HANDBOOK:

Definition of standardised procedures for testing thermal storage prototypes for concentrating solar thermal plants

SFERA Project

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1. Introduction

This report is the first approach at international level to define appropriate testing procedures for commissioning thermal storage prototypes, either using sensible or latent heat, designed for solar thermal plants. Thermochemical storage and buffer storage (i. e. those intended to protect the components of the power plant from the effects of high thermal transients resulting from sudden variations in solar insolation) are out of the scope of this report, because the first one is still at its infancy, seeming too early for an attempt of standardizing its testing procedures, and the second one has operational characteristics (short reaction times, high discharge rates and thermal capacities shorter than 1 hour) that require different specific procedures.

The testing procedures proposed in this report are the result of the know-how on testing TES prototypes of the different partners involved in the SFERA project WP15 Task 2. The terminology proposed here is coherent with the discussions currently ongoing at the Spanish Organization for Standardization (AENOR). This AENOR committee launched a proposal in January 2011 to the International Electrotechnical Commission (IEC) for creating an international committee to draft standards in the field of solar thermal power plants in which thermal storage will be included. The just created Technical Committee TC-117 will start its activities on March 2012. However, while standardization bodies consider thermal storage as a solar thermal electricity (STE) plant component, the activities of Task 2 WP15 are focused on thermal storage prototypes so their specific features are taken into account.
In Annexe A, a list of laboratory capacities of the different partners involved in this report is included.

Thermal storage prototypes are scale models that are able to absorb/deliver energy from/to a heat transfer fluid (HTF) under certain working conditions and whose performance is studied in a test facility. A prototype allows testing a specific design prior to building a large scale module and its main features should follow the results of a previous similarity analysis in both geometry and testing conditions for ensuring that prototype test results are applicable to a full-size design. It must be taken into account that, in many cases, geometry can not simply be scaled-up, since the influence of some variables directly depends on storage module size.

If both HTF and storage medium are different fluids or they are phases that cannot be in contact, a heat exchanger is required. This heat exchanger may be integrated in the prototype itself or in the test facility as an additional component. In any case, the performance of a “storage prototype” includes hereinafter the thermal performance of the heat exchanger if needed, although it was part of the test facility.

2. Definitions

Nominal or Rated conditions

Characteristic heat transfer fluid (HTF) working conditions established when designing the storage prototype. These conditions are flow (mass flow, $\dot{m}$, kg/s; or volumetric flow, q_{HTF}, m^3/s), inlet temperature ($T_{HTF,in}$) and pressure ($p_{HTF,in}$). Nominal conditions must be established for both charge and discharge and can be the same or different for each process.

Charge process

Process during which energy is transferred or supplied to the storage prototype. If nothing else is said, it is assumed that the process takes place under nominal charging conditions. This definition can be qualified depending on the supplied thermal power:

- Full charge: process in which the storage unit is fed under nominal charging conditions (inlet temperature and pressure and flow).
- Half charge: process in which the storage unit is fed under nominal charging inlet temperature and pressure but half nominal HTF flow[1].

[1] Since the storage prototype is designed for concentrating solar thermal plants, working under half nominal HTF flow is equivalent to working with half thermal power.

- Minimum charge: process in which the storage prototype is fed with the minimum thermal power required to transfer energy to it (i. e. minimum HTF flow and nominal inlet temperature and pressure)[2].

Discharge process

Process during which energy is transferred or extracted from the storage prototype. If nothing else is said, it is assumed that the process takes place under nominal discharging conditions. This definition can be qualified depending on the extracted thermal power:

- Full discharge: process in which the storage unit is discharged under nominal discharging conditions (inlet temperature and pressure and flow)
- Half discharge: process in which the storage unit is discharged under nominal discharging inlet temperature and pressure but half nominal HTF flow[1].
- Minimum charge: process in which the storage prototype is discharged under the minimum thermal power required to extract energy from it (i. e. minimum HTF flow and nominal discharging temperature and pressure)

Charging time, between storage levels A and B, $t_{\text{charge}}^{A->B}$

Required time during charge to have storage level B, coming from storage level A, under defined working conditions (HTF flow, inlet temperature and pressure). If working conditions are nominal for charge, this is the ***nominal charging time***. Additionally, if A is the minimum storage level and B is the maximum (100%), the corresponding charging time is known as the ***characteristic nominal charging time***.

Discharging time, between storage levels A and B, $t_{\text{discharge}}^{A->B}$

Required time during discharge to have storage level B, coming from storage level A, under defined working conditions (HTF flow, inlet temperature and pressure). If the working conditions

[2] If a heat exchanger is needed for a TES where the prototype is integrated, the minimum charge comes from the minimum power of such heat exchanger

are nominal or rated for discharge, this is the ***nominal discharging time***. Additionally, if A is the maximum storage level (100%) and B is the minimum, the corresponding discharging time is known as the ***characteristic nominal discharging time***.

Response time at charge/discharge

The period of time a storage prototype takes to increase the power output from zero to the maximum discharging power or any other referenced power under nominal.
It represents how quickly storage prototype can react to power variations.

HTF power in charge/discharge, $P_{HTF}(t)$

Thermal energy per unit time provided by (during charge) / given to (during discharge) the HTF, at a certain time *t*, under defined working conditions. These working conditions can be nominal or any other. Units: W

Mean thermal power, $P_{A \to B,\, mean}$

Average HTF power of a storage prototype delivered during a certain discharging process (from *A* storage level to lower one *B*). It is expressed in W

$$P_{A \to B, mean} = \frac{1}{t_{\text{discharge}}^{A \to B}} \int_{t^A}^{t^B} P_{HTF}(t) dt$$

Thermal capacity or storage capacity, φ_A

Thermal energy that the storage system can deliver under defined conditions in a full discharge process. The maximum useful energy the storage prototype is able to provide defines the ***design thermal capacity*** or ***design storage capacity***. When the storage prototype is at a state that it's able to provide the design thermal capacity, it is said that it is ***fully charged*** and has ***100***% storage level. Storage capacity is expressed in J or W·h.

$$\varphi_A = \int_{t^A}^{t^{0\%}} P_{HTF}(t)dt$$

$$\text{Design thermal capacity} \equiv \varphi_{design} = \int_{t^{100\%}}^{t^{0\%}} P_{HTF}(t)dt$$

Since the storage capacity is quantified using the HTF power, it relates to the useful thermal energy the storage system can supply.

Storage level, $H_{storage}$

Quotient in percentage of the useful energy the storage unit can deliver or thermal capacity, and the design thermal capacity.

$$H_{storage} = \frac{\int_{t^A}^{t^{0\%}} P_{HTF}(t)dt}{\int_{t^{100\%}}^{t^{0\%}} P_{HTF}(t)dt} = \frac{\varphi_A}{\varphi_{design}}$$

When the prototype is in such a state that it may be able to provide the maximum useful energy has 100% storage level and it is said that the prototype is ***fully charged***. When the prototype is unable to give any useful energy, it has 0% storage level and it is said that the prototype is ***complete discharged***.

When the useful energy is given by certain volume of storage medium at disposal at one temperature (two-tank molten salt systems, for example) the storage level can be translated to a physical height (in percentage). The temperature of such a volume has to be the one corresponding to the maximum energy.

Stored energy, $Q_{A,stored}$

Gross energy assumed to be stored by the prototype at a time t (i.e., having certain storage level). In the case of indirect storage, the heat transferred between HTF and storage prototype is assumed to be an ideal process with 100% efficiency. Stored energy is expressed in J or Wh. It is related to mean thermal power in a complete discharge from certain storage level, *A*, by

$$Q_{A,stored} = \int_{t^A}^{t0\%} P_{HTF}(t)dt = P_{A,mean} \cdot t_{\text{discharge}}^{A \to 0\%}$$

Thermal Efficiency at a time *t**, η_{t*}

Ratio of the useful energy delivered by the thermal storage prototype, being at certain storage level, *A*, becoming complete discharged, and the energy provided to the thermal storage prototype to have it fully charged, when a time *t** has passed between the charge and discharge processes

$$\eta_{t*} = \left. \frac{\int_{t^A}^{t^{0\%}} P_{HTF}(t)dt}{\int_{t^{0\%}}^{t^{100\%}} P_{HTF}(t)dt} \right|_{t*} = \left. \frac{\varphi_A}{\int_{t^{0\%}}^{t^{100\%}} P_{HTF}(t)dt} \right|_{t*}$$

The storage level *A* from which the discharge process begins depends on the idle thermal losses along the time *t**

Thermal losses at a temperature T_{SM}, P_{lost}

Power thermal losses of the storage prototype at a mean temperature, T_{SM}, to the environment at a temperature T_∞, ($T_{SM} > T_\infty$). Units: W

In prototypes the influence of thermal bridges are much more important than in large scale systems, so the experimental results related to thermal losses are expected to be overestimated when applying them to a large scale system.

