by fitting that function to the results of a numerical model already validated with experimental results. For the dynamic processes, *S* can be expressed as quotient of two independent contributions: $S_{z_C^*}$ depending on thermocline position z_C^* divided by S_{v^*} depending on dimensionless velocity, v^*. It has been found that S_{v^*} becomes maximum and constant for large velocity values ($v^* > 2500$), whereas $S_{z_C^*}$ proportionally increases with $\sqrt{S_{z_C^*}}$. or $\sqrt{v * t *}$. This means that even when *S* becomes independent on v^*, its value will always increase due to the progress of thermocline zone inside the tank. For the case of the stand-by periods, *S* parameter proportionally increases with$\sqrt{t *}$. In this way if the thermocline thickness is assumed to be zero at the beginning of the stand-by period, thermocline zone is expected to occupy the whole tank height when t* attains $1.5\text{x}10^{-3}$. It has been demonstrated that thermocline thickness is proportional to S parameter although its value will depend on which temperature accuracy is established for determining thermocline limits.

Logistic-CDF allows obtaining, by a simple calculation, tank outlet temperature versus time for both charge and discharge processes. Moreover being expressed in dimensionless coordinates this function is valid for any thermocline storage tank (with solid filler or only liquid) containing any kind of storage medium (water, oil, molten salt, rock, sand). However since dimensionless variables are only a mean for simplifying calculations and have no real meaning, the results must be converted to dimensional variables for each particular case in order to have realistic values of velocities, times and temperature intervals.

The main advantage of describing thermocline tank behavior with an analytical function is that it can be implemented easily in any computing model used for simulating the annual performance of a solar thermal power plant.

- Fraunhofer ISE contribution

Different modeling approaches will be used to investigate the influence of filler materials on the performance of stratified thermal energy storage. The effect of different physical phenomena on stratification will be shown. Some basic definitions account for all the approaches. The storage is modeled as cylindrical tank, whereas the dimensions depend on the required capacity and the inserted filler material. The computational domain consists of an equally spaced grid with n nodes of the thickness dx. Inlet and outlet are located at top and bottom.

The following assumptions are employed to simplify the analysis:

- The molten salt flow is treated as laminar and incompressible fluid
- The spatial discretization of the fluid is only one-dimensional
- The filler particles will be approximated as spheres
- The heat flux to the filler is equal in circumferential direction
- The model is limited to the solution of the energy equation
- Explicit forward time stepping

Three different modeling approaches have been compared during this investigation. In the first model the fillers are modeled as lumped capacitance, in a second step also intra-particle conduction is implemented to take into account the conductivity of the filler. The third approach includes additionally axial conduction between the filler particles in the different nodes. Inter-particle conduction has almost no impact on the results but intra-particle conduction gets more important with increasing thermal resistance of the particles. The theoretical limit for the Biot number of 0.1 for lumped capacitance model is not mandatory for the stratified storage. Higher biot numbers still give small deviations between lumped capacitance models and models with intra-particle conduction. If the influence of particle size and properties especially is investigated lumped capacitance models should not be used.
A comparison of three materials: Cofalit, Plasmalit and a rock-sand mixture, has only revealed small differences since the properties are quite similar. An evaluation for full day operation has shown a good performance when compared to an ideal case. The used model is likely to overpredict the performance of the system since the numerical implementation is quite good compared to other approaches. This is explained more detailed in the appendix.

- CNRS Promes contribution (D3.5)

Thermocline storage is the term attributed to the storage systems based on the single-tank configuration, where due to buoyancy forces higher temperatures are concentrated at the top of the tank while lower temperatures are concentrated at the bottom of the tank. The relatively thin layer that separates the two volumes of the HSM is called thermocline due to its steep temperature gradient in the vertical direction.
Significant developments have been made to develop such storage, however the models are not without flaws. From the original configuration, fluid filled tanks, to the innovative packed bed tanks comes the next stage in sophistication: the structured bed thermocline tank. The structured bed is seen to be an important cornerstone in reducing the cost of construction, in a similar light to the packed bed tanks, by limiting the quantity of fluid required, and, most of all, by avoiding the risk of thermal ratcheting, which can lead to dramatic structural failure of the tank, hence reducing large maintenance expenditures. Furthermore, by designing the structure with a view to making it out of bricks composed of recycled industrial waste, the environmental benefits would be greatly

improved as well the material costs. Emerson and al. propose a structured thermocline storage integrating simple rectangular bricks made of a mixture of concrete and fly ash. Some mixtures were found to be compatible with molten solar salt up to 585°C. Thermophysical and thermomechanical properties were characterized. The residual compressive and tensile strengths are high enough to ensure mechanical stability under their own weight. These mixtures are potentially suitable for a structure thermocline storage.
This report is intended to present and validate a simulation model to be used in the optimization of such a structured bed thermocline storage tank. This research investigates the feasibility of building a structure from a simple brick made from industrial waste (Cofalit) that requires no extra no-how to put together than that of building an average brick wall. The considered transfer fluid is the well known solar salt.
A numerical study of the thermal behavior of an innovative structured thermocline storage is presented. A specific geometry has been drawn and our model has been tested undervarious geometrical and physical variations, and reacts well in all tested cases. Our model maybe used to optimize the geometrical parameters of a brick structure to help find the most optimalgeometric configuration regarding the physical properties of the selected material, the Cofalit, made from industrial waste. The first observation that can be done is that, unlike the packed bed configuration, the convective transfers are lower and bring to view the necessity of improving ourstructured geometrical configuration in order to increase the total heat transfer between the molten salt and the structured filler material. It is hence useful to note the limiting parameters, with regards to the physical constants of the system and the geometrical ratios.

Together with D3.1 and D3.4 , D3.3 and D3.5 contribute to the achievement of MS11.

Task 3.3: Project executive of the stratified MS Storage tank with integrated Steam Generator (deliverable D3.2)

Deliverable D3.2 relates to the Task 3.3.

- ENEA contribution

ENEA contribution is concerned with mechanical stress analysis of the full-scale (25 MWth) Storage Tank for the 25 MWth SG.
Suspension system for steam generators proposed in Ansaldo solution (see below), particularly advantageous from thermal deformations point of view (leaving "free" to deform all the components of the generators thus preventing mechanical over-stresses) is expensive in relation to mechanical characteristics required for examined application also in consideration of large number of generators provided in project.
Taking these aspects into account, in this document are described two proposals for a cheaper suspension system that leaves "free" to deform components of generators as in Ansaldo solution.
Two proposed solutions differ by type of anchorage. In the first, support structure is external of the tank and tank walls bear overall weight (support frame and steam generators); in second solution, instead, a portal of vertical beams, anchored on floor of tank, bears weight on basis of tank. So, in this solution, structure support is completely positioned inside the tank.
Also, for both proposals we can consider two different types of fastening support for housing of generators on support structure:
1) 4 supports realized with plates and reinforced with ribs;
2) 1 flange DN1600 attached to steam generator ferrule.

In all proposed cases, steam generators may be dropped from above by handling systems without pay attention to the centring of steam generator on support system (thanks to the use of round shape for support system proposed in following paragraphs).
Results are reported and discussed in the deliverable.

- Ansaldo contribution

The object of the activity reported in this document is the Thermal/Hydraulic (T/H) design of the full scale helical coil steam generator in the frame of the OPTS project (OPtimization of a Thermal energy Storage system with integrated Steam Generator).

The project foresees the steam generator to remove the design thermal power from a mixture of molten salts (NaNO3 60%w and KNO3 40%w). The molten salts are outside the tubes at ambient pressure and the natural circulation sustains the design flowrate; the water flows inside the steam generator tubes at the design pressure (about 105 bar(a)) and exits from the tubes in superheated condition.

The T/H design of the steam generator activity reported in this document consists of:

- T/H sizing of the steam generator tube bundle: this activity leads to determine the required steam generator heat transfer surface in term of number, diameter and length of tubes and size of the steam generator shell.
  The final T/H sizing of the steam generator results from an extensive sensitivity activity in which different tube bundle configurations have been investigated; among all the possible configuration fulfilling the input requirements (i.e. thermal power, molten salt and water inlet/output temperature, pressure drops, etc.), the final steam generator tube bundle configuration is the one which accomplishes the most the input requirements in term of steam generator gross dimension (i.e. tube bundle height and shell diameter) and thermal performance.
  This activity has been executed using the computational code Elica and in accordance with the Ansaldo steam generator mechanical design group.

- T/H performance of the steam generator at different power levels: the final steam generator configuration has been investigated at different thermal power levels in order to determine the steam generator performance and to size the orifice to insert at the tube inlet. Usually the orifice at the tube inlet is designed to introduce an additional pressure drop into the tube which prevents from flow instabilities such as parallel flow oscillations; however the T/H analyses that have been performed demonstrate that the parallel flow instabilities do not occur even at low power level in the range of operation of this steam generator (secondary pressure, temperatures, etc.). Nevertheless, the orifice at the tube inlet has been designed in order to limit the mass of water discharged into the molten salt pool tank in case of steam generator tube break, limiting the pool tank pressurization.
  The computational code Relap5 3D 2.4 has been used to perform this activity.

