NEW StOrage Latent and sensible concept for high efficient CSP plants

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Project Deliverable 2.1:

Preliminary selection of materials compositions and TES system predesign

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1 INTRODUCTION

1.1 Project objective

Concentrated Solar Power (CSP) is viewed as one of the most promising technologies for electricity production. However, as most of the renewable energy sources, some problems arise from the discrepancy between the availability of the resource and the demand, yielding a low dispatchability (this is the capability of fitting the production to the demand). In order to increase the dispatchability of a solar power plant, Thermal Energy Storage (TES) is an additional technology that allow us to store thermal energy when available until it is needed, within some small periods of hours.

The NewSOL investigation and demonstration project will focus on the development of durable materials solutions for high efficient thermal solar energy harvesting in new and existing Concentrated Solar Power (CSP) plants. Two TES architectures have been proposed to combine the advanced materials solutions into an optimum configuration design improving the thermal performance of the whole system. First, a Thermocline Tank, (combining sensible and latent heat up to 550ºC) has been proposed to provide storage capacity to new CSP plants at a lower cost than commercially available 2-tank system using molten salts at 400ºC. Second, a Concrete module tank (sensible heat up to 550ºC) has been proposed for retrofitting of existing CSP plants. The module of concrete is thought to provide a flexible and low-cost option for enhancing TES capacity of existing thermal power plants without TES capabilities or with storage capacities lower than the standard of 8-9 hours.

1.2 Aim and scope of the document

The deliverable D.2.1"*Preliminary selection of materials compositions and TES system predesign"* deals with the pre-selection of the materials implied in the prototypes to be built in the NewSOL project, namely the thermocline concrete tank and the concrete module.

The next sections of D.2.1 present a list of material composition and formulations that will be used to deliver the new advanced materials solutions to be developed in the NewSOL project. In addition, D.2.1 provides a preliminary definition of the variables of interest and sensors to be implemented in the demonstration case of the project.

The optimal combination of the advanced materials into the TES architectures, (thermocline concrete tank and concrete module), will finally come up with the prototypes to be built and validated in the demo case of Évora Molten Salt Platform (Portugal).

2 NEWSOL ARCHITECTURES: THERMOCLINE CONCRETE TANK AND CONCRETE MODULE

A map of the different materials solutions and architectures proposed for each TES system configuration is given in Figure 1.

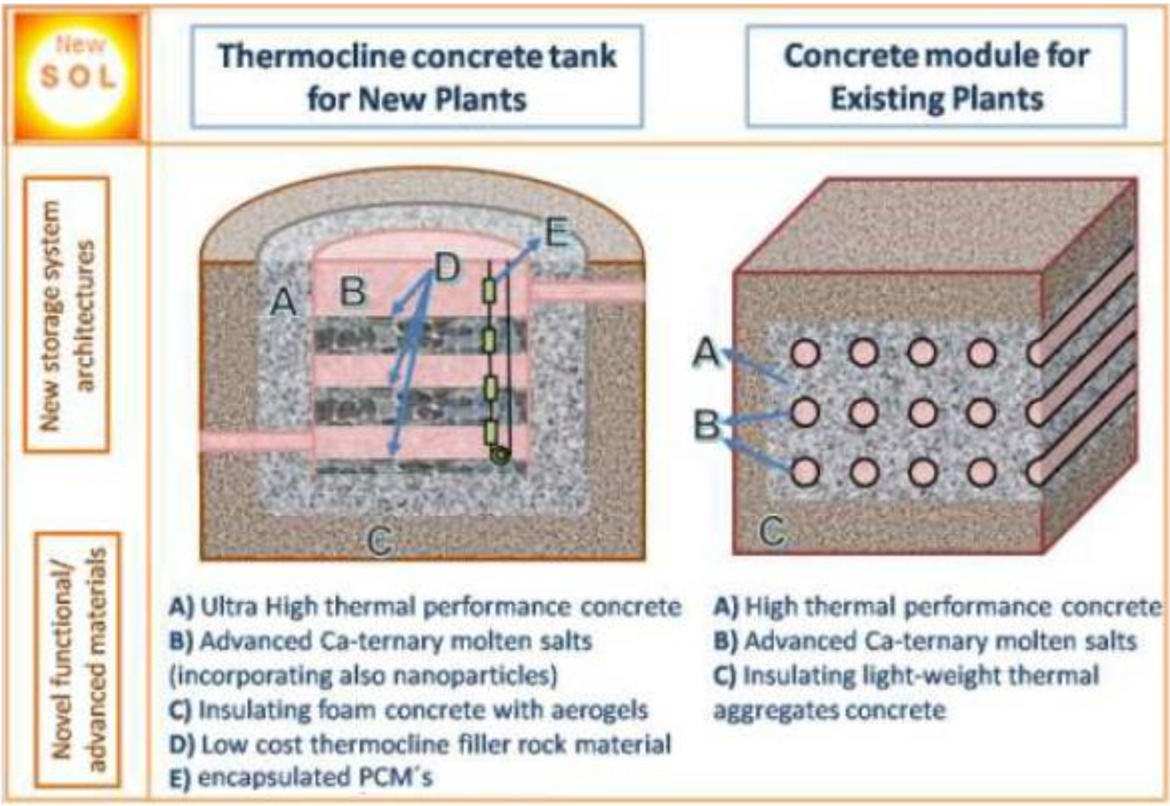

Figure 1: Concept overview of the NewSOL project

2.1 Novel Hybrid Energy Storage System for New Plants: Thermocline Tank.

The design consists of a single thermocline tank with concrete walls, instead of the classic 2–tank system with steel walls , containing filler materials and encapsulated PCMs inside the tank for sensible and latent heat storage from 290ºC up to 550ºC. The new thermocline concrete tank will take advantage of the thermocline effect to combine both the hot and the cold molten salt in the same tank by separating them through a thin layer of a high-temperature gradient. This thermocline tank will be filled with low cost solid filler materials that displace the more expensive molten salts and act as the primary thermal storage medium. These filler materials will be arranged in several layers along the tank height (Figure 1D). In addition, encapsulated Phase Change Materials (PCMs) will be incorporated inside the tank through a new movable system that allows positioning the PCMs along the tank height (Figure 1E) and controlling the thermocline gradient during charging/discharging operations.