Idle thermal losses along a time *t*, $P^{A}_{Idle\_lost,t}$

Power thermal losses of a storage prototype with storage level *A*, along a time interval, *t*, to the environment without any kind of external manipulation. This power accounts for the thermal resistance of the heat storage medium and makes no distinction between thermal losses and internal degradation due to diffusion in the storage medium. Units: W

In prototypes the influence of thermal bridges are much more important than in large scale systems, so the experimental results related to thermal losses are expected to be overestimated when applying them to a large scale system.

Half capacity cycles, $N_{1/2}$

Required number of consecutive cycles (charge and discharge), under nominal conditions, to reduce the storage capacity to half the design capacity. Units: cycles

Comparison factor of storage prototype power, *CF*

Similar to power determination, a comparison factor *CF* for power can be generated in order to compare different storage prototypes of the same type. The definition of the comparison factor depends on the kind storage prototype under study.

A. Indirect Sensible Regenerative-Type Storage Prototypes

During discharge and ignoring thermal losses, the power of the storage medium, $P_{SM}(t)$, of a sensible-regenerative heat storage prototype is transferred to the HTF flow, so

$$\left|P_{SM}(t)\right| = \left|P_{HTF}(t)\right|$$

diminishing the temperature of the storage medium (subscript $_{SM}$)

$$P_{SM}(t) = m_{SM}\bar{c}_{p,SM}\left(\frac{dT_{SM}(t)}{dt}\right); \qquad P_{SM}(t) < 0$$

and increasing the HTF temperature (see (Eq.4)),

$$P_{HTF}(t) = \rho_{HTF} q_{HTF}(t)\bar{c}_{P,HTF}\left(T_{HTF,out}(t) - T_{HTF,in}(t)\right); \qquad P_{HTF}(t) > 0$$

m_{SM} and $\bar{c}_{p,SM}$ are the mass and mean heat capacity of the storage material and $T_{SM}(t)$ its mean temperature at a time *t*. Assuming an ideal energy transfer between the storage medium and HTF, $T_{HTF,out}(t)=T_{SM}(t)$,

$$\rho_{HTF} q_{HTF}\left(t\right)\bar{c}_{p,HTF}\left(T_{SM}(t)-T_{HTF,in}(t)\right)=-m_{SM}\bar{c}_{p,SM}\left(\frac{dT_{SM}\left(t\right)}{dt}\right)$$

This equation is solved by integrating

$$\int_{0}^{t_{ideal}}\frac{\rho_{HTF} q_{HTF}\left(t\right)\bar{c}_{p,HTF}}{m_{SM}\bar{c}_{p,SM}}dt=-\int_{T_{HTF,out}}^{T_{SM,ideal}}\frac{dT_{SM}}{\left(T_{SM}-T_{HTF,in}\right)}$$

In which we assume that for an ideal discharging time (t_{ideal}), the storage medium is at a temperature $T_{SM,ideal}$ that has to be higher than $T_{HTF,in}$. Solving the above equation,

$$t_{ideal}=c\ln\left(\frac{T_{HTF,out}-T_{HTF,in}}{T_{SM,ideal}-T_{HTF,in}}\right) \qquad \text{(Eq. 1)}$$

were c is:

$$c=\frac{m_{SM}\bar{c}_{p,SM}}{\rho_{HTF} q_{HTF}(t_{ideal})\bar{c}_{p,HTF}}=\frac{m_{SM}\bar{c}_{p,SM}}{\dot{m}_{HTF}\left(t_{ideal}\right)\bar{c}_{p,HTF}}$$

A factor *f* accounting for how far the ideal temperature of storage medium is from HTF exit temperature can be defined according to

$$\left(T_{SM,ideal}-T_{HTF,in}\right)=f\left(T_{HTF,out}-T_{HTF,in}\right)$$

Substituting this expression in (Eq.1),

$$t_{ideal}=c\ln\left(\frac{1}{f}\right) \qquad \text{(Eq. 2)}$$

This theoretical ideal time to discharge can be compared to the measured time, $t_{measured}$, to discharge to 0.9 (or f) of the step function temperature difference to ascertain a comparison factor *CF* for the quality of the storage.

$$CF=\frac{t_{ideal}}{t_{measured}} \qquad \text{(Eq. 3)}$$

The measured time to discharge will necessarily be longer than the ideal time, as the ideal time assumes uniform storage temperature, i.e. an ideal heat transfer and conductance as well as no losses.

B. Indirect Latent Storage Prototypes

For determining the comparison factor of a latent heat storage prototype, a similar procedure can be followed. In this case, the HTF discharging power is given by (see (Eq.7)):

$$P_{HTF}(t) = \rho_{HTF} q_{HTF}(t)\left(x_{out}(t) - x_{in}(t)\right) L_{HTF}^{(T_{HTF,in},p_{HTF,in})}$$

In the particular case of latent heat storage, the phase change process of the storage material strongly depends on the prototype design and configuration. Therefore, a theoretical model for the prototype behaviour has to be proposed previously and then it can be compared with the experimental results. In this way the comparison factor can indicate how far from the ideal situation the prototype behaves but also how accurate the theoretical model is.

Example:

If we consider a prototype in which parallel tubes are embedded in the storage medium, in this case called phase change material (PCM) (see Figure 1); we can apply the quasi-static model in cylindrical coordinates for obtaining the time evolution of PCM melting front ($r_m(t)$):

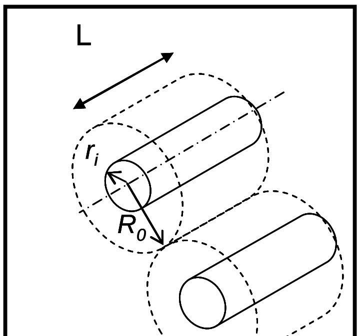


Figure 1

$$2\left(\frac{r_m(t)}{r_1}\right)^2 \ln\frac{r_m(t)}{r_i} = \left(1 - \frac{2}{Bi}\right)\left[\left(\frac{r_m(t)}{r_i}\right)^2 - 1\right] + 4\tau$$

Where: $Bi = hr_i/k_{PCM}$, $\tau = SteFo$, $Ste = \dfrac{c_{p,PCM}\left(T_m - T_{HTF,in}\right)}{L_{PCM}}$

and $Fo = \dfrac{k_{PCM}t}{\left(\rho c_p\right)_{PCM} r_i^2}$.

From this equation, HTF steam quality at prototype exit ($x_{out}(t)$) can be calculated and so can discharging power. Assuming $x_{in}(t)$ = 0 and ignoring thermal losses:

$$x_{out}(t) = \frac{2\pi L k_{PCM}}{\dot{m}(t) L_{HTF}} \frac{\left(T_m - T_{HTF,in}\right)}{\ln\dfrac{r_m(t)}{r_i}}$$

$$P_{HTF}(t) = 2\pi L k_{PCM} \frac{\left(T_m - T_{HTF,in}\right)}{\ln\dfrac{r_m(t)}{r_i}}$$

In this case, the ideal discharging process will end when:

$$r_m\left(t_{ideal}\right) = R_0$$

And comparison factor can be calculated by (Eq.3).

A different prototype configuration would be described by another theoretical model that should lead to the corresponding ideal discharging time, with which the comparison factor could be calculated.

3. Test SFERA15T2#1: HTF power curve in discharge/charge

Characterizing a storage prototype according to the above definitions requires charging it up to 100% storage level and, just after that, discharging it down to 0% storage level. Before charge, the storage prototype (including the external heat exchanger if required) should be preheated to a temperature close to nominal (~10 K below nominal charging temperature) and this situation should be verified by measuring the temperature inside the prototype.

During these two processes of charge and discharge some variables have to be measured, depending on the type of HTF. These are sensible and phase change HTF and as a third case there are storage units that are charged via electrical energy:

	Heat Transfer Fluid (HTF)
CASE I	sensible (ΔT)
CASE II	latent (T=const.)
CASE III	electricity

CASE I: If the energy is transferred to/from a **HTF** that **changes temperature** the following variables have to be measured:

- $T_{HTF,in}(t)$: HTF temperature measured at a time *t* just prior to transferring energy with the whole storage system (i. e. storage prototype and heat exchanger, if any).
- $T_{HTF,out}(t)$: HTF temperature measured at a time *t* just after transferring energy with the whole storage system (i. e. storage prototype and heat exchanger, if any).