Results are reported and discussed in the deliverable.

- Cobra contribution

COBRA contributed to this deliverable by a sharing of technical data with TK. These data have been employed in the present deliverable as well as in the D4.2.
Regarding specifically the "Design of the modifications of the existing Test Facility" in D3.2, Cobra contribution is included in the D4.2 report, where the results of the Cobra/KT collaboration on this topic are reported.

- KT contribution

The final drawings concerning the full scale facility, prepared by KT, are inserted as pdf attachments, and can be accessed by a linked table present in the deliverable document.

<u>This task achieves the milestone MS10.</u>

<u>Task 3.4:</u> Implementation of TES models in CSP performance models (deliverable D3.4)

This task is about the study of optimized control strategies for a thermocline storage tank in a solar thermal power plant, CIEMAT is the responsible for this task, and developed the deliverable D3.4 in collaboration with Fraunhofer-ISE and LNEG.

- CIEMAT contribution

The Task 3.4 of the OPTS project is focused on the implementation of thermal storage models for thermocline tanks in concentrating solar power (CSP) plants. The thermocline models developed in previous tasks will be integrated in a complete CSP plant model that can be used to both define and analyze optimized control strategies and study specific aspects of thermocline storage behavior.
The complete model of a solar thermal power plant can be used to carry out yearly simulations and performance assessments that could lead to optimize the operation strategies of the storage system. Previous studies have analyzed the electricity yield of CSP plants with a thermocline storage tank and have compared the results with the corresponding to a plant with a 2-tank storage system. However, those analyses have not taken into account the different operation possibilities associated to a thermocline storage system.
In the case of parabolic trough plants, it would be interesting to analyze effect of using different heat transfer fluid (HTF) in order to apply the corresponding operation conditions and find out the issues and possibilities of thermocline storage. In this way, molten salts have recently been analyzed and tested in parabolic troughs as HTF alternative to the conventional synthetic oil [2]. Due to their characteristics, the operation possibilities of thermocline storage systems could yield more interesting results when molten salts are used as HTF in the solar field.
The objective of this study is both the analysis and definition of different operation strategies that could be applied to a thermocline storage system integrated in parabolic trough CSP plants. The CSP plants here considered use either oil or molten salts as HTF and the results have been compared with the corresponding to plants with 2-tank systems, which represent nowadays the commercial reference.

An annual performance analysis has been carried out for different operation strategies regarding charge and discharge processes that could be applied to a thermocline storage system integrated

in parabolic trough CSP plants, using either oil or molten salts as HTF. The results have been compared with the corresponding to plants with a 2-tank storage system.
In general terms, the electricity yield and fossil fuel saving of the analyzed strategies show a similar behavior for synthetic oil and also for molten salts. This means that the best strategies are the same for both kinds of solar field HTF's.
It has been found that the best strategy for charge processes in terms of electricity yield and fossil fuel consumption is to lead thermocline heat to solar field up to the maximum allowable inlet temperature, keeping the rest in tank (see strategy "A" in Table 3 of the report). This strategy presents the additional advantage that it is the simplest one to implement in a parabolic trough CSP plant.
In terms of electricity yield, the best strategy for discharge process is to lead thermocline heat to the power block down to the minimum allowable temperature, and to use the remaining energy for preheating power block in startup procedure (see strategy "E" in Table 3 of the report). This strategy is easy to implement in a parabolic trough CSP plant, and it does not require more fossil consumption than the base strategy ("A" in the deliverable), i. e. lead thermocline heat to the power block down to the minimum allowable temperature. However, the net electricity gain is not very significant.
In terms of fossil fuel saving, the best discharge strategy is to lead thermocline heat to the power block down to the minimum allowable temperature, and to use the remaining energy for safety heating of solar field, replacing some of the fossil fuel consumption (strategy "D" in Table 3 in the deliverable). This strategy presents an intermediate complexity to be developed in a parabolic trough CSP plant, and generates a lower electricity yield than the base strategy ("A").
In order to choose the best strategy for a parabolic trough plant from an overall point of view, an economic assessment that considered electricity prices, fossil fuel cost, additional/alternative circuit components, etc. would be required. The convenience of using a thermocline tank with direct (molten salts as HTF) or indirect storage (synthetic oil as HTF), instead of a 2-tank system, would also depend on this economic analysis.
This study has proved that the electricity yield of a thermocline tank is always lower than the corresponding to a 2-tank system. Nevertheless, the economic saving of building a single storage tank and the reduction of molten salts amount of thermocline storage systems due to the presence of a solid filler should be taken into account, as well as the country in which the plant is going to be installed. The country and its financial conditions will determine the electricity price, fossil fuel cost and total money saving. The results present in the report (Table 3, Figure 11 and Figure 12) could be used as a guideline for the economic comparison of electricity yield and fossil fuel consumption for each operation strategy with respect to a 2-tank system.

- LNEG contribution

This report presents the main results from LNEG activities within WP3's task 3.4 – Implementation of TES models in CSP performance models. According to the Description of Work, task 3.4 aims to, using the results from task 3.1 and 3.2, develop thermal energy storage (TES) models suitable for full year performance models of complete solar thermal power plants, in order to enable a TES impact assessment over the concentrated solar power (CSP) plant behavior and an optimization analysis for different CSP plant operation modes.
This LNEG's study analyses the impact of the use of different TES systems in a molten salt power tower plant. Due to the lack of available models and results describing the behavior of single-tank thermal energy storages with integrated steam generator, only two types of TES technologies are were studied: two-tank technology and thermocline tank technology. The modeling approach used for this work is described in section 2, while the results for an annual simulation are presented in

section 3.
Additionally, a set of parametric analyses were performed in order to study the impact of some design and control options of the single storage thermocline TES system. The results of those analyses are presented in section 4.
Finally section 5 presents the main conclusions and suggests future work directions.

The impact of the use of two different thermal energy storage systems in a molten salt power tower CSP plant was studied. It was found that both systems behave in a very similar fashion, with nearly coincident charging/discharging patterns. However, for the studied system, the plant using the single-tank thermocline TES system (TC) has slightly better performance than the plant using the two-tank TES system (TT). In fact, the TC plant supplies 0.86% more electricity to the grid than the TT plant, achieving also a 0.6% higher capacity factor.
When comparing with the two-tank system, the single-tank thermocline system eliminates the use of one tank and decreases the HTF volume used for storage (due to the usage of quartzite as a filler material), using a tank slightly smaller than the tanks used by the two-tank TES system (the thermocline TES system needs a tank with a volume of 3298 m^3 while the two-tank TES need two tanks with a volume of 3477 m^3 each). Additionally, the thermocline system supplies more 2.1% of thermal energy to the power block than the two-tank system (thermocline stores and supplies 133879 MWh of thermal energy while the two-tank system stores and supplies 131187 MWh).
The conclusions stated in the last two paragraphs seem to support the use of single-tank thermoclines storages systems, although a definitive conclusion can only be achieved after performing more detailed studies, including an economic analysis in order to compute the levelized cost of electricity.
The parametric analyses were dedicated to the study of the impact of some of the single-tank thermocline TES system design and control options. Some of the parameters studied may impact the plant performance; however this impact is usually low. It was also possible to conclude that the parameters chosen to run the main simulation are within an adequate range of values that maximize the plant performance in terms of net electricity production.
As a future reference, this work can and should be expanded in order to study other performance factors, including economic factors. Some of the component models may also be improved in order to better capture the plant's real behavior. Additional models for new components must be developed and integrated in global plant models, such as a TES model with integrated steam generation, in order to achieve performance comparisons between current and novel TES technologies and designs.

- Fraunhofer ISE contribution

A wide range of aspects concerning the TES-SG subsystem will be covered in the following sections. At the beginning a detailed description of the storage model is given including the implemented physical phenomena and the various functionalities. The impact of the model complexity on the simulation time for a simple charge-and discharge process for a full annual simulation will be shown. Besides, the implementation of the integrated steam generator is shown, followed by an explanation of the algorithm simulating natural circulation. The effect of the design parameters on the performance of a pure natural circulation driven operation will be analysed and a recommendation for the design given. Furthermore a method to improve the computational effort for the natural circulation operation is introduced. The difference between forced and natural circulation will be shown and the efficiency of the storage investigated. It will be explained how the remaining fluid in the storage with a lower temperature can be used beneficial and how different operation strategies affect the overall plant performance.
The fundamentals of the storage model have been shown at the beginning and illustrated how

numerical methods influence the stratification profile. The QUICK scheme in combination with the ULTIMATE algorithm reduces the influence of spatial and temporal resolution on the stratification. The computational effort for the storage model itself is quite low. However, some computational time can be saved if an overall heat transfer coefficient is used for the steam generator model instead of calculating the heat transfer coefficients for both sides each node and time step. The comparison between natural and forced circulation showed that forced circulation gives good results if the system is designed properly. Only in the morning and evening when the storage level is relatively low, natural circulation shows a lower output. When the temperature at the storage top drops and the SG power is too low for steam generation, a considerable amount of energy remains in the storage. It can be used for freeze protection. Several methods have been presented an analysed. FP11 and FP12 were the most suitable ones and an annual simulation showed that up to 50% of backup heater energy can be saved by using the thermocline storage for freeze protection. Another results of the annual simulations showed that natural circulation can exceed forced circulation, this is, however, dependent of the control strategy of the complete plant and needs further investigation. A comparison of different storage efficiency definitions showed that the analysis is not straightforward and the thickness of the thermocline not best suitable method.