The thermocline concrete tank relies on the following advanced materials:

- **Three-layer concrete wall** composed of three different types of concrete (from inside out): **(1)Ultra high thermal performance concrete** in the inner rim of the tank, withstanding temperatures up to 550ºC, **(2) High Insulation foam concrete** in a second layer to insulate the tank's wall and minimize thermal losses, **(3) Structural Concrete** rim in the outer layer to carry the loads of the whole structure
  An ad-hoc **commercial high-temperature protective layer** will be applied on the inner side of the tank, (directly on the ultra-high thermal performance concrete layer), to protect the concrete from MS corrosion attack and, thus, ensuring their lifespan.

- **Foundation of lightweight thermal aggregates concrete** with enhanced insulating properties to minimize the heat storage loss through the foundations
- An innovative **Molten Salts (MS) ternary mixture** will be used inside the tank as sensible heat storage media with the inclusion of alumina nanoparticles. The new ternary mixture is designed to enable lower minimum operating temperatures to cope with salt freezing and increase its chemical and thermal stability at temperatures above 550ºC. The addition of nanoparticles in the new Ca-ternary mixture will provide higher heat capacities for improved energy harvest and, thus, higher energy storage efficiency
- Low-cost **filler rock materials with enhanced heat capacity** for sensible heat storage with a higher thermal capacity than conventional filler (quartzite type) to substitute molten salt within the tank.
- **Latent heat-based encapsulated PCMs** with high conductivity and optimized design for improved transfer rate between inside/outside of encapsulation will be also incorporated inside the tank. This is to increase the power density of the storage system.

2.2 Novel Thermal Energy Storage System for Existing Plants: Module.

This TES system is formed by a modular high-temperature solid-media concrete for sensible heat storage, which consists of a high-temperature concrete embedding the tube bundle that contains the high-temperature fluid circulating inside. The new concrete module is designed to operate at temperatures up to 550ºC by means of the new Ca-ternary molten salt mixture circulating inside the pipes. In order to increase heat transfer within the concrete module, a heat transfer structure consisting of graphite foil deposited onto a metallic mesh (Figure 2-left) placed inside the module is being simulated and, alternatively, finned tubes (Figure 2-right) with an optimized design will be employed.

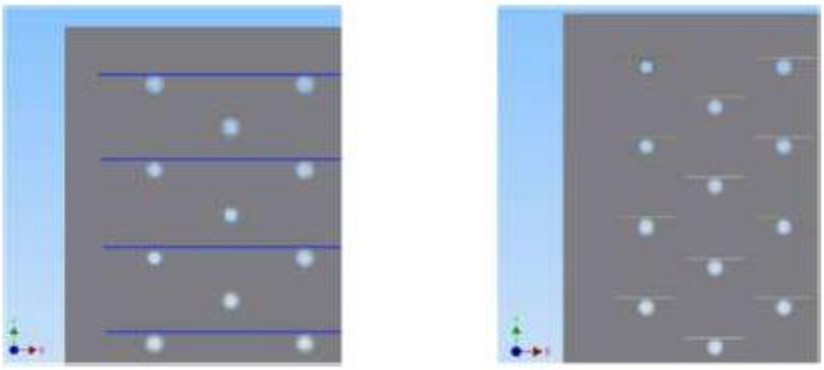

Figure 2: NewSOL concrete module including a heat transfer structure inside (left), and embedded finned tubes (right).

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The module relies on the following materials listed below:

- **High thermal performance concrete core** with enhanced heat capacity concrete for sensible heat storage
- **High-temperature resistant insulating foam concrete** on the outer sides to minimize thermal losses
- **Foundation of structural lightweight concrete with thermal aggregates** to minimize thermal losses through the foundations
- **Advanced Molten salts** as heat transfer fluid enabling the operation of the module at temperatures up to 550ºC

- **Embedded pipes** to circulate the molten salts (MS) at 550ºC inside the concrete module. The pipes are made of a especial steel resistant to MS and temperature

3 PRELIMINARY SELECTION OF MATERIALS COMPOSITIONS FOR THE ADVANCED MATERIAL SOLUTIONS

3.1 Ultra high thermal performance concrete

A high thermal performance concrete will be used in the inner layer of the tank's wall and in the module's storage core. For this application, CAC based concrete mixtures with mineral admixtures and thermal aggregates have been proposed as an alternative to the OPC based concretes.

The table below presents a list of material compositions that will be considered to deliver the final concrete design. The main approach for the pre-selection of the materials has followed three main criteria:

- Selection of a cement/binder having refractory properties after dehydration
- "Fit for the purpose" combination of aggregates from different sources to control shrinkage due to thermal cycling and to maximise heat capacity
- Use of specific admixtures to control the thermal properties of the mixture

Calcium Alumina Cement (CAC) blended with high silica content mineral additions can provide higher thermal stability and increased heat capacity after dehydratation for their utilization in thermal energy harvest. Although dehydration of CAC paste also occurs at high temperature, causing decay of mechanical properties, the dehydrated CAC cement paste is thermally more stable after cooling than OPC cement paste. Consequently, the use of CAC potentially reduce the risk for swelling and cracking of concrete after temperatures above 500ºC exposure. NewSOL proposes to investigate different hybrid binder mixes based on CAC and combinations with OPC and mineral admixtures, such as fly-ash (FA), blast furnace slag (BFS), silica fume (SF) and nanosilica (NS), as an alternative to increase the stability of the overall cementitious mix to thermal stresses and the residual strength after heating.