  Both temperatures can be recorded by any temperature sensor such as a thermocouple or an RTD sensor, provided that the measuring head is well inserted in the HTF core flow and withstands the HTF contact. An accurate measurement of $T_{HTF,in}(t)$-$T_{HTF,out}(t)$ difference may be done by connecting two thermocouple heads in parallel. In any case, both temperatures have to be measured as absolute values in order to have the appropriate reference for calculating the HTF thermal properties. The measured values should be very close to the nominal ones with a deviation no larger than ±1.5 ºC. Units: ºC or K.

- $q_{HTF}(t)$: HTF volumetric flow (m^3/s) feeding the storage prototype measured at a time *t*. It can be recorded by any flow meter before or after the storage system, provided that a minimum distance is kept according to equipment specifications and pipe diameter. Although unusual, the measured flow may be the HTF mass flow, $\dot{m}$ (kg/s). Then it should keep in mind that $\dot{m} = \rho_{HTF} q_{HTF}$, where ρ_{HTF} is the HTF mean density in the temperature range [$T_{HTF,in}$, $T_{HTF,out}$]. In any case, the measured HTF flow should be very close to nominal one with a deviation no larger than 0.75%.

If the HTF is a gas, the pressure drop between the inlet and outlet should be measured as well, since this variable affects the values of HTF thermodynamic properties.

With the variables described above, the HTF power transferred in charge/discharge, $P_{HTF}(t)$, can be calculated using one of the following equations:

$$P_{HTF}(t) = \rho_{HTF} q_{HTF}(t) \left| h_{HTF}^{T_{HTF,in}(t)} - h_{HTF}^{T_{HTF,out}(t)} \right| = \rho_{HTF} q_{HTF}(t) \bar{c}_{P,HTF} \left| T_{HTF,in}(t) - T_{HTF,out}(t) \right| \quad \text{(Eq. 4)}$$

Where $h_{HTF}^{T_{HTF,in}(t)}$ and $h_{HTF}^{T_{HTF,out}(t)}$ are the HTF specific enthalpies (J/kg) at the temperatures $T_{HTF,in}(t)$ and $T_{HTF,out}(t)$, respectively, and $\bar{c}_{p,HTF}$ corresponds to the HTF mean heat capacity [J/(kg·K)] in the temperature range [$T_{HTF,out}$, $T_{HTF,in}$]. The values of these thermodynamic properties can be found in literature (if HTF is water or air) or should be provided by the manufacturer (if HTF is oil, molten salt, etc). The choice between the two expressions in Eq.1 is determined by the accuracy of data available for the HTF properties. The uncertainties of the thermophysical properties should not be neglected since, unfortunately, in most of cases, such uncertainty is important and relevant when calculating the uncertainty in indirect parameters such as HTF power.

The entire procedure is carried out under steady state conditions (i. e. $q_{HTF}(t)$ and $T_{HTF,in}(t)$ are kept constant).

Using (Eq.4), HTF power curves for charge and discharge can be drawn (see Figure 1) and from here identified the characteristic and response times for charge and discharge.

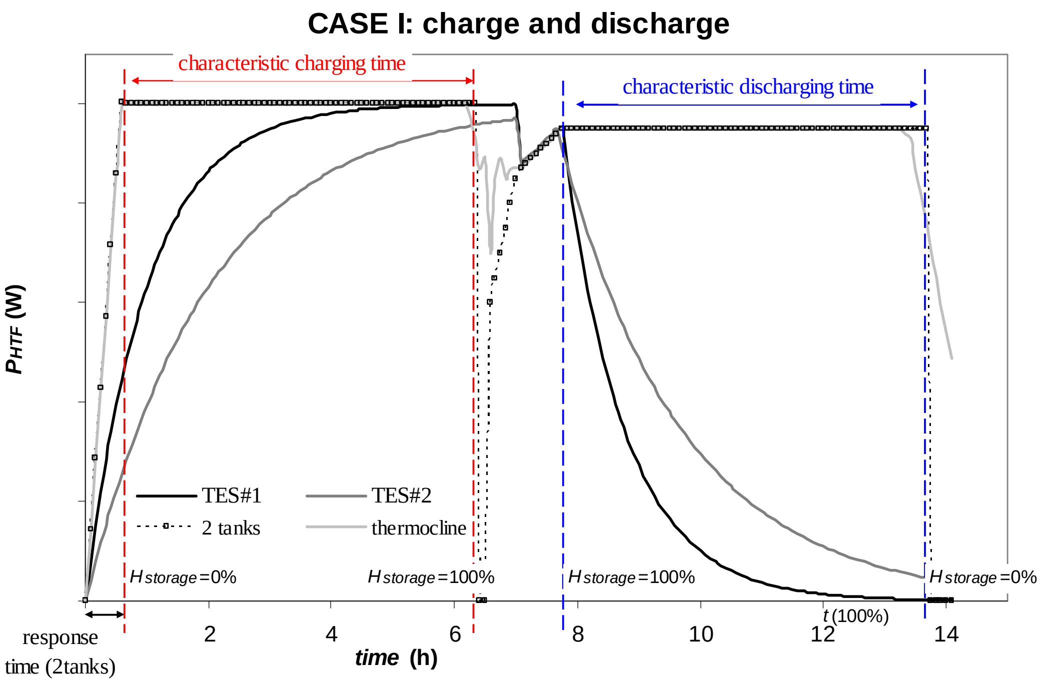


Figure 1: HTF power curves for Case I and different types of storage prototypes. Response and characteristic times and storage levels are referred to the 2-tank curves.

From the HTF discharge curve it is possible to calculate:

Mean thermal power for the complete discharge: $$P_{100\%,mean} = \frac{1}{t_{\text{discharge}}^{100\%\rightarrow 0\%}} \int_{t^{100\%}}^{t^{0\%}} P_{HTF}(t)dt$$

and

Design thermal capacity: $$\varphi_{design} = \int_{t^{100\%}}^{t^{0\%}} P_{HTF}(t)dt$$

Using also the HTF power curve for charge, the Thermal efficiency can be calculated by

$$\eta_{t^*=0} = \left. \frac{\int_{t^{100\%}}^{t^{0\%}} P_{HTF}(t)dt}{\int_{t^{0\%}}^{t^{100\%}} P_{HTF}(t)dt} \right|_{t^*=0} = \frac{\varphi_{design}}{\int_{t^{0\%}}^{t^{100\%}} P_{HTF}(t)dt}$$

<u>CASE II</u>: If the energy is provided/removed by a **HTF** which **condenses/evaporates**, in addition to the variables already described in CASE I, the following variables have to be measured:

- $p_{HTF,in}(t)$: HTF pressure measured at a time *t* just before any energy is transferred to/from the storage prototype. It can be recorded by any pressure gauge and its value should be very close to the nominal value with a deviation no larger than 0.075 %-base line. Units: Pa or bar.
- $x_{out}(t)$: HTF steam quality measured at time *t* just after the energy has been exchanged with the storage prototype. Since it is rather difficult to measure steam quality directly, it has to be calculated from an energy balance; for which an additional cooling system is required. Up to now, two options for cooling systems have been used:

  a) At DLR: A separator that splits HTF liquid and vapour phases followed by a condenser where the vapour is cooled down and condensed. This equipment should be designed to ensure that all HTF steam is condensed and no bubbles are present in the condensate. Although the condenser may use the same liquid HTF as coolant, better efficiencies are obtained if the coolant is a liquid with higher thermal capacity than the liquid HTF.

  b) At PSA-CIEMAT: A mixer system included in an independent pipeline, where a controlled cold liquid HTF flow ($q_{mixer,in}(t)$) at a certain temperature ($T_{mixer,in}(t)$, measured), is mixed with the HTF flow that exits the storage prototype ($q_{HTF}(t)$ and $T_{HTF,out}(t)$, both measured). The liquid mixture leaving the mixer increases its temperature ($T_{mixer,out}(t)$, measured) and acquired a certain flow ($q_{mixer,out}(t)$). In addition to theses variables, the pressure of the HTF that exits the storage system, $p_{HTF,out}(t)$, has to be recorded as well. This pressure must be measured by a gauge placed just after the HTF has left the storage prototype and not far from it to minimize that pressure drops hide the real pressure value. The previous recommendations for measuring temperatures and flows apply here for $q_{mixer,in}(t)$, $q_{mixer,out}(t)$, $T_{mixer,in}(t)$ and $T_{mixer,out}(t)$.