Along with D3.1 D3.3 and D3.5, D3.4 contributes to the achievement of MS11.

DEVIATIONS FROM ANNEX I, REASONS AND THEIR IMPACT ON OTHER TASKS AS WELL AS ON AVAILABLE RESOURCES AND PLANNING

The performed wp work is fully compliant to the expected objectivies, and all the wp milestones have been achieved. Some task was completed late, the motivation and justification for the delays are reported in the first period project report.

MILESTONES ACHIEVMENT DURING THE PROJECT PERIOD

The following table summarizes the expected milestones and the related deliverables.

Milestone		Associated deliverables	Status
MS9	Preliminary design of the full-scale stratified MS Storage Tank with integrated Steam Generator	D3.1	Achieved
MS10	Project executive of the full-scale stratified MS Storage Tank with integrated Steam Generator	D3.2	Achieved
MS11	Completion of the analysis, modelling, simulation and comparison of the various TES concepts	D3.1,D3.3,D3.4,D3.5	Achieved

WP4: REDUCED SCALE TES-SG TEST SECTION: SCALED MODELING, ANALYSIS, SIMULATION AND DESIGN

RESUME OF WP4 OBJECTIVES

The purpose of WP4 the design of the one-tank Molten Salt (MS) Thermal Energy Storage (TES) concepts (stratified MS Storage Tank (ST)) with integrated Steam Generator (SG), presenting a size of 12.5 MWth (about 5 MWel) to be actual constructed by the Cobra site. WP4 was intended to contain all the simulations and engineering necessary in order to complete the following activities:

1) Modeling and engineering of the "test section" system, that is, a TES/SG system with an integrated steam generator, presenting 12.5 MWth (corresponding to about 50 MWel) to be implemented by the Cobra plant.
2) Design of the necessary modification for the Cobra test facility.
3) Definition of a test matrix of experimental tests to be performed on the stratified MS Storage Tank with integrated SG test section

Task 4.1: Analysis, modeling and simulation of the Test Section (TS) simulating the integrated Steam Generator inserted in the stratified MS Storage Tank (deliverable D4.1)

In the D4.1 deliverable, reporting the T4.1 accomplishments, the numerical activity aimed at the analysis and design optimization for the Thermal Energy Storage-Steam Generator (TES-SG) integrated system for the OPTS Reduced Scale configuration is presented. The work has been performed within task 4.1 by ENEA, CEA and the Fraunhofer Institute with the support of ANSALDO with regards to the SG performance data (that are reported in Deliverable D4.2 and summarized within CEA contribution in sections 3.1.1 and 3.1.4) and engineering support for the analysis of possible improvements.

ENEA presents the Computational Fluid Dynamics (CFD) simulations of the TES-SG systems, during a discharge phase, for both the PCS experimental facility (where experimental data on temperature stratification in the tank are available) and the OPTS Reduced Scale configuration.

CEA activity is presented. The work has been divided into two parts: first a model has been developed to reproduce the thermal behaviour of the steam generator. It calculates the heat exchanges between the molten Salt and the water and reproduces the water phase change. It has been validated thanks to the data provided by ENEA, and transient calculations were run on the 12.5 MWth reduced steam generator. Secondly the rest of the tank has been simulated with the CFD software Fluent. Transient simulations of the discharge have been realised to measure the influence of the molten salt flow at the exit of the SG on the thermocline stratification.

In the Fraunhofer Institute contribution, design guidelines are given, e.g. for the optimization of the natural circulation of molten salt through the primary side of the steam generator. A diffuser design is proposed and design features are discussed, aimed at preventing destratification. At the end a storage analysis is performed and different evaluation methods discussed. For this purpose the storage is investigated in combination with solar field as heat source and a heat sink. Different operational states which occur during the operation of solar thermal power plant are discussed and an explanation on how they affect the evaluation parameter is given. The prototype to be constructed will be charged with a natural gas fired boiler. A hardware in the loop system can be used to emulate a real power plant with a solar field as heat source.

The conclusions of the different contribution can be summarized as follows.

- ENEA contribution

The results of the CFD simulations performed by ENEA for a discharge phase on the TES-SG systems of the PCS facility and on the OPTS REDUCED Scale configuration are presented. The simulation of the PCS facility TES-SG system has been performed on a full 3D domain. The results stress the importance of both the diffuser geometry and initial conditions on thermocline evolution. The simulation predicts more thermal diffusion than indicated by the experimental temperature measurements but the reasons for this misprediction are identified and partially confirmed by other simulations performed in the MATS FP7 EU project [2]. The results of the simulation of the TES-SG system for the OPTS REDUCED Scale configuration, performed on a 2D domain, also suggest the importance of properly studying a diffuser for the cold MS leaving the steam generator in order to keep the thermocline extension as small as possible. In addition, the high ratio between the tank height and diameter chosen for this configuration, beside widening the SG operational range in natural convection, also appears to reduce turbulent effects on the thermocline extension when the thermocline is set at middle height in the tank. However, full 3D simulations and grid sensitivity tests are needed before drawing final conclusions on this side. By comparing the results for REDUCED and FULL SCALE (Deliverable D3.1) simulations it seems to be confirmed the importance to keep the average Reynolds number in the tank during the discharge phase below the fully turbulent regime in order to keep the extension of the thermocline region as small as possible.

- CEA contribution

Two modelling approaches have been used by CEA to simulate the test section storage: a numerical model has been developed to simulate the SG behaviour while transient simulation has been run to analyse the tank behaviour. The model of the steam generator has firstly been validated with experimental data provide by ENEA. Then the calculation on the half size steam generator leads to the Ansaldo designed values (12.44 MWth against 12.5 MWth). Finally two different injection modes were compared: the same flow rate or the same residence time in each tubes: it appears that the overheated steam exit at a more uniform temperature between the different H2O tubes, when the water the resident time is the same. The simulations obtained with fluent of the tank have shown that the central SG position doesn’t break the gradient but its bottom design generates a large gradient.

- Fraunhofer ISE contribution

Fraunhofer Institute analyzed some design issues to be considered when a TES-SG system is constructed. A key element is the design of the SG when it is only driven by natural circulation. The system has to work even at a low charging level, the frictional forces have to be reduced and the driving buoyant force to be increased. This is achieved by placing the heat sink as high as possible without stretching the aspect ratio of the storage too much. A tank height of 10 m was found to be a good trade-off. The SG reaches full load at a charging level of 30%. Another point is the proper location of the pump inlet, it has to be located above the lower rim of the SG to avoid warmer fluid rising in the SG section and causing a resistance for the molten salt circulated through the primary side of the steam generator. Furthermore, a design for the diffusers was proposed which should reduce mixing guarantee a good fluid distribution over the cross-section. Care has to be taken during the standby or storing periods of the storage convective mixing currents can cause a lot of exergy loss and since the driving force for natural convection is high. The temperature difference between fluid and tank wall is relatively high due to the large temperature difference of the storage medium to the ambient. However, horizontal baffles at the wall improve the performance considerably. Internal insulation is another way to solve these issues, the performance is not as good as the configuration with baffles but the temperature at the tank wall is lower allowing the utilization of different construction materials. The analysis of the thermocline system has shown that energetic and exergetic efficiencies which use the difference between inlet and outlet do not take into account the eventual higher inlet temperature for the solar field which results in a lower accumulated power. An exergy analysis which considers only the hot streams at the top seems to be appropriate.

The accomplishment of the task is concerned with milestone MS12

Task 4.2: Design of Test Section (deliverable D4.2)

Deliverable D4.2 relates to the Task 4.2 and is concerned with the enginnering design and final drawing preparation for the “test section” size (12.5 MWth) TES (thermal energy storage) SG plant.

- ENEA contribution

Collection and organization of the data provided by Ansaldo, Cobra and KT.

- Ansaldo contribution

The object of the activity performed in this task is the Thermal/Hydraulic (T/H) design of the scaled helical coil steam generator in the frame of the OPTS project (OPtimization of a Thermal energy Storage system with integrated Steam Generator).

The project foresees the steam generator to remove the design thermal power from a mixture of molten salts ($NaNO_3$ 60%w and KNO_3 40%w). The molten salts are outside the tubes at ambient pressure and the natural circulation sustains the design flowrate; the water flows inside the steam generator tubes at the design pressure (about 105 bar(a)) and exits from the tubes in superheated condition.