Regarding the aggregates, it has been proposed an optimum combination of thermal aggregates with better thermal expansion and higher chemical and physical stability characteristics at temperatures in the region of TES heat cycles, when compared to siliceous type aggregates alone, as they induce lower strength decay under thermal fatigue cycles. Moreover, it is also very important to define the optimum grading distribution of aggregates to compensate the changes in volume of concrete components due to the thermal expansion and the dehydration reactions of the cement paste. The aggregate/cement paste interface results affected due to the aggregate size and shape, so that limitations on the maximum aggregate size grade distribution should be taken into consideration in the concrete design. The use of hybrid aggregates with different thermal stability is an alternative in order to increase the overall mix adaptability to thermal stresses[1].

The list is completed with a pre-selection of admixtures, which could be splitted into three main groups:

- **Mineral Admixtures**. As mineral admixtures are considered BFS and FA to adjust the properties of the concrete but without loss of refractory properties. The SF and nanosilica NS, a very fine mineral addition silica-based, are expected to contribute to enhance the compactness of the mix and certainly to improve the interfaces of the cement-paste with the steel fibres (SF) and the aggregates.

- **Steel, PVA, and PP fibres**. Fibres are expected to control the cracking and improve mechanical performance
- **Thermal conductive Admixtures**. The purpose of adding conductive admixtures is to tune the thermal behaviour of the mixtures. In the case of the module, the conductive admixtures become especially important to design a high-conductivity concrete able to transfer the heat fast to the heat transfer fluid (HTF) and vice versa.

Table 1: Pre-selection of materials to be used in the mix design of the ultrahigh thermal performance concrete

TYPE OF MATERIAL	SUBTYPE	DESCRIPTION	BASIC CHEMICAL COMPOSITION	THERMAL PROPERTIES
Cement	CAC	Calcium Alumina Cement	CaO, Al_2O_3 Fe_2O_3	K_{exp}: 6-8 10^{-6} ºC λ: 1.4-3.6 $Wm^{-1}ºC^{-1}$ C_p: 0-5-1.13 kJ Kg^{-1}
	OPC	Ordinary Portland Cement	Ca_3SiO_4, Ca_2SiO_5, Ca_3Al2O_6, $Ca_4Al_2Fe_2O_{10}$	Kexp: 18-20 10-6 ºC[2] (cement paste w/c= 0.4-0.6) λ: 0-5 Wm-1ºK-1 (cement paste w/c=0.5)[3] to 1 Wm-1ºK-1 (cement paste w/c=0,3)[4] Cp: 1.4 J g-1 K-1(cement paste w/c =0,4)[2]
Aggregate	Aggegate 0-6 Aggregate 6-12	Silicieous	SiO_2	ʎ 3.24 W/mK (sandstone), Cp 0.92 J/gK (sandstone)
	Aggegate 0-6 Aggregate 6-12	Dolomitic	$CaMg(CO_3)_2$	ʎ 2.11 W/mK, Cp 0.92 J/gK
	Aggegate 0-6 Aggregate 6-12	Calcareous	$CaCO_3$	K_{exp}: 8.3 10^{-7} ºC ʎ 2.2 W/mK Cp 0.85 J/gK
	Aggegate 0-6 Aggregate 6-12	Basalt	SiO_2 Al_2O_3	ʎ 1.69 - 2 W/mK Cp 0.84 J/gK
	Aggegate 0-6 Aggregate 6-12	Slags Waste Alentejo	Fe (55%) Si (20%)	ʎ 1 W/mK
	Aggregate 0-4	Calcium Alumina Clinker	CaO, Al_2O_3 Fe_2O_3	-
Mineral Admixtures	FA	Fly ash	SiO2, Al2O3,CaO	-
	BFS	Blast Furnace Slag	SiO_2, Al_2O_3,CaO	-
	SF	Silica Fume	SiO_2	-
	NS	nanosilica	$nSiO_2$	-

	Gypsum	Gypsum	SO_3	
Fibres	SF	Steel Fibres	Fe	-
	PVA	PVA fibres	PVA	
	PP	PP fibres	polypropilene	-
Conductive Admixtures	organic based	Carbon Fibres	C	-
	Graphite	Carbon based	C	ʎ 25-470 W/mK
	CNF	Carbon Nano Fibres	C	ʎ 2.5 W/mK (300 K, multiwall nanotube)
	inorganic based	Silicon Carbide	CSi	ʎ 120 W/mK
	inorganic based	Boron Nitride	BN	ʎ 400 W/mK
	inorganic based	Alumina	Al_2O_3	ʎ 20-30 W/mK
	inorganic based	Aluminium Nitride	AlN	ʎ 170 W/mK
Other additives	Calcium Nitrate	Calcium nitrate	$CaNO_3$	-
	Superplasticizer	Water reductor	-	-

3.2 High Insulation Foam concrete

In NewSOL, a high insulation foam concrete will be used as main insulator of the walls of the thermocline tank and the module. This insulating concrete layer must be designed to minimise heat losses to the environment and therefore to improve the overall thermal performance of the TES system. For the pre-selection of the components of the foam concrete mix showed in .

Table 2, three main design requirements have been considered:

- Thermal stability up to 550ºC
- High resistance to thermal fatigue due to cyclical temperature variation (thermal cycles foreseen during charging/discharging operations of the TES systems between 290 and 550ºC)
- Very low thermal conductivity, comparable to conventional insulation materials used for this application, such as mineral wool.

The main objective is to develop a very low-density concrete: the lower the density, the higher the insulation. Therefore, NewSOL proposes the use foaming agents, (able to create many small air voids in the mix,) to reach densities below 400 kg/m^3. Moreover, the excellent insulating behavior of the foam concrete due to its high air content will be improved further by the addition of aerogels. Aerogel is porous ultralight material with extremely low density and thermal conductivity that will potentially enable a decrease in thermal conductivity below 0.1 W/mK.