  The following heat balance in the mixer allows the calculation of the HTF steam quality just after the storage prototype, $x_{out}(t)$:

$$P_{HTF,out}(t) + P_{mixer,in}(t) = P_{mixer,out}(t) \qquad \textbf{(Eq. 5)}$$

$$\rho_{HTF} q_{HTF}(t)\left[h_{HTF,steam}^{(p_{HTF,out};T_{HTF,out})} x_{out}(t) + h_{HTF,liquid}^{(p_{HTF,out};T_{HTF,out})}\left(1 - x_{out}(t)\right)\right] + \rho_{mixer,in} q_{mixer,in}(t) h_{HTF}^{T_{mixer,in}} = \rho_{mixer,out} q_{mixer,out}(t) h_{HTF}^{T_{mixer,out}} \quad \textbf{(Eq. 6)}$$

Where $h_{HTF,steam}^{(p_{HTF,out};T_{HTF,out})}$ and $h_{HTF,steam}^{(p_{HTF,out};T_{HTF,out})}$ are the specific enthalpies [J/kg] of the HTF vapour and liquid at temperature $T_{HTF,out}(t)$ and pressure $p_{HTF,out}(t)$; $h_{HTF}^{T_{mixer,in}}$ and $h_{HTF}^{T_{mixer,out}}$ are the specific enthalpies [J/kg] of the liquid HTF before and after the mixer, respectively. Like before, ρ_{HTF} is the HTF mean density in the temperature range [$T_{HTF,in}$, $T_{HTF,out}$], while $\rho_{mixer,in}$ and $\rho_{mixer,out}$ are the liquid HTF density before and after the mixer. The values for these thermodynamic properties can be, usually found in literature, since, when using condensation/evaporation of a HTF, water is normally used.

With the variables measured above, the power transferred between the HTF and the storage module, $P_{HTF}(t)$, can be calculated by:

$$P_{HTF}(t) = \rho_{HTF} q_{HTF}(t)\left| x_{in}(t) - x_{out}(t)\right| L_{HTF}^{(T_{HTF,in},p_{HTF,in})} \quad \textbf{(Eq. 7)}$$

Where $L_{HTF}^{(T_{HTF,in},p_{HTF,in})}$ is the latent heat [J/kg] of the HTF at temperature $T_{HTF,in}$ and pressure $p_{HTF,in}$.

In charge x_{in} should be 1, since it is assumed that the prototype is fed by 100% saturated steam. Feeding the storage with a steam temperature a bit higher than saturated temperature may assure to have x_{in}=1. In discharge x_{in} is 0, since HTF is saturated liquid.

HTF power curves for charge and discharge can be drawn (
Figure **2**). From these curves it is possible to calculate:

Mean thermal power for the complete discharge: $$P_{100\%,mean} = \frac{1}{t_{\text{discharge}}^{100\% \to 0\%}} \int_{t^{100\%}}^{t^{0\%}} P_{HTF}(t)dt$$

Design thermal capacity: $$\varphi_{design} = \int_{t^{100\%}}^{t^{0\%}} P_{HTF}(t)dt$$

and

Thermal efficiency

$$\eta_{t^*=0} = \left.\frac{\int_{t^{100\%}}^{t^{0\%}} P_{HTF}(t)dt}{\int_{t^{0\%}}^{t^{100\%}} P_{HTF}(t)dt}\right|_{t^*=0} = \frac{\varphi_{design}}{\int_{t^{0\%}}^{t^{100\%}} P_{HTF}(t)dt}$$

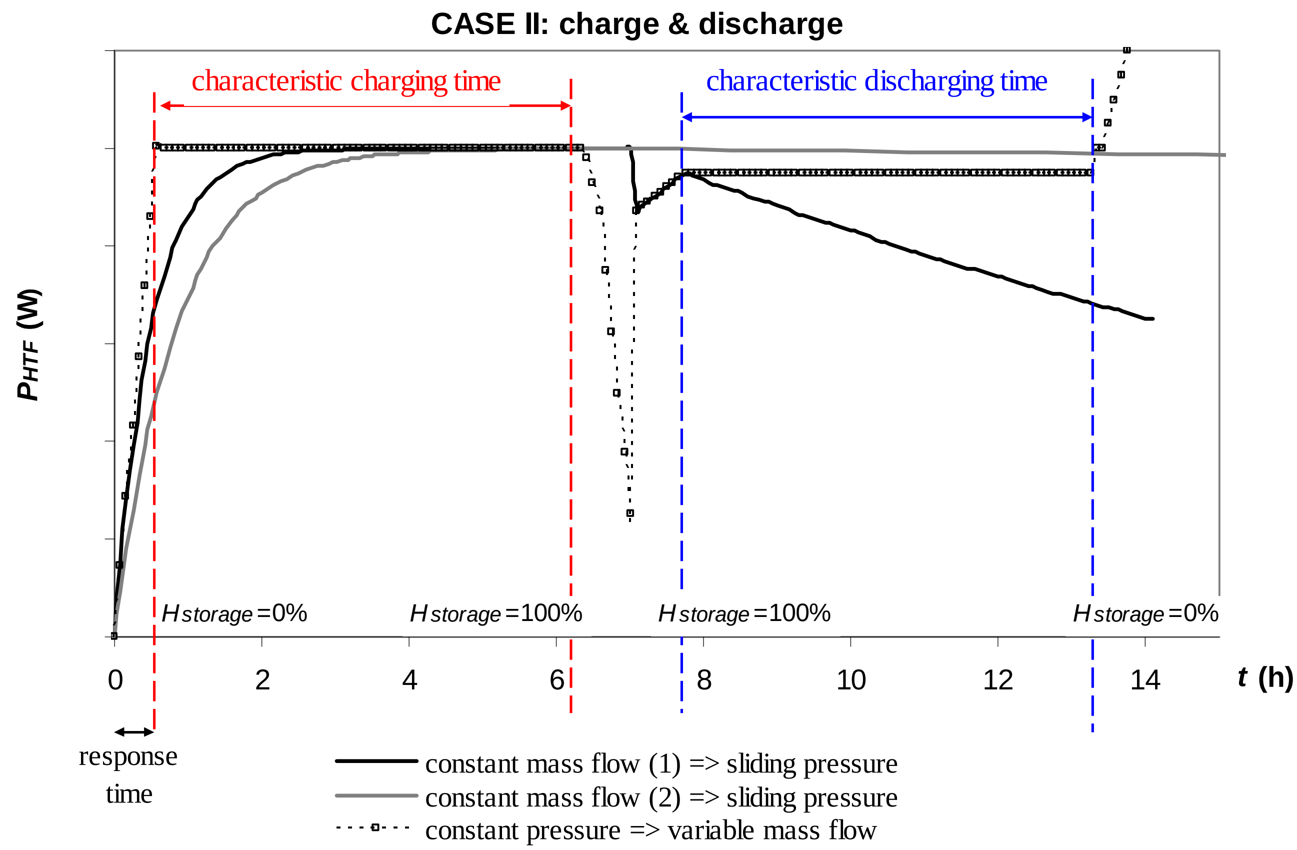


Figure 2: HTF power curves for Case II and different types of storage prototypes. Response and characteristic times and storage levels are referred to constant pressure curve.

CASE III: When the prototype in charge is fed with energy provided by an electricity source. In this case the electric power has to be measured:

$$P_{HTF}(t) = P_{electric}(t) \qquad \textbf{(Eq. 8)}$$

Discharging of a CASE III storage would need to be analyzed via the procedures under CASE I or II, depending on the design.

4. Test SFERA15T2#2: Thermal losses at a temperature T_{SM}, P_{lost}

Although thermal losses in prototypes can not be extrapolated to larger systems, it is always interesting to have an idea of the thermal losses of the prototype.