The T/H design of the steam generator activity reported in this document consists of:

- T/H sizing of the steam generator tube bundle: this activity leads to determine the required steam generator heat transfer surface in term of number, diameter and length of tubes and size of the steam generator shell.

  The T/H sizing of the steam generator has been done in order to scale opportunely and to be representative of the full scale steam generator design, as reported in deliverable 3.2.

This means that the T/H design of the scaled SG object is to maintain as much as possible the same tube length, active tube bundle height, radial and axial pitches, etc. of the full scale SG.

- T/H performance of the steam generator at different power levels is expected to be similar to the full scale, as reported in Deliverable 3.2, The orifice at the tube inlet that has been designed in order to limit the mass of water discharged into the molten salt pool tank in case of steam generator tube break for the full scale SG is still applicable for the scaled SG since the water mass flow rate per SG tube is almost the same due to the fact that the SG T/H operating parameters (except for the thermal power and consequently the water and molten salts flow rates) and the SG geometry (except for the number of parallel tubes) are the same.

- Cobra contribution

For the design of the plant TES-SG, COBRA has worked and collaborated with KT in the following issues:

- Supply of data about CSP Casablanca:

- General arrangement of CSP Casablanca and the reserved area for TES-SG.
- Drawings of equipment, piping and steel structure.
- Data (flow, pressure, temperature) for the different fluids involved in the process (molten salt, steam, natural gas, water supply, nitrogen, etc...)
- Technical soil report.
- Specifications of piping and equipment data sheet.
- BASIC DATA DESIGN for the project TES-SG

- **Approval and comments of drawings and documentation prepared by TKT for the project:**

- PFD / HMD
-Drawings of equipment.
-EQUIPMENT SUMMARY
-TES-SG General Arrangement.
-Preliminary PLANNING

The related documents and drawings are reported in deliverable D4.2

- KT contribution

The final drawings concerning the test section scale facility, prepared by KT, are inserted as pdf attachments, and can be accessed by a linked table present in the deliverable document.

Task 4.3: Design of the modifications of existing test facility (deliverable D4.2)

- Cobra activities regarding the modifications of the existing test facility

The description of this work is included in D4.2. The objective was the study and design of the connection between the TES-SG and CSP Casablanca.

The following activities are described (in D4.2 report):

- Background concerning the technical data of the plant CSP Casablanca
- TES-SG steam connection with CSP CASABLANCA
- Connection TES-SG with CSP CASABLANCA SYSTEMS

The related documents and drawings are reported in deliverable D4.2

This task is related (with T4.2) to the achievement the milestone MS13.

Task 4.4: Test matrix of experimental tests on the stratified MS Storage Tank with integrated SG (deliverable D4.3)

The topic of the Task 4.4 of the OPTS project is described as following: “By utilizing the s/ws and the models developed in Task 3.1, will be decided the matrix of all the experimental tests to be carried out in the experimental facility, in order to investigate and to study all the phenomena occurring and the behaviour of the components, so characterizing deeply the whole system under examination. CyI will focus on the parts of the test matrix pertaining to thermo-hydraulic flow instabilities, which are modelled numerically and are anticipated to occur in the reduced scale pool-type TES-SG system”.
In order to complete the required tasks, several data are to be assessed and collected:

1) A detailed project regarding the experimental equipment to be installed at the facility in order to allow the characterization of the necessary chemical-physical parameters. The boundary conditions (maximum/minimum max flow rate, maximum/minimum steam pressure and temperature, maximum/minimum molten nitrates temperature, and so on) should be set according to the results reported in the test section final drawing document (D4.2) and the experimental results obtained in wp2.
2) Each partner involved in the modeling campaign (especially the ones involved in the modeling of the test section, D4.1) should suggest an experimental tests matrix necessary to validate the results attained by the a priori simulation methods. All the suggestions should be collected and organized in a test matrix shared and accepted by all. According to this final matrix, it will be determined the number of parameters to be measured in order to study equilibrium and transient behaviors, the carrying out of specific tests to certain

conditions of the parameters and the implementation procedures of both steady state and transient tests (time intervals of the variation of the primary parameters, duration of tests, etc.).

Evidently, given the premature termination of the OPTS project, it will be no possible to build up the test facility and and the test section and, consequently, the matrix of experimental tests. In principle, the assessment of a test matrix could be potentially useful for possible future works on the very same topic but, due to the lack of specific elements of detail on the experimentation, object of the present study, this work would be only a theoretical exercise afterwards not applicable to the possible future experimental campaign.
For these reasons, the expcted D4.3 report just includes a document prepared by CIEMAT, containing their considerations about possible issues for data acquisition procedures in a test section size (about 12.5 MWth) facility, on the basis of the experience gained during the CIEMAT experimental campaign at the PCS facility located at the ENEA Casaccia centre (task 2.2).

- CIEMAT contribution to wp4 (included in deliverable D4.3).

WP4 is aimed at designing a reduced scale TES-SG test section starting from simulation and modelling but also by analysing of the already existing 300kWth test section at ENEA centre in Casaccia. In this report experimental data of such installation is analysed in order to:

(1) detecting problems in specific measuring gauges. The coherency of experimental values of different data gauges will be checked as well as the coherency of indirect variables obtained from experimental data. Some recommendations will be given to solve the found problems.

(2) defining a procedure to check the validity of the experiment, according to specific purposes. Some recommendations will be given to check experiments during execution.

(3) improving the experimental set up for a future potential new installation of the type here considered.

Nine days have been analysed but, for clarity, the report follows experimental data on 29th October 2012. After this analysis the following recommendations and conclusions have been achieved:

Related to experimental gauges the following recommendations are given to improve the experimental set up for a future potential new installation of the type here considered:

- Including a liquid level gauge for bulk molten salts. It would give a quick check to assure the minimum molten salt level to come into the SG. It would also give a indirect measure of molten salt density change with temperature.
- The lowest part of the tank should be instrumented with temperature gauges. Today the prototype has the lowest thermocouple just below the lowest heigth of the helical tubes in the SG, missing a lot of information about temperature evolution and mixing in the lowest part of the tank (which in terms of molten salt volume is about a quarter of the total amount). This information would be very useful to better understand the physical phenomena occurring at the SG outlet
- Temperature gauges in the rear part of the SG outlet, along the tank, should be included.
- These gauges will give information about the molten salt stratification symmetry –or the absence of it- aroung SG.

- The todays mass flow meters for every helical tube based on pressure drop on calibrated orifices are not adequate since they fluctuate as much as their nominal value, given sometimes, ilogical values. Maybe a question of an inappropriate orifice design. The figures this approach gives are not useful.

Related to procedures and methods of evaluating experimental data:

- It is very worthy to check every gauge before starting any test and, repair them or correct their values, if possible. Thus, the missing information due to problems with specific gauges would be avoided.
- The position of the water phase change front within the SG tubes can be perfectly defined by analysis of their skin temperature, mainly by observing their fluctuations along the time.
- The thermal capacity of a storage tank with an integrated SG is given by the molten salt amount flowing through the SG till a security low temperature is achieved. Optimization of the molten salts total volume can be obtained from an energy balance between water/steam loop at the SG. The prototype in Casaccia is oversized in terms of molten salt amount.

<u>This task is related (with T4.3) to the achievement the milestone MS13.</u>

DEVIATIONS FROM ANNEX I, REASONS AND THEIR IMPACT ON OTHER TASKS AS WELL AS ON AVAILABLE RESOURCES AND PLANNING

Most of the wp activities have been completed, according to the DoW indications. Task 4.1, 4.2 and 4.3 have been carried out and the milestone MS13 “Project executive: Design of the modifications of existing experimental test facility” can be considered achieved. T4.1 completed late, due to the motivations reported in the first period project report.For the reason expressed above, related to the problem suffered by the project, and detailed below, it has not been possible to achieve the milestone MS14 related to T4.4. Regarding this last activity, it was certainly mandatory and propedeutic for wp 6 and 7, but can be considered to represent a minor effort inside the wp.

MILESTONES ACHIEVMENT DURING THE PROJECT PERIOD

The following table summarizes the expected milestones and the related deliverables.

Milestone		Associated deliverables	Status
MS12	Project executive: Design of the reduced scale TES-SG Test Section	D4.1	Accomplished
MS13	Project executive: Design of the modifications of existing experimental test facility	D4.2, D4.3 (including CIEMAT contribution to wp4)	Accomplished
MS14	Definition of the matrix of the experimental tests	D4.4	Not Accomplished

WP5: CONSTRUCTION AND COMMISSIONING OF THE TEST SECTION AND INTEGRATION IN THE EXISTING FACILITY

RESUME OF WP5 OBJECTIVES

The objective of this WP was the realization of the test-section in order to perform experimental tests for the new concepts and solutions proposed under real solar irradiation conditions, with the goal to validate the physical-mathematical models under development and to experimentally check the viability of the new TES concept.