Regarding the binder, CAC cement has been proposed to ensure higher stability under high-temperature operation. Similarly, the thermal stability of the aggregates has been taken into account in the pre-selection, as well as the insulation properties. In fact, expanded glass will be proven as very low-conductivity aggregate to improve the insulation properties of the mixture.

Finally, as can be seen in .

Table 2, PVA and PP fibres will be employed to improve the mechanical properties of the foam concrete, since compressive and flexural strength decreases when increasing the concentration of aerogel.

Table 2: Pre-selection of materials to be used in the mix design of the high insulation foam concrete

TYPE OF MATERIAL	SUBTYPE	DESCRIPTION	BASIC CHEMICAL COMPOSITION	THERMAL PROPERTIES
Cement	CAC	Calcium Alumina Cement	CaO, Al_2O_3 Fe_2O_3	K_{exp}: 6-8 10^{-6} ºC λ: 1.4-3.6 $Wm^{-1}ºC^{-1}$ C_p: 0-5-1.13 kJ Kg^{-1}
Aggregate	Aggregate 0-4	Calcium Alumina Clinker	CaO, Al2O3	-
	Aggegate 0-6	Calcareous	$CaCO_3$	K_{exp}: 8.3 10^{-7} ºC ʎ 2.2 W/mK Cp 0.85 J/gK
	Aggegate 0-6	Slags Waste Alentejo	Fe (55%) Si (20%)	ʎ 1 W/mK
	Aggregate 0-4	Expanded Glass	Recycled glass (SiO2 > 70%; K2O+Na2O > 10%; CaO+MgO > 8%)	ʎ < 0.15 W/mK
Mineral Admixtures	FA	Fly ash	SiO2, Al2O3,CaO	-
	Lightweight filler	Alumino-silicato	SiO2, Al2O3	-
Chemical Admixtures	Foaming agent	Foaming agent	surfactant	-
	Aerogel	Porous ultralight material	SiO_2	ʎ < 0.015 W/mK
PVA fibres	PVAF	Polyvinyl alcohol fibres	$(C_2H_4O)_x$	PVA alone[5]: Meling point: 200 ºC Thermal degradation: 230ºC In fiber reinforced cement composites[6]: (FRCC): ʎ (200ºC) ≈0.50-0.75 W/mK ʎ(400ºC) ≈0.60-1 W/mK ʎ(600ºC) ≈0.70-1.3 W/mK Cp(200ºC) ≈700 J/kgK Cp(400ºC) ≈1050 J/kgK Cp(400ºC) ≈1050 J/kgK
PP fibres	PPF	Polypropylene fibres	$(C_3H_6)_n$	PPF alone[7] Melting Point: 160~170

3.3 Structural concrete for the tank's walls

A layer of reinforced concrete will surround the whole tank's wall, with the only function of bearing the loads and the weights that act over the tank to the foundation and the soil level. This structural concrete layer will be placed on the outer part of the tank, in direct contact with the insulation layer of foam concrete. Because of the presence of this insulating layer in between, the structural concrete will not withstand temperatures up to 100 ºC, neither thermal cycling, and thus, no special thermal components are required for its formulation (as for the previous concrete mixes).

Table 3 shows the materials shortlisted for the fabrication of the structural concrete. Since there is no temperature restrictions, no refractory cements or thermal aggregates have been considered. Regarding the admixtures, BFS and FA are expected to adjust the properties of the mixture and might help to ensure a good interphase with the neighboring insulating foam concrete layer. Finally, steel rebar type B500S, typically used to reinforce concrete, will provide the structure with the required structural strength.

Table 3: Pre-selection of materials to be used in the mix design of the structural concrete layer of the NewSOL thermocline tank

TYPE OF MATERIAL	SUBTYPE	DESCRIPTION	BASIC CHEMICAL COMPOSITION	THERMAL PROPERTIES
Cement	OPC	Ordinary Portland Cement	Ca_3SiO_4, Ca_2SiO_5, Ca_3Al2O_6, $Ca_4Al_2Fe_2O_{10}$	Kexp: 18-20 10-6 ºC[8] (cement paste w/c= 0.4-0.6) λ: 0-5 Wm-1ºK-1 (cement paste w/c=0.5)[9] to 1 Wm-1ºK-1 (cement paste w/c=0,3) [10] Cp: 1.4 J g-1 K-1(cement paste w/c =0,4)[2]
Aggregates	Aggregate 6-12 Aggregate 0-4	Siliceous	SiO_2	ʎ 3.24 W/mK (sandstone) Cp 0.92 J/gK (sandstone)
	Aggegate 0-6 Aggregate 6-12	Calcareous	$CaCO_3$	K_{exp}: 8.3 10^{-7} ºC ʎ 2.2 W/mK Cp 0.85 J/gK
Mineral Admixtures	BFS	Blast Furnace Slag	SiO_2, Al_2O_3,CaO	-
	FA	Fly ash	SiO2, Al2O3,CaO	-
Chemical Admixtures	Superplasticizer	Water reducing / rheological additive	Organic	-
Reinforcing rebar	B500S	Steel reinforcement	Fe, C	-

3.4 Foundation Concrete: Lightweight high thermal aggregate concrete

The foundations of both concrete TES architectures, thermocline tank and module will be made of a structural lightweight concrete with high insulation capacity to minimise the heat loss of the foundations. In addition to the structural function, the foundation will have the job of insulating the TES system from the soil, and therefore it will support notable thermal fatigue. The desired properties sought for this application are summarized below:

- Resistance to high temperature and thermal cycles. The expected temperature range is not as high as for the inner layers of concrete, because it is partially insulated by the foam concrete insulation layer, but still, it will be proven against high temperature conditions
- High insulation properties to minimize heat loss
- High strength to play properly the structural role

This type of concrete will be improved for lower densities by decreasing as much as possible the content of conventional aggregates and maximizing the content of thermal stable aggregates, such as expanded clay, with very low conductivity values but also with good mechanical properties for structural applications. The planned approach will be to use thermal stable binders in the same way than for the foam concrete-aerogel composite approach. With regard to the reinforcement rebar, the use of conventional steel rebar B500S or austenitic steel (stable at high-temperature) will depend on the level of thermal stress suffered by the prototypes' foundations, which will be thoroughly determined in latter stages of the project. Table 4 contains all the materials pre-selected for the concrete of the foundations.