The procedure to quantify thermal losses at a temperature T_{SM} is the following:

1. Preheat the storage prototype (including the external heat exchanger if any) to a temperature close to T_{SM}. This situation should be verified by measuring the temperature inside the prototype.
2. Charge the storage prototype until the system is isothermal to a constant temperature, $T_{SM}(t)=0.5\cdot[T_{HTF,in}(t)+T_{HTF,out}(t)]$. Therefore, it is necessary to measure $T_{HTF,in}(t)$, $T_{HTF,out}(t)$ as well as ambient temperature, T_∞.
3. Measuring the HTF flow, $q_{HTF}(t)$, calculate power heat losses, P_{lost}, at the assumed constant storage medium temperature, T_{SM}, by balancing it with HTF power in charge

$$P_{HTF}(t) = \rho_{HTF} q_{HTF}(T_{HTF,in}(t) - T_{HTF,out}(t)) = P_{lost}(t, T_{SM} - T_\infty) \qquad \textbf{Eq. 9}$$

To eliminate measurement errors of temperature gauges, the HTF flow direction has to be changed during the isothermal phase (HTF inlet becomes the outlet and vice versa). Then the mean values for inlet and outlet temperatures have to be corrected to the same level, since the heat losses should be the same for both directions.

5. Test SFERA15T2#3: Idle thermal losses along a time *t*, $P_{Idle\_lost,t}$

This test is recommended to be carry out after performing test SFERA15T2#1, so mean thermal power for a complete discharge,

$$P_{100\%,mean} = \frac{1}{t_{\text{discharge}}^{100\% \to 0\%}} \int_{t^{100\%}}^{t^{0\%}} P_{HTF}(t)dt$$

is known. A new charge up to having the storage prototype fully charged is performed. Leave the storage unit without any external manipulation during a certain time, *t*. Due to thermal losses, the storage level after that *t* time is diminished to new storage level *A*. Then, carry out a complete discharge, and calculate the corresponding mean power, $P_{A,mean}$,

$$P_{A,mean} = \frac{1}{t_{\text{discharge}}^{A \to 0\%}} \int_{t^{A}}^{t^{0\%}} P_{HTF}(t)dt$$

Calculate $P_{Idle\_lost,t}$ taking into account that

$$t \cdot P_{Idle\_lost,t}^{A} = t_{\text{discharge}}^{100\% \to 0\%} \cdot P_{100\%,mean} - t_{\text{discharge}}^{A \to 0\%} \cdot P_{A,mean} \qquad \text{Eq. 10}$$

Ambient temperature should be as constant as possible.

6. Recommended accuracy in probes and times

Temperatures

Temperature probes should be adapted to the medium to which they are in contact and the testing conditions. For example, thermocouples type J can be used in reducing environments but not in oxidizing environments where thermocouples type K are much more appropriate.

Accuracy depends on the type of the probes: while thermocouples can give accuracies between ± 1.5 ºC and ± 1 ºC (Class 1); Resistance temperature detectors (RTD) -Class A can provide accuracies of ± 0.3 ºC.

The type of probes and accuracy of the different laboratory capacities are listed below

PSA-DSG: Thermocouple Type K-Class 1; Accuracy

CNRS- SOLACLIM: Thermocouple Type T

CNRS- CLIMSOL: Thermocouple Type K

WIS- RHTS: Thermocouple Type K; Accuracy: ± 1.0 ºC

DLR: thermocouples type K and RTD

Pressure

PSA-DSG: Accuracy: 0.075% base line

CNRS- SOLACLIM: radial gauge

WIS- RHTS: Accuracy: 0.1% base line

Steam mass flow

PSA-DSG: Vortex; ± 0.75% recorded value (Re>20000) or ± 0.75% base line (4000<Re<20000)

DLR: (Recommendation) flow adjustment not close to the measurement margins, most accurate around nominal flow range

Liquid mass flow

PSA-DSG: Electromagnetic (low temperature); Accuracy: ± 0.5% recorded value (mixer); Vortex type (high temperature)

CNRS- CLIMSOL: Turbine

DLR: (Recommendation) flow adjustment not close to the measurement margins, most accurate around nominal flow range

Time step

Sampling rate is commonly defined by the Nyquist limit, the shortest period of time requested to be able to fully recognize the measuring signal. For solar power system, the power changes can be accurately measured on the minute time-scale, so it is reasonable to choose 1-min as the order of magnitude for the time step.

Nevertheless, when testing a prototype, which is much smaller, the recommended sampling rate is no higher than 15s.

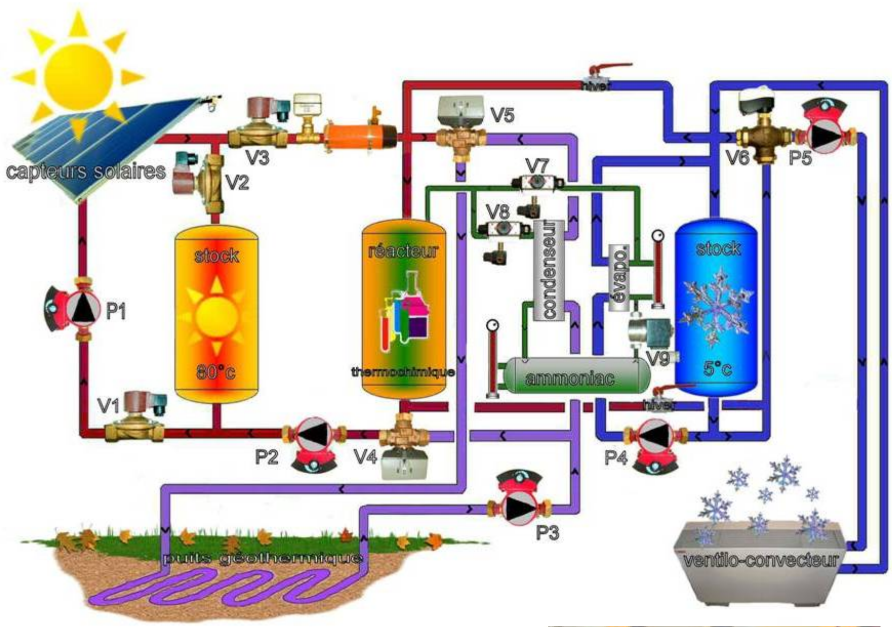
7. Annexe A: Test facilities for evaluating thermal storage prototypes

CLIMSOL	
Location	Promes – Perpignan (FRANCE)

Main features of heat source	
Type	Flat Plate Solar Collectors
Components	HelioAkmi - ST2000
Working conditions	Power: up to 10 kW_{th} Mass flow rate: 0.9 m^3/h Temperature range: 60-90 ºC Pressure range: up to 2 bars

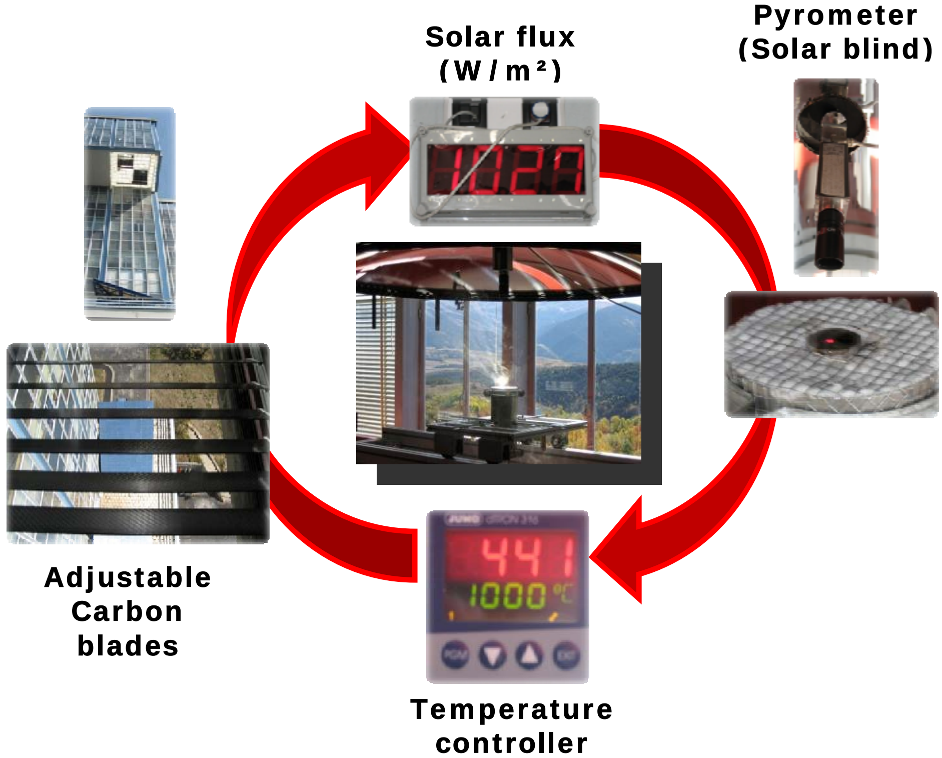
Special features in relation to the storage interface	
Hydraulic circuit	For water used in charge tests up to 2 bar