In this WP it was expected to be achieved the construction and the commissioning of a Test Section (TS) at a significant scale (12.5 MWth, corresponding to ½ power of the modular base of the SG and to 1/10 of full-scale power)

WP5 STATUS

All tasks, and in general all the wp5, wp6 activities were not finalized for the main reason of the KT withdrawal from the project. In fact, KT was the responsible for the test section construction. Besides, Cobra manifested some doubts about their further participation in the project, because they needed to find an agreement about the exploitation of the TES/SG technology (based on an ENEA/Ansaldo patent) after the project completion.

These problems were discussed during an appropriate management board meeting hold in Rome the last 27th June 2013. Unfortunately, despite a considerable effort made both by ENEA (as coordinator) and othe project partners, it was not possible to find a proper solution within the deadline given by the EU. Some solutions were discussed, and an appropriate amendment to the project will be proposed by the next October. A detailed description of the timeline of the project situation is provided below.

DEVIATIONS FROM ANNEX I, REASONS AND THEIR IMPACT ON OTHER TASKS AS WELL AS ON AVAILABLE RESOURCES AND PLANNING

Only preliminary wp5 activities were performed, and no task was finalized

MILESTONES ACHIEVEMENT DURING THE 1st PROJECT PERIOD

Milestones MS15, MS16 and MS17 were not achieved.

WP6: EXPERIMENTAL TESTS, ANALYSIS OF RESULTS AND CODES VALIDATION

RESUME OF WP6 OBJECTIVES AND WP STATUS

The objective of WP6 is the experimental campaign to be carried out employing the « test section » facility. This work package was expected to start at the 24th project month, but, due to the situation described in wp5, it was not possible to reach and finish the activities included in the WP6.

DEVIATIONS FROM ANNEX I, REASONS AND THEIR IMPACT ON OTHER TASKS AS WELL AS ON AVAILABLE RESOURCES AND PLANNING

Only preliminary wp6 activities were performed, and no task was finalized

MILESTONES ACHIEVEMENT DURING THE 1st PROJECT PERIOD

Milestones MS18, MS19 and MS20 were not achieved.

WP7: TECHNICAL – ECONOMIC ANALYSIS OF COMMERCIAL SCALED–UP SYSTEM

RESUME OF WP7 OBJECTIVES

The purposes of this wp are:

• Definition of the potential market and application opportunity, also for different uses from CSP industrial sectors, including exploitation standards and competing technologies.

• Assessment of the cost for up scaling from pilot (or pre – industrial) scale to industrial scale;

• Development of a business plan, including a scheme for the protection of intellectual properties and a LCA study.

Clearly, the work package was intended to be completed at the end of the RTDs activities; however KT, also by using data provided by Cobra, decided to complete its part in advance, this in order to obtain some evaluation about the feasibility of the proposed TES/SG based on a MS thermocline. Therefore the following tasks description will just report a summary of the KT (and Cobra) contribution. The complete KT report will be uploaded in the reserved zone of the OPTS site. Since, according to KT, the motivation for their withdrawal from the project are based on the results of these evaluations (that is, on the part regarding T7.2), we'll came back to this topic in the « PROJECT MANAGEMENT DURING THE PROJECT PERIOD » section

In response to KT, Ansaldo and ENEA prepared a response document, which also includes a market cost research showing that an immersed SG, as proposed in the OPTS project, is actually significantly less expensive than an external heat exchanger.

These activities are reported and summarized in D8.1 (wp8) but they are clearly related to the task T7.2 (Assessment of the cost for up scaling from pilot (or pre – industrial) scale to industrial scale) and milestone MS22, which can be considered as partially achieved.

DEVIATIONS FROM ANNEX I, REASONS AND THEIR IMPACT ON OTHER TASKS AS WELL AS ON AVAILABLE RESOURCES AND PLANNING

Activities related to task T7.2 were partially carried out by KT, ENEA and Ansaldo; results, however uncomplete given the unavailability of the expected experimental data from the "test section" facility, present high interest for further considerations about possible future on integrated TES-SG sytems

MILESTONES ACHIEVEMENT DURING THE 1st PROJECT PERIOD

MS22 was partially accomplished, along with (see D8.1) a little part of MS21. MS23 was not accomplished.

WP8: DISSEMINATION OF PROJECT RESULTS

RESUME OF WP8 OBJECTIVES

The purposes of this wp are:

- Establish dissemination standards;
- Promote dissemination of results and look for their exploitation by a specific "dissemination and technology transfer plan";
- Ensure the effective integration and coordination of the work with other related topics and international initiatives.

Task 8.1: Final Report on possible exploitation and implementation of project results (deliverable D8.1)

The deliverable D8.1 includes the activities performed primarily in wp 7 (see below "KT 'kinetics technology' withdrawal and ENEA/Ansaldo response" for a summary and the deliverable for details).

The task is related to the achievement of milestone MS24.

Task 8.2: Final Report on dissemination activities (deliverable D8.2)

Dissemination activities can be divided into two main topics:

- Dissemination of the technical project results, carried out by all project partners, both participating at international meetings or by publication in peer-reviewed scientific papers.
- Creation and maintenance (by ENEA) of a dedicated website, containing updated information about the project development, and also including a multimedia scientific educational section, dedicated to topics related not only to thermal storage, but in general to the solar energy field.

The latter activity has been realized employing particular innovative features, which will be illustrated in this document.

DISSEMINATION BY PUBLICATIONS AND MEETING PARTICIPATION

Considering the project topics, a particular preference has been given to the Solar Paces 2013 and 2014 meetings. The following table resumes the presented articles and posters.

ORGANIZATION	*AUTHORS*	*TITLE*	*Conference*
CIEMAT	Rocío Bayón, Esther Rojas	Analytical description of thermocline tank performance in dynamic processes and stand-by periods	ISES Solar World Congress 2013
CIEMAT	Rocío Bayón, Esther Rojas	Study of thermocline tank performance in dynamic processes and standby periods with an analytical function	*SolarPaces* 2013
CIEMAT/ENEA	Esther Rivas, Esther Rojas, Walter Gaggioli, L. Rinaldi, F.Fabrizi	CFD analysis of a molten salt tank with integrated steam generator	*SolarPaces* 2013
CNRS	Fabrice Motte, Sam Bugler, Quentin Falcoz, Xavier Py	Numerical study of a structured thermocline storage tank using vitrified waste as filler materials	*SolarPaces* 2013
ENEA	W. Gaggioli, F. Fabrizi, F. Fontana, L. Rinaldi, P. Tarquini	An innovative concept of a thermal energy storage system based on a single tank configuration using stratifying molten salts as both heat storage medium and heat transfer fluid, and with an integrated steam generator	*SolarPaces* 2013
Fraunhofer-ISE	B. Seubert, T. Fluri, W. Platzer	Thermocline Storage with integrated Steam generator: Investigation of different operation modes	*SolarPaces* 2013
ENEA	E. Veca, S. Sau, C. Felici, A.C. Tizzoni	Characterization of thermal fluids for application in solar concentration plants	*SolarPaces* 2013

ENEA	W. Gaggioli, F. Fabrizi, P. Tarquini and L. Rinaldi	Experimental validation of the innovative thermal energy storage based on an integrated system "storage tank/steam generator"	*SolarPaces* 2014
ENEA	A.C. Tizzoni, S. Sau, E. Veca, P. Tarquini, M. Agostini, A. Giaconia	Thermal fluid for integrated CSP storage system: thermo-physical, stability and compatibility study on a molten nitrates binary mixture	*SolarPaces* 2014
CIEMAT	M. Rodriguez-Garcia, A. Lopez-Tamayo, E. Rojas,	*Components test device with molten salt at high temperature and pressure,*	SolarPACES2014
Fraunhofer ISE	B. Seubert, A. Vogel, T. Fluri, W. Platzer	Freeze Protection Strategies for Molten Salt Parabolic Trough Solar Fields using Residual Heat of Thermocline Storages	SolarPACES2014
Fraunhofer ISE	B. Seubert, T. Fluri, W. Platzer	Numerical Investigation and Improvement of the Standby Performance of Thermocline Storages	SolarPACES2014

Besides, OPTS activities carried out by ENEA Ph. D students (A.C. Tizzoni and S. Pistacchio), were presented at the last Sollab 2014 meeting.

Several scientific results obtained during the OPTS project have been the subject of publications in peer-reviewed journals. The table below shows a summary of this activity.

ORGANIZATION	*AUTHORS*	*TITLE*	*Journal/ bibliographical reference*
CIEMAT	Rocío Bayón, Esther Rojas	Simulation of thermocline storage for solar thermal power plants: From dimensionless results to prototypes and real-size tanks	International Journal of Heat and Mass Transfer 60 (2013) 713–721
CIEMAT	Rocío Bayón, Esther Rojas	Analytical function describing the behaviour of a thermocline storage tank: A requirement for annual simulations of solar thermal power plants	International Journal of Heat and Mass Transfer 68 (2014) 641–648
CNRS	Fabrice Motte, Sam Bugler, Quentin Falcoz, Xavier Py	Numerical study of a structured thermocline storage tank using vitrified waste as filler materials	Energy Procedia (2013)
CREF-Cyl	E. V. Votyakov , A. M. Bonanos	CFD analysis of a molten salt tank with integrated steam generator	International Journal of Heat and Mass Transfer 75 (2014) 218–223
CIEMAT	Rocío Bayón, Esther Rojas	Study of thermocline tank performance in dynamic processes and stand-by periods	Energy Procedia, 49, (2014) 725- 734
CIEMAT	M. Biencinto; R. Bayón; E. Rojas; L. González	Simulation and assessment of operation strategies for solar thermal power plants with a thermocline storage tank	Solar Energy, 103, (2014) 456- 472
CIEMAT/ENEA	Esther Rivas, Esther Rojas, Walter Gaggioli, L. Rinaldi, F.Fabrizi	CFD analysis of a molten salt tank with integrated steam generator	Energy Procedia, 49, (2014) 956-964

All considered, the described scientific dissemination covers prevalently and exhaustively the activities on wps 2, 3 and 4.