Table 4: Pre-selection of materials to be used in the mix design of the lightweight high thermal aggregates concrete

TYPE OF MATERIAL	SUBTYPE	DESCRIPTION	BASIC CHEMICAL COMPOSITION	THERMAL PROPERTIES
Cement	CAC	Calcium Alumina Cement	CaO, Al_2O_3 Fe_2O_3	K_{exp}: 6-8 10^{-6} ºC λ: 1.4-3.6 Wm^{-1}ºC^{-1} C_p: 0-5-1.13 kJ Kg^{-1}
	OPC	Ordinary Portland Cement	Ca_3SiO_4, Ca_2SiO_5, Ca_3Al2O_6, $Ca_4Al_2Fe_2O_{10}$	Kexp: 18-20 10-6 ºC[11] (cement paste w/c= 0.4-0.6) λ: 0-5 Wm-1ºK-1 (cement paste w/c=0.5)[12] to 1 Wm-1ºK-1 (cement paste w/c=0,3) [13] Cp: 1.4 J g-1 K-1(cement paste w/c =0,4)[2]
Aggregate	Aggregate 0-4	Calcium Alumina Clinker	CA	
	Aggegate 0-6	Calcareous	$CaCO_3$	ʎ 2.2 W/mK Cp 0.85 J/gK
	Aggegate 0-6	Slags Waste Alentejo	Fe (55%) Si (20%)	ʎ 1 W/mK
	Aggregate 3-8	Expanded clay	SiO_2, Al_2O_3, Fe_2O_3	ʎ< 0.15 W/mK
	Aggregate 4-8 Aggregate 6-14	Lightweight aggregate from power station fly ash	fly ash	ʎ< 0.35 W/mK (500ºC)
Mineral Admixtures	BFS	Blast Furnace Slag	SiO2, Al2O3,CaO	-
	FA	Fly ash	SiO2, Al2O3,CaO	-
	Lightweight filler	Alumino-silicato	SiO2, Al2O3	-

TYPE OF MATERIAL	SUBTYPE	DESCRIPTION	BASIC CHEMICAL COMPOSITION	THERMAL PROPERTIES
Reinforcing rebar	B500S	Stainless Steel reinforcement	-	Modulus of Elasticity > 206 GPa (at ambient Tª)
	1.4401/1.4404	Austenitic stainless steel reinforcement (ACX 240 by Acerinox)	-	Max. Tª 870 CTE (600ºC) 18.5x10-6/K Modulus of Elasticity = 165 GPa (at 500ºC)
	1. 4948	Austenitic stainless steel reinforcement (Therma 304H/4948 by Outukumpu)	-	Max. Tª 750 CTE (600ºC) 18.8x10-6/K Modulus of Elasticity = 155 GPa (at 600ºC)
	1. 4878	Austenitic stainless steel reinforcement (Therma 321H/4878 by Outukumpu)	-	Max. Tª 850 CTE (600ºC) 18.8x10-6/K Modulus of Elasticity = 150 GPa (at 600ºC)
	1. 4828	Austenitic stainless steel reinforcement (Therma 4828 by Outukumpu)	-	Max. Tª 1000 CTE (600ºC) 18.8x10-6/K Modulus of Elasticity = 150 GPa (at 600ºC)
	1. 4833	Austenitic stainless steel reinforcement (Therma 309S/4833 by Outukumpu)	-	Max. Tª 1000 CTE (600ºC) 18.8x10-6/K Modulus of Elasticity = 150 GPa (at 600ºC)
	1. 4818	Austenitic stainless steel reinforcement (Therma 153 MA by Outukumpu)	-	Max. Tª 1100 CTE (600ºC) 18.5x10-6/K Modulus of Elasticity = 155 GPa (at 600ºC)

3.5 Filler Rock Material (thermocline tank)

NewSOL will investigate the use of thermocline filler materials in combination with solar salts in the thermocline tank TES system. The inclusion of filler materials inside the tank has the aim of reducing the amount of MS but maintaining the heat storage capacity. Particularly, NewSOL has the ambition to demonstrate the viability of using waste materials from past mining activity as filler material.

The filler rock selected for the project is a modern slag type that comes from São Domingos old mines site, located near the village of Mértola, in Portugal. Recent studies at UEvora revealed significant presence of Fe, Zn, Pb and rich silicates in the composition of these rocks demonstrating their potentiality as filler materials. The high-thermal conductivities (around 7W/m K) found in these materials due to the presence of metals, together with their good dimensional stability at high temperatures make them a good candidate for solar energy harvesting. In addition, the high hardness of the selected rocks would ensure high wear resistance while preventing their deterioration during charging/discharging operations of the thermocline TES system.

Table 5. shows the filler rocks pre-selected for the project, including chemical composition (XDR analysis) and density values. The filler rocks have been collected from five different sampling areas in São Domingos old mines (NS1, NS2, NS3, NS4 and NS5). Also different sizes have been considered for investigation (small, medium, big).

In the project, the best sampling area(s) for TES application will be identified based on the thermal behaviour the filler rocks. This best sampling area(s) will provide the filler rocks for the demo-case in Évora.