Scheme of test facility



SESCO	
Location	Promes – Perpignan (FRANCE)
Main features of heat source	
Type	Concentrated Solar flux
Components	Temperature control loop Pyrometer (solar blind) Temperature controller Adjustable Carbon blades Reactor Isolating box Thermocouples (Type K) Acquisition Central (Agilent)
Working conditions	Temperature range: up to 2000 ºC

Special features in relation to the storage interface	
Compressed air	To increase the amplitude and rate of the surface thermal shock under cooling

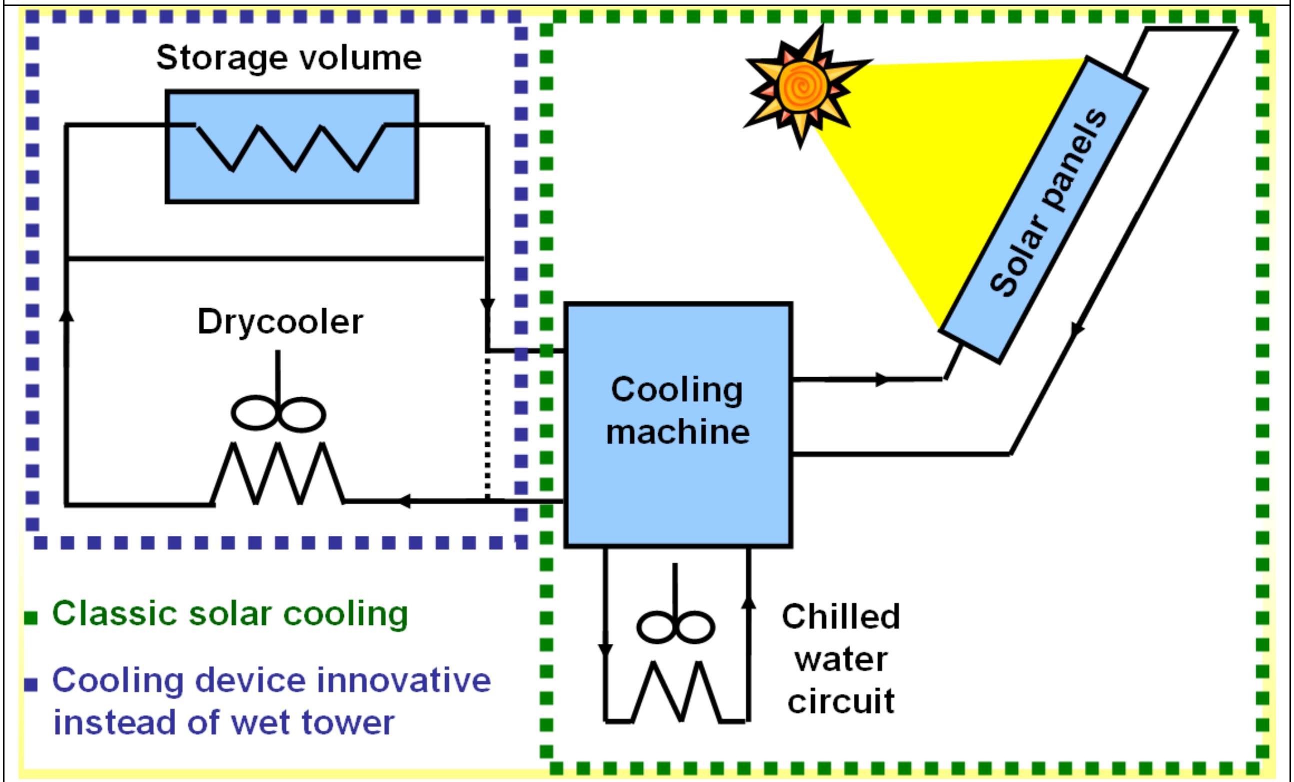


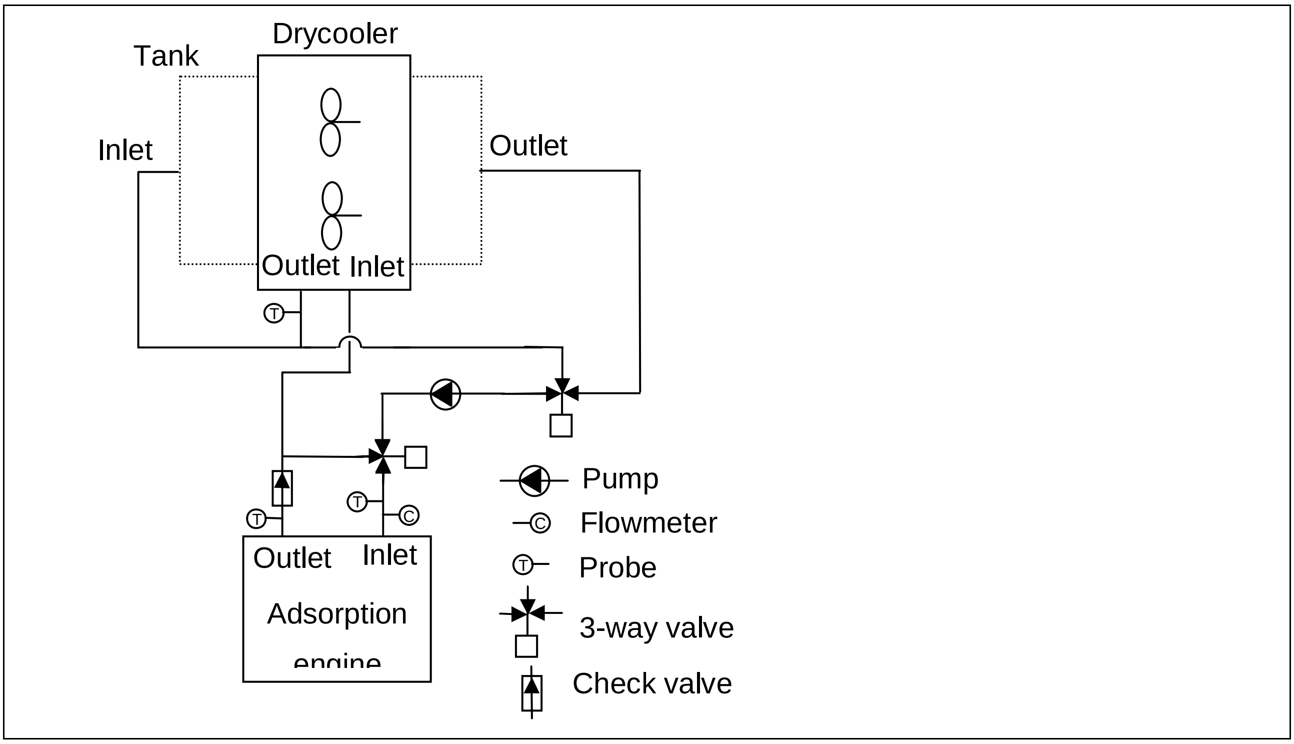
SOLACLIM	
Location	Promes – Perpignan (FRANCE)

Main features of heat source	
Type	Flat Plate Solar Collectors
Components	SchücoSol U.5 Double Glass
Working conditions	Power: up to 15 kW_{th} Mass flow: up to 2 m^3/h Temperature range: up to 95 ºC Pressure range: up to 2 bars

Special features in relation to the storage interface	
Hydraulic circuit	For water used in charge tests up to 3 bar