PROJECT WEBSITE

A very important part of the dissemination activities is represented by the realization of a dedicated website, which presents some innovative characteristics, especially regarding the multimedia sections.

The site address is:

http://www.opts.enea.it/index.htm

It is organized with a private (dedicated to project internal activities, in particular, documents, meeetings presentations and minutes and reports) and a public section. Concerning the latter, it is present:

- A project description, along with a news and a newsletter section
- An updated section describing the events (meetings, conferences) related to solar energy or heat storage topics
- A section including the project documentation in public domain (i.e., dissemination, periodic reports summaries)
- A multimedia section, used both for educational (public domain) purposes and for communication between project partners.

In particular, the assessment and management of the last described site area, has been performed following innovative criteria, and represents something particularly new in the field of European project websites. The main features of this section are:
The project website has been continuously worked and managed over the project duration.

The activities of this task allow to complete milestone MS25.

GENERAL CONSIDERATIONS ABOUT RTD AND DISSEMINATION ACTIVITIES

The achievments expected in the DoW project, having as final aim the developing of innovative TES sytems for concentration solar plants, can be roughly divided into four main categories:

- Thermocline tank with filler inside: the objective was to evaluate and to optimize the technological solutions of the thermocline tank concept, one of the goals was to perform comparisons with the concept of the system with stratified molten salts and integrated TES-SG. These activities have been carried out in wp2 (experimental) and wp3 (modeling).
- Stratifying MS (molten salts, alkaline nitrate mixture) TES with integrated SG: the objective wasto evaluate and to optimize the technological solutions of Pool type SG and its multiple version for TES in large power plants. Validation of computer codes developed will be done by data from the ongoing experimental activities at small-scale. These activities have been carried out in wp2 (experimental) and wp3, wp4 (modeling).
- Engineering design of a “full scale” TES SG plant (125 MWth) and of a “test section” one (12.5 MWth). The latter is necessary and propedeutic both for the actual construction and integration in a pre-existing CSP plant and to allow the design of the “full scale” system, which, in turn, is essential in order to carry out technical-economic evaluations and comparison with alternative TES configurations (as, for instance, the ones employing filler materials, as described above).
- Construction of a TES-SG “test facility” necessary both to demonstrate on a pre-commercial scale the scientific and simulation results obtained in the other wp and to show the feasibility of the proposed technology, also considering its integration into an existing CSP plant.

Summarizing all the performed activities, it clearly results that three out of four of the forecasted activities have been completed. However it was not possible to finalize the main target of the project, the technical validity of the work carried out, considering its contribution to the developing of the thermal storage technology is absolutely clear. Considering the obtained progresses respect to the state of art of TES-CSP technology at the moment of the starting of the project, the following applies:

- Considering, in general, thermo-physical characterization of the binary “solar salt” mixture, very few data were present in the scientific literature concerning thermal stability; about this topic an exhaustive experimental campaign was carried out, which clearly defines the upper temperature limits to be employed and the degradation rate (that is, the time period during which the mixture can remain at high temperatures without being significantly damaged);
- Regarding material compatibility, the possibility to employ cheaper carbon steel material has been tested up to 2000 hours, results are interesting enough to think about further experiments on this topic. Concerning filler materials, their compatibility with molten nitrates has been established;
- The behaviour of CSP equipment under thermal and mechanical stress has been deeply investigated, and the results are very interesting for improving the handling of CSP plants operations.

The last three points are concerned with CSP in general, about solid fillers based TES:

- A complete modeling campaign has been performed about TES- thermocline with filler;
- A comparison has been carried out about these systems and the TES with immersed SG without fillers.

Regarding, more specifically, TES-SG applications:

- Very few data were previously available regarding molten nitrate thermal stractification and the conservation of the thermocline over several charging/discharging cycles, at this aim an experimental campaign has been performed both at laboratory scale and at the PCS facility. Results clearly show the potential feasibility of this innovative storage technique
- A compete modeling analysis has been performed considering the “test section” configuration, which was preliminary to the simulation analysis of the “full scale” size system
- The integration of several developed TES simulation results (in wp3) in CSP performance models
- Final drawings have been prepared for both the “test section” facility (including data about its integration in a pre-existing CSP plant) and the “full scale” plant. The design of the latter is necessary in order to establish a realistic technical/economic analysis, needed to make comparison with other available TES CSP technologies; regarding the former, besides being related to the plant planned to be constructed, the design of the single components was necessary in order to obtain information about the actual cost to be expected for this configuration; as an important example, it was shown that the market cost of the SG designed by Ansaldo can actually be (as expected in the DoW document) a quarter respect to an external SG presenting the same power. These data are quite important for possible future projects based on the same OPTS subject, in order to overcome from the beginning some objections and doubts raised during the project.

- The integration of several developed TES simulation results (in wp3) in CSP performance models has been carried out

All the results obtained by the above mentioned activities are clearly of high interest and utility for the developing of TES technology, also considering the information disseminated during the project period.

MANAGEMENT ACTIVITIES DURING THE PROJECT PERIOD

The general objectives of the WP1 can be summarized as follows:

- coordinate and manage the administrative, legal and financial issues of the OPTS Project and Consortium
- manage contacts with the European Commission, with the Coordinator representing the only interface with the European Commission
- promote dissemination of results and look for their exploitation

These tasks have been performed by the project Coordinators with OPTS partners over the project period.

A project kick-off meeting has been organized by ENEA in in Bruxelles. After that, several WP technical meetings have been organized between the involved partners. Also a project plenary progress meeting was held in June 2012 in Rome and a Management Board meeting has been organized in June 2013 by the ENEA Casaccia research center (Rome). ENEA and other partners in charge of the coordination of different tasks have produced distributed the Minutes of Meetings related to Project, Management Board and WP meetings.

A project logo has been designed at the beginning of the project and templates for reports/deliverables have been distributed in advance to the participants for standardisation of report formats.

A project related website (www.opts.enea.it) was created, representing also the project deliverable D1.3, and maintained throughout the project period. This website has a public domain dedicated to the dissemination of project results and a members-only password protected domain dedicated to efficient exchange of confidential information among the partners and the EC. This exchange and management tool ensures a permanent interchange of project related documents, minutes, reports, results, presentations between all the partners, the EC and the appointed project reviewer. The website is located on an ENEA server. A screen-shot of the homepage is represented here.

At the end of December 2012 a very serious illness struck the former project coordinator, Eng. Fabrizio Fabrizi. ENEA needed some time to reorganize its position in the project and name another coordinator; of course, also this situation affected the foreseen timing of the OPTS activities.

From a management point of view, two major problems occurred during the implementation of the project have been: the withdrawal of one investor partner of the Consortium, namely KT kinetics technology, and the issues about the IP rights for the exploitation of the TES/SG after the end of the project raised by Cobra.

Description of the major management issues arising during the first period of the project

- KT “kinetics technology” withdrawal and ENEA/Ansaldo response

The KT motivations for their withdrawal from the project were at the beginning communicated to the coordinator (ENEA) and eventually described during a progress meeting held in Madrid (April 2013), here is an extract from the minutes:

“Iaquaniello (TKT) T7.2: shows the results of an estimated cost analysis comparing three different systems with the same stored thermal energy: a “conventional” two tanks plant architecture employing thermal oil as heat transfer fluid (HTF) and molten nitrates as storage materials (HSM), a two tanks plant where MS are employed as HTF and HSM and the single tank storage system as proposed in the OPTS project. Remarkable economic advantages are clearly present when molten nitrates are employed as HTF instead of thermal oils but, according to TKT results, the cost advantages with a single tank with an immersed SG are minimal, if any, than the ones expected at the beginning of the project (at least 50% less)."

In general, the KT considerations about this topic can be found in the D8.1 deliverable.

They confirmed their position in a request for termination letter, sent to ENEA the last 8th June 2013, and during the management board meeting held the last 27th June 2013.

The answer from ENEA and Ansaldo was sent to KT later than expected, especially for the difficult in the period concerned to find a proper and valid commercial evaluation of the immersed steam generator, whose price is one of the reason, according to KT, of the non-economic profitability of the TES/SG system respect to the "two tanks" system, and also because it was difficult to decide about a reliable estimation of some technical features before the foreseen OPTS modeling and experimental campaign is concluded.