Table 5: Filler rocks pre-selected to be used as filler materials in the thermocline tank

SAMPLE	GRANULOMETRY	DENSITY (TON/M³)	BULK DENSITY (MG/M³)	FAYALITE	MAGMHITE	PENDUNNITE	OTHERS
NS1	Small (2,8mm- 6,3mm)	3.59	1,79	**	vgt	*	vgt
	Medium (6,3mm- 12,5mm)	3.71	1,62	***	vgt	**	vgt
NS2	Small (2,8mm- 6,3mm)	-		**	*	*	*
	Medium (6,3mm- 12,5mm)	-		***	*	**	*
NS3	Small (2,8mm- 6,3mm)	3.56	1,83	vgt	vgt	vgt	vgt
	Medium (6,3mm- 12,5mm)	3.61	1,74	**	*	*	*
	Big (> 12,5mm)	3.66	-	***	**	*	*
NS4	Small (2,8mm- 6,3mm)	3.5		vgt	vgt	vgt	vgt
NS5	Small (2,8mm- 6,3mm)	3.43	1,78	**	vgt	vgt	vgt
	Medium (6,3mm- 12,5mm)	-		***	vgt	vgt	vgt
Classification	**** - Very Abundant		*** - Abundant	**- Present	*- Present in small quantities		vgt - Remais

3.6 Advanced Molten Salts

In NewSOl, two methodologies will be followed to overcome the limitations of current molten salt systems, aimed at increasing the working temperature range and enhancing the thermal characteristics of the liquid mixture for high efficiency solar energy harvesting:

1. **Innovative low-melting point and high stability MS Ca-ternary mixtures**: Ca-ternary mixtures with low freezing temperature and enhanced thermal stability at high temperatures (above 500 ºC), while maintaining favourable thermal properties, such as low viscosity, high-thermal conductivity and specific heat together with low vapour pressures.
2. **MS incorporating nanoparticles:** this is a pioneering methodology that takes advantage of the physical interactions occurring at the interface of solid nanoparticles and a liquid media that form a nanofluid, and result in the enhancement of the properties of the base fluid (Molten Salt). In particular, the increase of the specific heat capacity of molten salts incorporating nanoparticles is attributed to the layer of liquid at the surface of solid particles that behaves as a liquid solid phased change, showing higher thermal properties than the bulk liquid[14]

With regard to the first methodology, the variety of molten salts available in the literature has been screened extensively and a number of potential candidates, suitable for the temperature ranges intended in the project has been selected. Three molten salts have been identified as candidates for further evaluation. Table 6 comprises the final selection of the salts for NewSOL including the single salts they are produced from.

Table 6: Pre-selection of molten salts to be used in both NewSOL TES sytems.

NAME/SUB-TYPE	DESCRIPTION	TMIN (°C)	TMAX (°C)
Calcium Potassium Nitrate Hydrate	5 Ca(NO3)2 x 1 KNO3 x 10 H2O	not applicable for project	not applicable for project
Potassium Nitrate	KNO3	not applicable for project	not applicable for project
Sodium Nitrate	NaNO3	not applicable for project	not applicable for project
Lithium Nitrate	LiNO3	not applicable for project	not applicable for project
Ca,K,Na//NO3 ()	5Ca(NO3)2-KNO3, NaNO3, KNO3	170	500
Li,Na,K//NO3 ()	LiNO3, NaNO3, KNO3	150	550
Ca,Li,Na,K//NO_3 ()	$Ca(NO_3)_2$, $LiNO_3$, $NaNO_3$, KNO_3	examined	500 (expected)

With regard to the second methodology, the **nanoparticles selected for the project will be oxide types (most prominently Al_2O_3)** which are freshly dispersed in molten salt and characterized regarding their thermal performance.

3.7 Encapsulated PCM (thermocline tank)

One novelty of the NewSOL thermocline TES system is the incorporation of encapsulated PCMs along the tank height in a cascade-type arrangement to regulate thermal stratification inside the tank. The benefits of this PCM type arrangement are the maximization of energy stored by latent heat harvesting when charging the storage system and the stabilization of the HTF outflow temperature during discharging operations, thus, improving the efficiency of storage system and power block, respectively[15]

The PCM selected for the project consist on salts encapsulated in metallic casings able to operate at high temperatures and featuring chemical resistivity to molten salts. PCMs were selected according to the underlying storage concept, According to the expected temperature spread of 170-530°C in the tank, PCMs were selected for three different temperature zones (> 200°C, 350°C and < 500°C, >500ºC). For this interval, a total of 6 PCMs could be selected that seem suitable for the intended use.

Table 7 below shows the pre-selected PCMs.

Table 7: Pre-selection of PCM to be used in NewSOL thermocline tank

NAME	TM [°C]	ΔH_M [J/G]	C_P [LIT. 30] [J/GK]	Λ W/(M·K)	ATM	CONTAINER
$NaNO_3$-KNO_3 (eu)	222	100	1.5 (500°C)	0.4	air	Stainless steel
$NaNO_3$	306	178	1.7 (500°C)	~0.6 (500°C)	air	Stainless steel
KNO_3	337	100	1.4 (500°C)	0.5	air	Stainless steel
K,Na,Li // CO_3	397	277	1.6 (500°C)	1.5 (398°C)	air	Stainless steel
Li,Na// CO_3	497	372	2.1 (500°C)	0.8 (525°C)	air	Stainless steel
$Al_{68.5}Cu_{26.5}Si_5$	*517*	*364*	3.0-4.0 (150-500°C)	160	N/A	Stainless steel

3.8 Module Pipes material

The strong oxidizing species from molten nitrate salts combined with operating temperatures plus salt impurities generate propitious conditions for corrosion acceleration of metallic materials, namely for stainless steels used in the pipes embedded in the concrete module. Therefore, it is crucial the use of special steels resistant to these conditions, since their failure could lead to severe damage of the CSP plants operation.