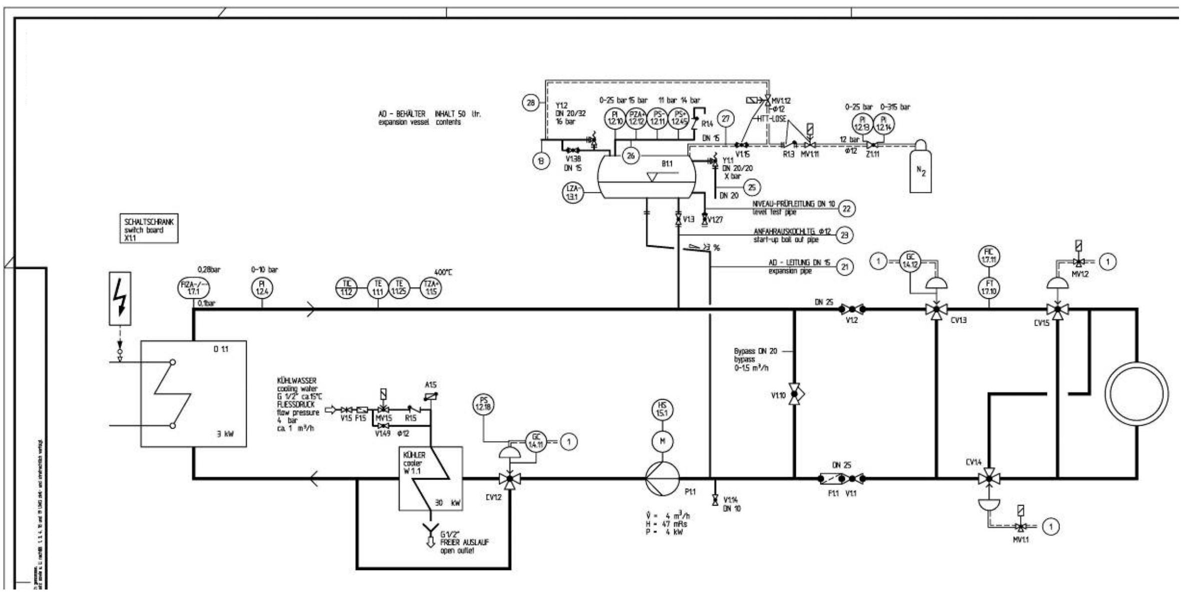
Scheme of test facility




Drycooler
Tank
Inlet
Outlet
Outlet
Inlet
Outlet
Inlet
Adsorption
engine
Pump
Flowmeter
Probe
3-way valve
Check valve

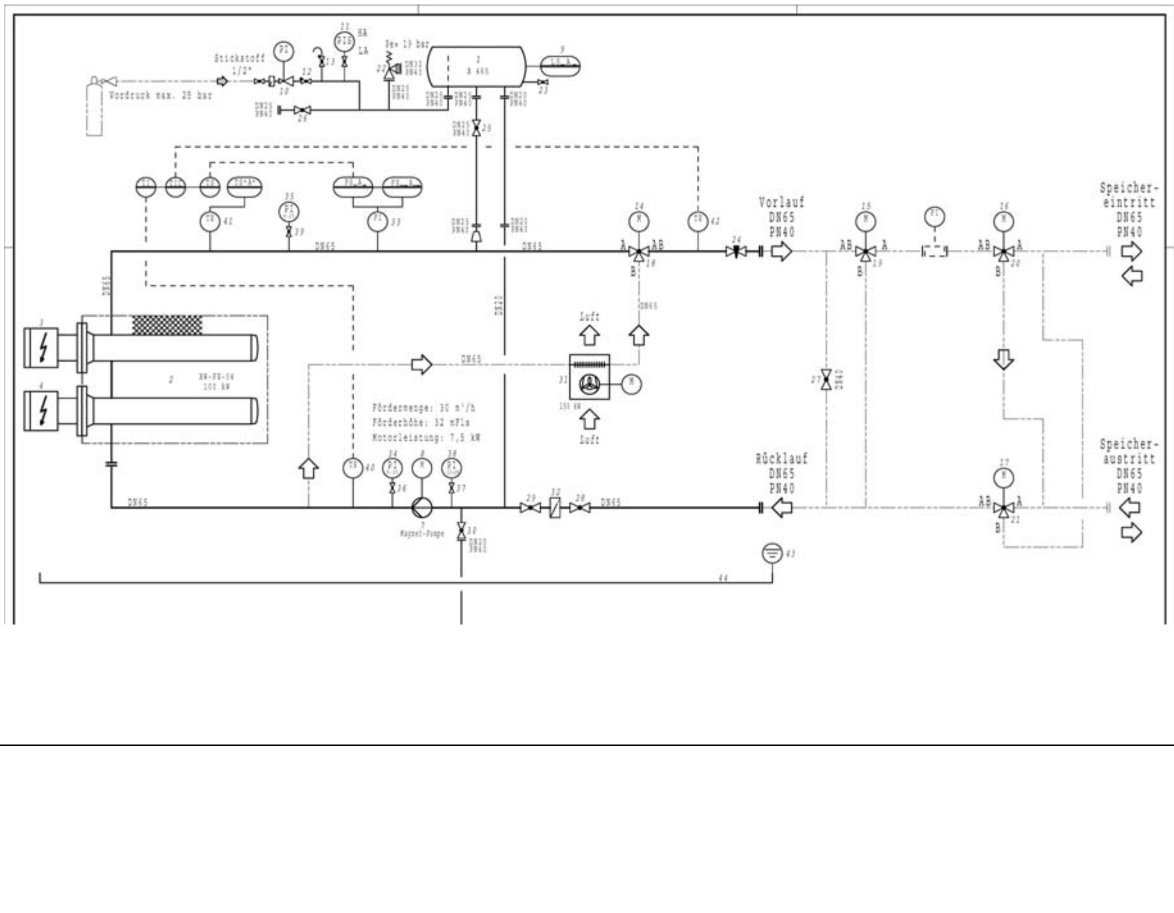
<table>
<tr><th colspan="2">Skoop</th></tr>
<tr><td>Location</td><td>DLR Stuttgart</td></tr>
<tr><td colspan="2">Main features of heat source</td></tr>
<tr><td>Type</td><td>Heating- and Cooling-Loop</td></tr>
<tr><td>Components</td><td>One circuit with Syltherm 800</td></tr>
<tr><td>Working conditions</td><td>Heating-power : 12 kW
Cooling-power : 30 kW
Mass flow : 4 m³/h
Temperature : up to 400°C
Pressure : 20 bar</td></tr>
</table>

Scheme of test facility



Birkhof	
Location	DLR Stuttgart
Main features of heat source	
Type	Heating- and Cooling-Loop
Components	One circuit with Syltherm 800
Working conditions	Heating-power : 110 kW Cooling-power : 150 kW Mass flow : 30 m³/h Temperature : up to 400°C Pressure : 20 bar