ENEA and Ansaldo don't agree with some of the KT approaches and, especially, with the KT conclusions. In particular, ENEA and Ansaldo contest the following aspects (see D8.1 report as reference for the topics discussed):

1) The only possible reference plant for CSP working at high temperatures, with MS as HTF and HSM at about 550 °C, is the "Archimede" plant.

In the DoW document is reported a list of preliminary costs concerning the main components of this installation.
For the OPTS configuration (TES/SG system with 12.5 MWth, as in the "Archimede" case) the following applies:

2) the MS volume is about equal in the two configurations (taking into account the dead volumes in the two tanks system, and given the lack of experimental data on the thermocline behavior, it can be supposed that the two system need about the same MS amount)

3) In the TES/SG system only one tank (321H) is present (in the "Archimede" system are present two tanks in 321H SS)

4) The SG weight in the TES/SG is reduced to 13% respect to the external SG in the "Archimede" configuration (the same cost is in principle assumed, in order to be conservative)

5) With these assumptions a minimum saving of about 16% is obtained by comparing the TES/SG system with the "Archimede" one.

6) A more precise estimation of a realistic SG cost and other materials (pipelines, valves, connections) will result in further TES/SG cost reductions. For instance, a 20 % reduction in the SG cost will lead to a value of about 21%.

Also, according to ENEA and Ansaldo, in order to obtain a proper economic evaluation of a TES/SG system, the following technical features have to be investigated in more detail during the OPTS design campaign:

- Tank design: to improve the natural circulation, the thermocline stability, and the tank geometry
- Steam generator supporting design: external from the top or internal on the bottom
- TES/SG modularity, in view of the scaling up of the system

Moreover, as final considerations, it is very interesting to report the results obtained during the investigation, performed by Ansaldo, for the cost of an integrated steam generator (ISG) for the test section (5 MWel/12.5 MWel of size) plant.
The following table resumes the results obtained during a preliminary inquiry (VAT not included):

Approximated ISG costs (k€)
200
400
700
1200

According to preliminary inquiries made by KT, a cost of about 1200 k was estimated for the immersed SG. Evidently, as can be noticed in a previous section, the cost of the SG was a significant parameter in their evaluation.
It is interesting to note that according to the information gathered during this preliminary market research, in general the offers represent the cost for a first realization of this type of SG, and they expect a significant decrease of the manufacturing rate, in case the demand for this type of products would growth. It is also worth noticing the wide gap between the obtained offers, which suggests a considerable uncertainty in the realization cost for the ISG; this can support the view that, in case of a continuative and consolidate production, manufacturing costs may still decrease.
At this point, it is also worth comparing the cost for the Archimede plant (see the DoW document) and for the test facility expected to be built up in the OPTS project (both practically present the same size, around 5 MWel).
In the first column are reported the costs approximately estimated by using the assumption of KT (see the corresponding paragraph), it is important to note that this is not the cost analysis reported in the DoW document, where the actual "Archimede" plant arrangement was considered. According to KT, the cold tank in an "Archimede" plant, that is, a two tanks configuration, can be made of carbon steel, given it is to be used at temperatures below 300 °C and only the hot tank has to be made of a costly stainless steel (321H or 347H), for similar reason, just the superheater section in the external SG is constructed with 321 or 347 SS, and the other two third of the heat

exchanger also consists of carbon steel. Evidently, these assumptions make less convenient an alternative use of an integrated storage system (see the section "ENEA/ANSALDO comments on KT contribution, general considerations on integrated storage systems" for further discussions on this topic).
In the second column is reported a TES-SG cost evaluation based, as close as possible, on the KT preliminary evaluations, including am immersed steam generator cost estimated at 1200 k€.
In the third column all the KT assumptions were maintained, but a realistic cost for an integrated SG was inserted.

	Modified ARCHIMEDE project		***OPTS project (KT hypothesis)***		***OPTS project (according to a more realistic SG cost estimation)***	
	Storage Tank					
	unit	***cost***	***unit***	***cost***	***unit***	***cost***
Number [-]	2	€ 1,300,000.00	1	€ 1,000,000.00	1	€ 1,000,000.00
Molten salts (1.8 k€/ m³)	785 [m³]	€ 1,410,000.00	785 [m³]	€ 1,410,000.00	785 [m³]	€ 1,410,000.00
Pumps n.	1	€ 200,000.00	1	€ 200,000.00	1	€ 200,000.00
Foundations (with cooling system)	-	€ 410,000.00	-	€ 250,000.00	-	€ 250,000.00
Bearing metallic structure	2	€ 200,000.00	1	€ 250,000.00	1	€ 250,000.00
Refractory and insulation	2	€ 200,000.00	1	€ 150,000.00	1	€ 150,000.00
Auxiliary electric heating system	-	€ 80,000.00	-	€ 40,000.00	-	€ 40,000.00
Total [€]		**€ 3,802,000.00**		**€ 3,300,000.00**		**€ 3,300,000.00**

- Intellectual property issues about the TES/SG system

The TES/SG system, that is, the system to be constructed by the Cobra site according to the DoW, is based on a patent owned by ENEA and Ansaldo.

Cobra asked about the IP rights exploitation during the last meeting in Madrid, after the meeting ENEA clarified to Cobra by mail that the patent can be used during the project duration. Regarding possible exploitation after the project termination, if new patentable features are not implemented into the system (in this case the consortium agreement rules apply), it is necessary to find an agreement between Cobra and the patent owners, that is, ENEA and Ansaldo.

Cobra complained that the situation about such patent, that is, the fact that it is present and is owned by ENEA and Ansaldo was not reported in the consortium agreement and indicating clearly that the OPTS Project would be the technical development of this patent.

Actually, in the background part of the CA document, is stated:

“All the know-how and knowledge relating to CSP Trough technology developed by ENEA , i. e. solar field, thermal energy storage, molten salts and others. The content of the patents owned by ENEA will be shared with the partners when it will be necessary for the project execution (ENEA) Patents having already been developed in collaboration with other parties outside the OPTS Consortium, will be made available to the partners after having informed the co-developers of the original patents (ENEA).”

Also, the situation of the patent propriety is cited inside the DoW document (for instance, T5.1).

In any case, the issue is not about the patent use inside the project, because, according to the CA, this is allowed to all partners, but about the exploitation of the IP rights after the project termination. At this purpose, the position of Cobra was summarized during the last management board meeting (from the minutes):

“Lasheras (Cobra) explained the reasons for the Cobra request concerning an IP negotiation about the patent rights, owned by ENEA and Ansaldo, regarding the TES/SG system, to be constructed by the Cobra site; in particular, about the exploitation of the IP rights also after the end of the project. Considering that Cobra is required to invest in the project a quite significant amount of money (4.5 million of euros between investment and EU contribution) it is absolutely necessary for them, before going on with the project, to reach an agreement about this issue.”

Unfortunately, despite a long negotiation carried out by Cobra, ENEA and Ansaldo it was not possible to reach an agreement about this topic before the project termination.

- Proposed solutions from the june 2013 management board meeting

With the aim to manage the problems described in 4.1.1 and 4.1.2 a management board meeting was organized the last 27th June in Rome (Casaccia – ENEA research centre). The following steps were planned:

“The consortium asks the EC Officer for a period of 4-months in order to prepare the amendment concerning TKT termination, including a survey of KT work until now, discuss budget re-allocation (internal, if possible, or external, only if necessary) including a review of the proposed set-up (plant size, budget and schedule), and contemporary to discuss exploitation of IP rights, as requested by COBRA.

Regarding a plan for the reallocation of resources and tasks assigned to KT, a preliminary hypothesis is:

- For WP3, ENEA can be responsible for the TKT assignments in T3.1 and T3.3

- For WP5, resources previously allocated to TKT can be reallocated to Cobra, excluding the SG construction (included in part of the Subtask 5.1.2 - integrated steam generator with supports, dedicated instrumentation, etc.); Ansaldo has been asked by other MB members to take the responsibility for this latter item of the Subtask 5.1.2. Ansaldo would examine the. If necessary, an external partner can be involved for the specific task.

- For WP6, resources previously allocated to TKT can be reallocated to Cobra"

More in particular, after other discussions with the involved partners, the following integrations and modifications were decided:

- WP3, T3.3. ENEA, for the time being and the next future, did not have the personnel to take in charge the development of the T3.3 part previously assigned to KT. For this reason, ENEA asked KT to complete their work on this topic and to postpone their withdrawal from the project after the accomplishment of this work. KT showed their availability to do it, and further discussions will follow as soon as possible.

- Cobra renunciation to take charge of activities previously charged to KT

Unfortunately everything changed the moment Cobra, in a letter dated 26th September 2013, decided, after considering technical and financial implications, to renounce to take charge of the activities previously assigned to KT.

At that point, it was necessary to look for a new industrial partner. In doing this ENEA was assisted by other partners (Fraunhofer, CEA, LNEG), a detailed description of that activity is reported in a paragraph below.