Furthermore, the thermal expansion of the pipes' material must be as similar as possible to that of the concrete matrix in which they are embedded, to prevent cracking, or compression of the tubes due to different expansion behaviour under thermal cycles because of charging/discharging of the module.

Table 8 shows the stainless steel pre-selected for the pipes of the module.

Table 8: Pre-selection of pipes materials to be used in the NewSOL module

Designation (AISI/ EN number)	Kind of stainless steel
AISI 321H / EN 1.4878	Austenitic
AISI 316 / EN 1.4401	Austenitic
AISI 348	Austenitic
AISI 430 / EN 1.4016	Ferritic Steel
AISI 444 /EN 1.4521 /	Ferritic Steel
/ EN 1.4003 (X2CrNi12)/ /	Ferritic Steel

4. VARIABLES OF INTEREST AND SENSOR TECHNOLOGY

When monitoring in harsh environments, such as in NewSOL, where temperatures reach 550ºC and highly corrosive molten salts are used, the employed transducers (or sensing technologies) are the key element. The most commonly used transducers are thermocouples for temperature monitoring[16], strain gages for strain monitoring and embedded or surface-bonded piezoelectric sensors for acoustic emission (AE). However, these technologies present serious drawbacks for monitoring applications at high temperature and corrosive environments. Thermocouples and strain gages are hard to multiplex and are subject to electric and magnetic disturbances. Piezoelectric sensors above temperature of Curie lose the piezoelectric effect (300ºC) and they exhibit degradation due to thermal cycling[17]. Previous projects have made improvement on conventional PZTs. However, their resistance to temperatures higher than 600ºC is not well resolved[18, 19]. Furthermore, they do not offer very good multiplexing capacities, or resistance to corrosion.

A sophisticated monitoring system based on fiber optic sensors (FOS) for harsh environments in MS tanks and concrete modules will be developed in NewSOL. The output of this system will provide the assessment of thermal performance of the materials and will be input also for structural health of the system in concentrated solar power (CSP) plants. The actual sensors to be deployed are fiber Bragg gratings (FBG) although fiber optic distributed sensors will also be studied. Monitoring Molten Salt and concrete at high temperature have been tested separately, but not together and at the technology readiness level required in NewSOL: harsh environment FOS for strain and temperature are already at a TRL3 level[20] and SHM is already performed in some harsh environments. Therefore, the developments in NewSOL for these technologies will include advances in sensing technology up to prototyping and installing the sensing technology in the pilot CSP plant. The technology developed in this section will be tested and validated in an actual pilot CSP-s at UEvora.

4.1. Sensors for the thermocline tank

The monitoring system for the thermocline tank will consist on a fiber optic sensor network that will monitor input and outlet temperatures of salt, molten salt temperature, concrete wall temperature, lateral wall temperature, base concrete temperature, cover temperature and PCM thermal behavior. Therefore, there will be two main groups of sensors: embedded sensors in the different concrete layers and temperature sensors immersed in molten salt. The sensors embedded in concrete layers will measure temperature and strain. In Figure 3 a schematic of the thermocline tank with the monitoring system is shown.

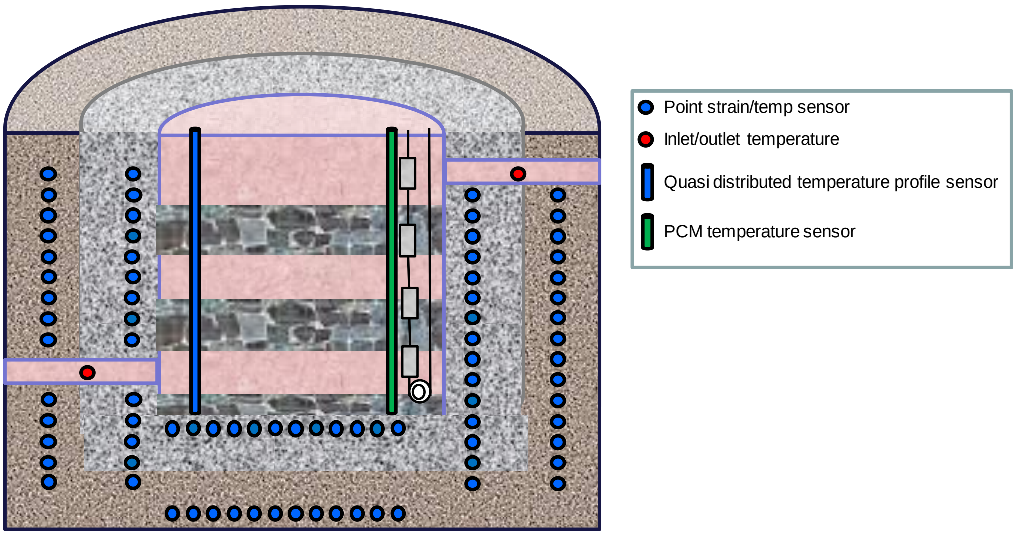

Figure 3 : Schematic monitoring system in the thermocline tank

4.2. Sensors for the concrete module

In the case of the concrete module, concrete embedded sensors will be employed only. The sensor type will be the same as for the thermocline tank concrete embedded sensors, as depicted in Figure 4. To ensure structural safety of the module, special care will be taken for accuracy and ranges in strain sensors, since during the first charge of the module, the high temperatures reached will generate the water evaporate and exit the concrete module. This phenomenon can endanger the structural safety of the concrete module so the strain sensors will monitor the integrity of the module. The same as the concrete embedded sensors for the tank, these sensors are good candidates to be substituted by Brillouin distributed sensors, so their deployment will be evaluated. Intermediate tests at different levels of development and scale will be performed so scalability and performance of the sensors is ensured.

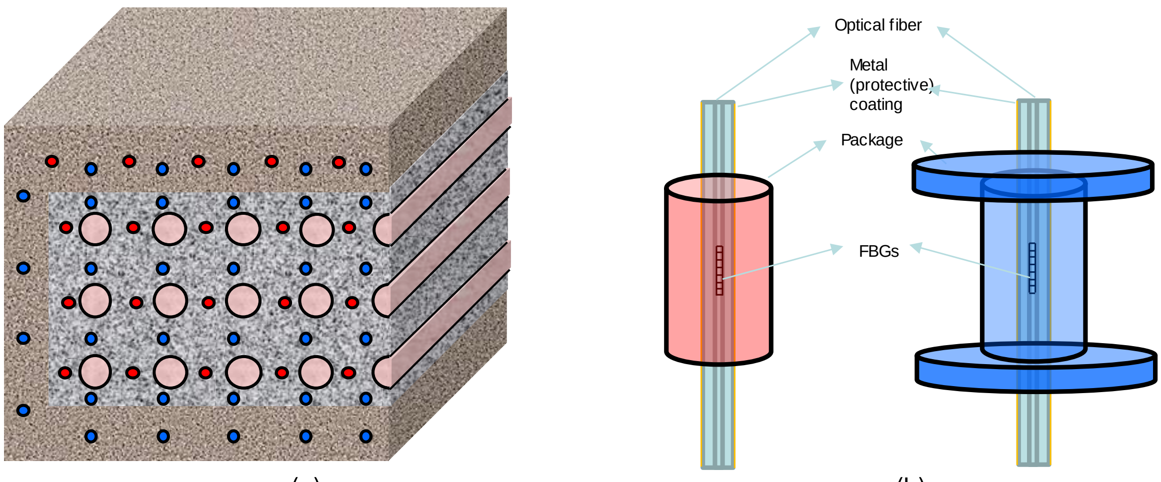

Figure 4: schematic of temperature and strain sensors positioning (a) and sensor encapsulating strategy for the concrete module monitoring.

4.3. Interrogator and network

Finally, a network design and interrogator that allows the simultaneous interrogation of all the sensors will be developed. The interrogators will be developed to increase the number of sensors to be addressed and offer more flexibility in how these sensors are networked and connected. When the temperature ranges to monitor are as high as in NewSOL, crosstalk between point FBG sensors can occur, so the number of sensors to be multiplexed is reduced. To increase the number of sensors per interrogator device, we will employ combinations of existing telecommunication multiplexing techniques. This way it will be possible to achieve an enhanced performance at a lower cost per point (sensor), without sacrificing the quality of individual measurements. Time division multiplexing using optical switches will be used, so crosstalk between different FBGs is avoided, by interrogating different FBG arrays at different times, as depicted in Figure 5, where in times T1, T2 and T3 different arrays with three FBGs of similar wavelengths are interrogated.

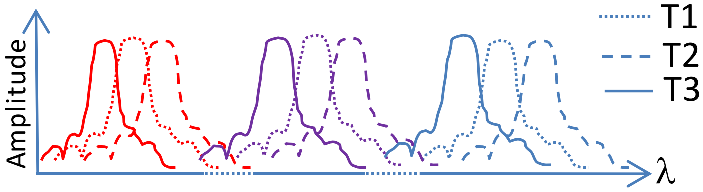

Figure 5: concept of time division multiplexing of three FBG arrays with three FBGs with similar wavelengths

A total of 500 sensors, for more than 250 measuring points distributed between thermocline tank and concrete module and some of them will be doubled to discriminate between temperature and strain. The final number of each type of sensor that have been presented in this document remains approximated, the same as their measuring range, but as an approximation and starting point for NewSOL project Table 9 is presented, where the maximum number of each type of sensor per array is defined, given that the range of the interrogator is 40nm.

Table 9: sensor wavelength range and number of sensor per array with preliminary ranges calculated with typical sensibility of FBGs unless stated otherwise.

Location	Type of sensor	location	Temp range (ºC)	Strain range due to thermal expansion (με)	Strain range due to structural loads (με)	Wavelength range (nm)	Number of sensor per fiber string
Thermocline tank	Concrete embedded sensors[1]	Thermal concrete	290-550	1820	1000	5.4	7
		Foam concrete[2]	100-550	3500	1000	9	4
		Structural concrete[3]	0-100	1200	3500	5.7	7
		Lightweight structural	0-350	1200	2000	6.7	6

[1] Approximated value, since it should be low

[2] Aproximated from shrinkage in *Applications of Foamed Lightweight Concrete; Kamarul Aini Mohd Sari, and Abdul Rahim Mohammed Sani, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor.*

[3] Although this is the expected value of strain, 0.3mm cracks are expected to appear. Depending on the sensor length, different strain values will be measured, so it will be taken into account.

Location	Type of sensor	location	Temp range (ºC)	Strain range due to thermal expansion (με)	Strain range due to structural loads (με)	Wavelength range (nm)	Number of sensor per fiber string
		concrete (foundations)					
	Molten salt temperature profile[4]	Temperature profile	290-550	-	-	2.6	15
		Inlet/outlet temperature	290-550	-	-	2.6	15
		PCM temperature monitoring	290-550	-	-	2.6	15
Concrete module	Concrete embedded sensors	Layer 1[5]	290-550	2200	1000	6.8	5
		Layer 2	0-100	1200	2000	4.2	9

5. CONCLUSION

D.2.1 contains a preliminary design of the NewSOL TES prototypes, namely the thermocline tank and the concrete module, to be built in Évora at the demonstration phase. Particularly, the document provides a breakdown of the preliminary selection of materials to be employed in the construction of the prototypes and a tentative monitoring plan to validate the performance of the TES prototyes in the field-tests of Évora. D.2.1 will serve as starting point to pave the way to technological WPs of the project in which all these concepts will be further developed.

[4] Using sensibility of encapsulated sensor calculated in ¡Error! Marcador no definido. of 13.5pm/ºC.

[5] The concrete will expand 8cm in 18m.

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