- Partial project suspension by the EC

While the search for a new partner was in progress, the EC decided to suspend, since the 21th February 2014, the wps that were not being carried out, namely, wp5, wp6 and wp7.

- Activities related to the search of a new industrial partner

The campaign is summarized in the following table:

Company	Approximated contact period	Reason for the refusal to join the project	Note
ALSOLEN	October-November 2013	"…despite the interest of OPTS project we have come to the conclusion that this project does not fully comply with the strategy nor with the philosophy of our group…"	Contacted by CEA
Bertrams	October-November 2013	I was contacted by phone by the Fraunhofer colleagues and I don't remember exactly the reason for the refusal. Probably, they could not provide the personnel for the facility construction	Contacted by Fraunhofer ISE
Linde	October-November 2013	I was contacted by phone by the Fraunhofer colleagues and I don't remember exactly the reason for the refusal. Probably, they could not provide the personnel for the facility construction	Contacted by Fraunhofer ISE
Estela (consortium)	October 2013	They acknowledged the request, but no reply since then	Contacted by the ENEA responsible for the ESTELA consortium
Renexia	End of 2013	No reply	

Flagsol (TSK)	November-December 2013	"…I have discussed the OPTS projects with the management of our parent company TSK. We came to the conclusion that the large contribution of personnel required by this project (even if reduced somewhat) cannot be handled by our R&D teams, which are fully planned for other projects. We recognize the potential of this interesting project and hope you'll find an adequate partner…."	Contacted by Fraunhofer ISE
ALSTOM	January 2014	No reply	
Eurotecnica	February 2014	"…with reference to your kind invitation to partecipate as partner at the final phases of the OPTS Project, I'm regret to inform you that the services requested at this stage of the project do not make part of our type of performances…"	Contacted by Fraunhofer ISE
Bono Energia	February 2014	After being contacted they didn't show further interest	
M+W	February-March 2014	Probable main reason: "…they cannot assign so much money to a new project within 2014…"	Contacted by Fraunhofer ISE
IDOM	February 2014	Not contacted because Cobra would prefer we did not	Proposed by ENEA and Fraunhofer ISE
SENER	February 2014	Not contacted because Cobra would prefer we did not	Proposed by ENEA and Fraunhofer ISE
EDP	March 2014	No reply	Contacted by LNEG

Hitachi	April 2014	No reply	
HEF	Not contacted		Proposed by Fraunhofer ISE, not contacted because we had been waiting the answer of other companies. Cobra was still to be asked about it
Areva	Not contacted		Proposed by Fraunhofer ISE, not contacted because we had been waiting the answer of other companies. Cobra was still to be asked about it
Paragone Europe*	June 2014	They have been informed about the project situation, but they insisted on having some more time to negotiate. They need to evaluate the project budget and situation, but they think there can be a concrete possibility for a positive decision within a reasonable period of time	

*They showed interest in joining the project, but the EC decided to not grant more time.

- Project termination

The 1st of August 2014 the EC sent a “"Formal written request to rectify a situation of breach of substantial obligation imposed by grant agreement and non performance of the work under project OPTS (grant agreement 283138)", where it was required to correct the project situation after 30 days from the receipt of the communication. Since the receipt of that letter also the work on the previously not suspended wps (1,2,3,4,8) was interrupted and no more costs could be justified in the project.
The termination letter was recived the 30th of September 2014.

RESUME OF DELIVERABLES AND MILESTONES

Deliverable Number	Deliverable Title	WP number	Nature	Dissemi-nation level	Status	Notes
D1.1	Project Periodic Report	1	R	CO	Completed	
D1.2	Project Final Report	1	R	CO	Completed	
D1.3	Project's website	1	R	PU	Completed	
D2.1	Report on the State of the art	2	R	PU	Completed	
D2.2	Report on thermal exchange properties of the MS HX tube bundle system	2	R	CO	Completed	
D2.3	Report on corrosion behaviour for selected HX/Tank materials	2	R	CO	Completed	
D2.4	Report on MS thermal stratification behaviour	2	R	CO	Completed	
D2.5	Report on HX materials durability	2	R	CO	Completed	
D2.6	Report on chemical compatibility and thermo physical properties of filler materials	2	R	CO	Completed	

Deliverable Number	Deliverable Title	WP number	Nature	Dissemi-nation level	Status	Notes
D2.7	Report on experimental tests on reliability and performance of the loop components	2	R	CO	Completed	
D3.1	Full-scale TES-SG system: analysis, modelling and simulation	3	R	CO	Completed	
D3.2	Full-scale stratified MS Storage Tank with integrated Steam Generator: Project executive	3	R	CO	Completed	
D3.3	Thermo-cline Storage Tank with internal filler: analysis, modelling, simulation and comparison	3	R	CO	Completed	
D3.4	Integrated performance model for CSP plants using MS TES with internal SG and Thermocline TES	3	R	CO	Completed	
D3.5	Thermocline tank simulation tool taking into account the nature and the geometry of the filler mater	3	R	CO	Completed	

Deliverable Number	Deliverable Title	WP number	Nature	Dissemi-nation level	Status	Notes
D4.1	Reduced scale TES-SG Test Section: analysis, modeling, simulation and design	4	R	CO	Completed	
D4.2	Reduced scale TES-SG Test Section: design of TS and its placement on existing experimental facility	4	R	CO	Completed	
D4.3	Report on definition of the matrix of the experimental tests to be carried out	4	R	CO	Delivered	Includes the CIEMAT contribution to wp4
D5.1	Completion Work Report: Realization and commissioning of the scaled TES-SG Test Section	5	R	CO	Not Completed	
D5.2	Completion Work Report: Construction and commissioning of modification of the existing test facility	5	R	CO	Not Completed	
D5.3	Commissioning Report: Commissioning of the whole experimental system	5	R	CO	Not Completed	
D6.1	Analysis of experimental data for the TES-SG little scale Test Section	6	R	CO	Not Completed	

Deliverable Number	Deliverable Title	WP number	Nature	Dissemi-nation level	Status	Notes
D6.2	Analysis of experimental data for the full-scale TES-SG	6	R	CO	Not Completed	
D7.1	Definition of the new potential markets and application opportunities	7	R	CO	Not Completed	
D7.2	Definition of the costs of the industrial scale project	7	R	CO	Not Completed	
D7.3	Development of the Business Plan	7	R	CO	Not Completed	
D8.1	Final Report on possible exploitation and implementation of project results	8	R	CO	Delivered	Partially completed
D8.2	Final Report on dissemination activities	8	R	CO	Completed	

Milestone	Milestone Title	WP number	Status	Notes
MS1	**First Project Meeting (kick-off meeting)**	WP1	Achieved	
MS2	**Opening of the Website**	WP1	Achieved	
MS3	**Final Project Meeting and closing Conference**	WP1	Not achieved	Due to premature project termination
MS4	**Assessment of the State of the Art on MS mixtures as Heat Storage Medium and Heat Transfer Fluid**	WP2	Achieved	
MS5	**Report on materials behaviour and thermal exchange properties**	WP2	Achieved	
MS6	**Full characterization of construction materials in the respect of MSs**	WP2	Achieved	
MS7	**Full characterization of MS mixture phenomena and thermal exchange properties**	WP2	Achieved	

Milestone	Milestone Title	WP number	Status	Notes
MS8	**Election of first hydraulic components to be tested and definition of testing procedures**	WP2	Achieved	
MS9	**Preliminary design of the full-scale stratified MS Storage Tank with integrated Steam Generator**	WP3	Achieved	
MS10	**Project executive of the full-scale stratified MS Storage Tank with integrated Steam Generator**	WP3	Achieved	
MS11	**Completion of the analysis, modelling, simulation and comparison of the various TES concepts**	WP3	Achieved	
MS12	**Project executive: Design of the reduced scale TES-SG Test Section**	WP4	Achieved	

Milestone	Milestone Title	WP number	Status	Notes
MS13	**Project executive: Design of the modifications of existing experimental test facility**	WP4	Accomplished	See D4.2
MS14	**Definition of the matrix of the experimental tests**	WP4	Not accomplished	
MS15	**Completion of the emission of the purchase orders for TKT**	WP5	Not accomplished	
MS16	**Completion of the reduced scale TES-SG TS and its integration in the existing test facility**	WP5	Not accomplished	
MS17	**Completion of the commissioning**	WP5	Not accomplished	
MS18	**Completion of the Test Section start up**	WP6	Not accomplished	
MS19	**Completion of the execution of experimental tests**	WP6	Not accomplished	

Milestone	Milestone Title	WP number	Status	Notes
MS20	**Experimental tests report**	WP6	Not accomplished	
MS21	**Completion of the definition of new scenarios**	WP7	Not accomplished	
MS22	**Completion of the cost analysis of the industrial project**	WP7	Partly accomplished	See D8.1
MS23	**Completion of the Business Plan**	WP7	Not accomplished	
MS24	**Definition of actions for the exploitation of the results with commercial potential**	WP8	Partly accomplished	See D8.1
MS25	**Completion of dissemination activities**	WP8	Accomplished	