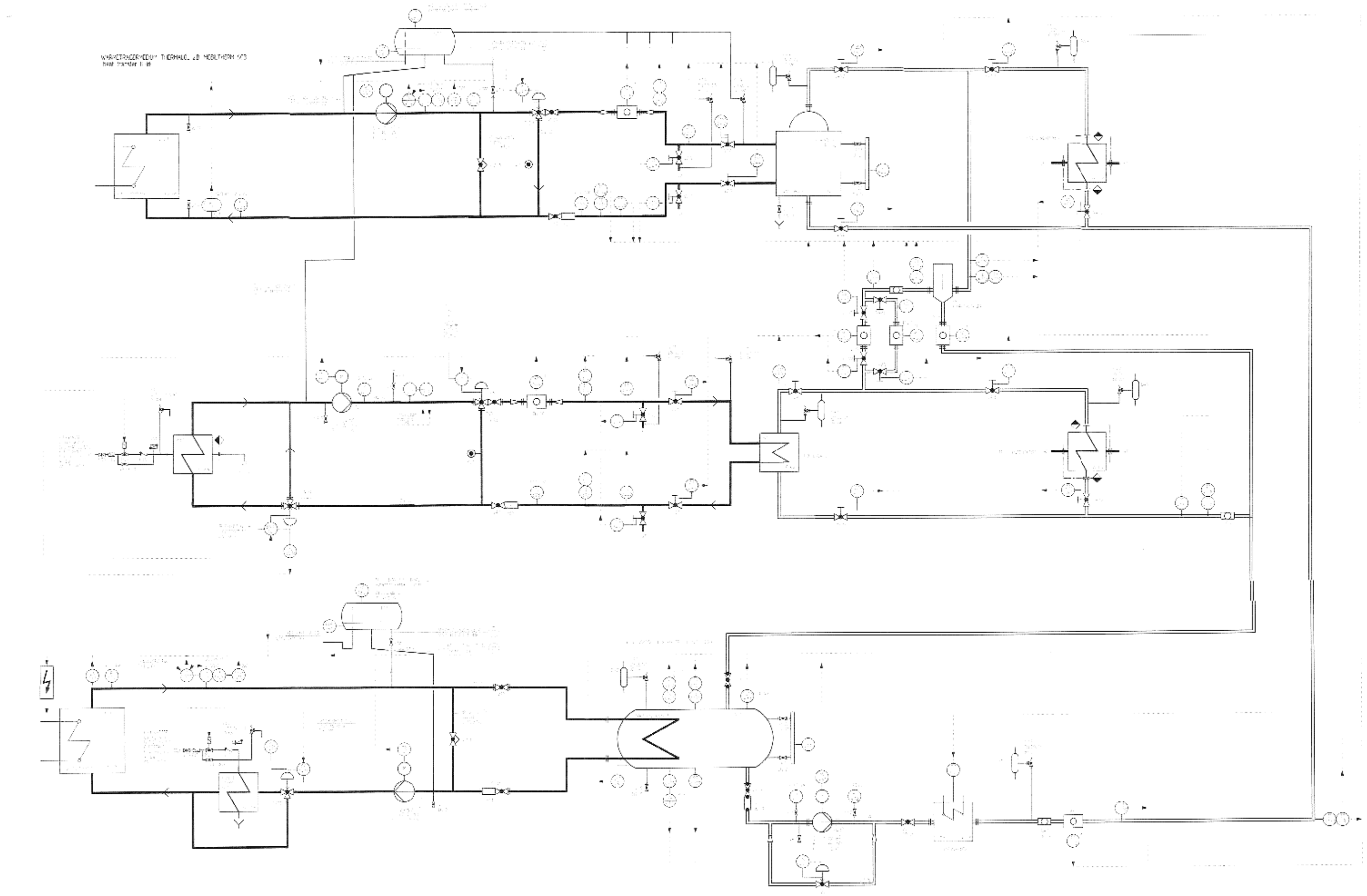
Scheme of test facility



WÜTA	
Location	DLR Stuttgart
Main features of heat source	
Type	Heating- and Cooling-Loop
Components	One circuit with water/steam Three circuits non-pressurized with Mobiltherm: Circuit one: heating/cooling for pressure regulation Circuit two: cooling to condense Circuit three: heating to evaporate
Working conditions	Water-circuit: Mass flow : up to 2 kg/min Temperature : up to 225°C Pressure : 25 bar Circuit one: Heating-power : 12 kW Cooling-power : 30 kW Temperature : up to 300°C Circuit two: Cooling-power : 60 kW Mass flow : 25 m³/h Temperature : down to 20°C Circuit three: Heating-power : 50 kW Mass flow : 20 m³/h Temperature : up to 300°C

Special features
All the circuits can work alone or in different combinations with the other circuits. They all have junctions to open the circuits and recombine.

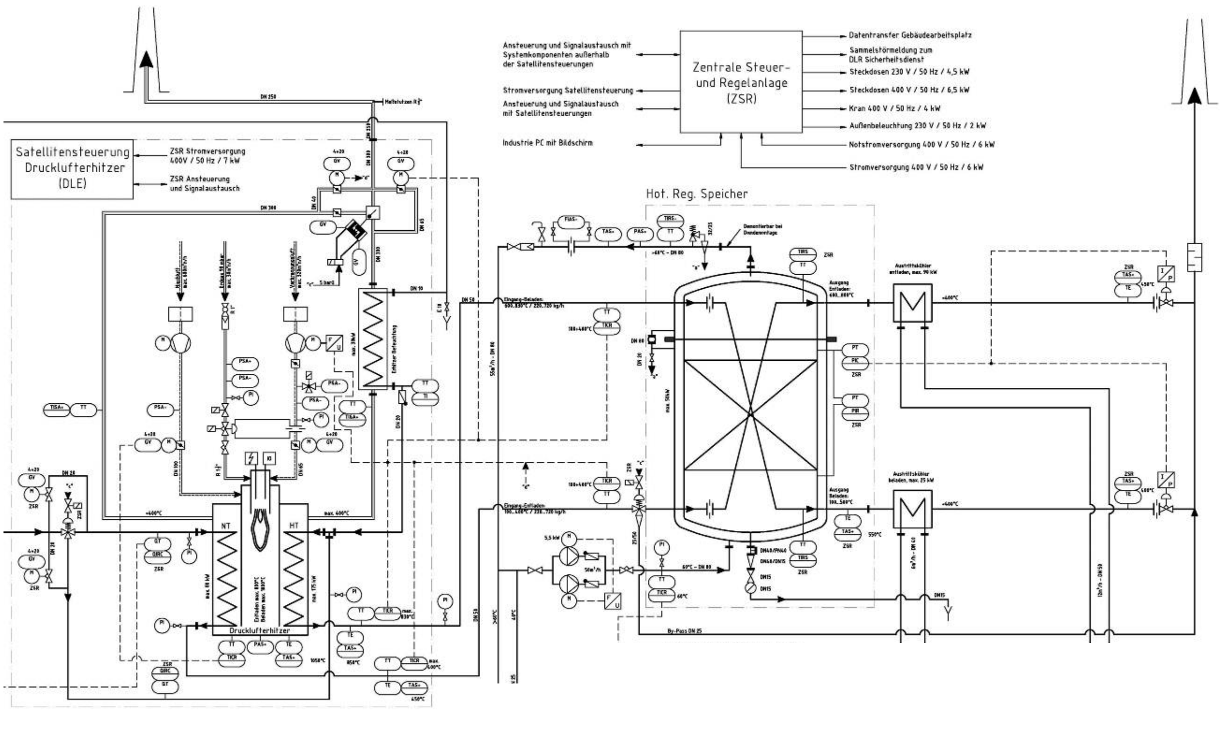
Scheme of test facility



HOTREG	
Location	DLR Stuttgart
Main features of heat source	
Type	Heat- and Cooling-Loop for packed bed storage
Components	One circuit with air
Working conditions	Heating-power : 150 kW Cooling-power : 200 kW Mass flow : 720 kg/h Temperature : up to 830°C Pressure : 10 bar

Special features in relation to the storage interface	
Air	It is possible to moisten the airflow up to 4 kg/h

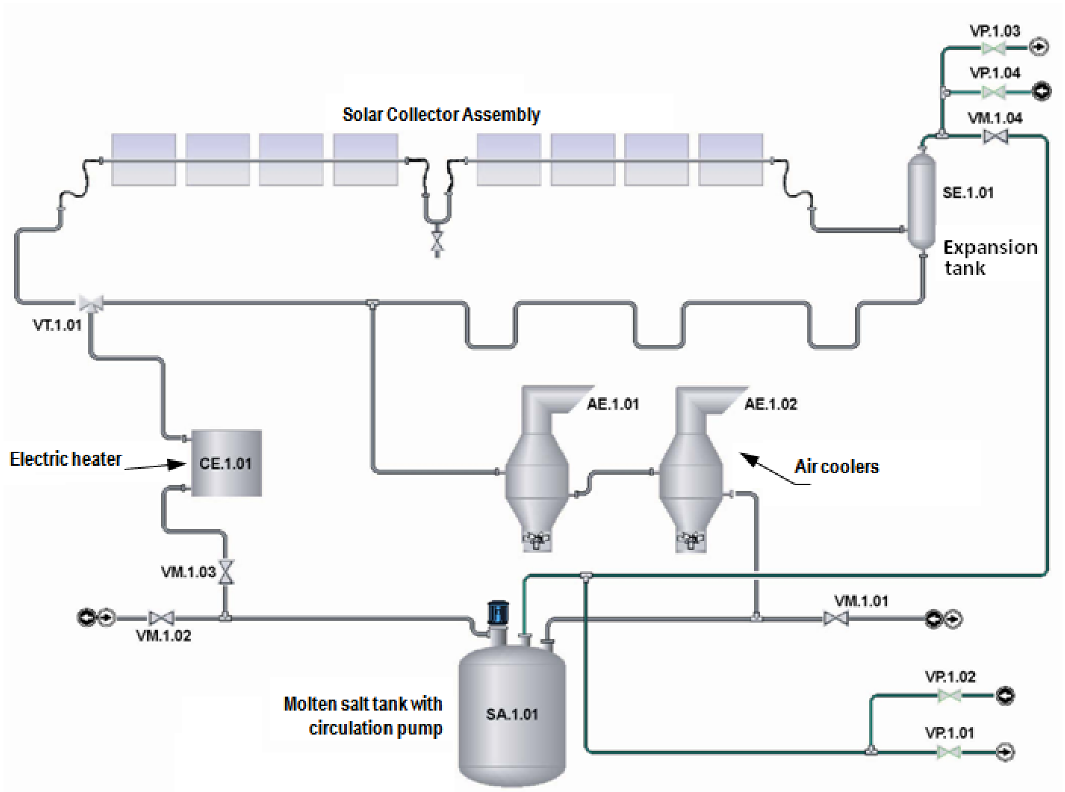
Scheme of test facility



ELIOSLAB – TES_SG	
Location	ENEA – Centro Ricerche Casaccia – Roma – Italy
Main features of heat source	
Type	Parabolic trough collectors with molten salts mixture
Components	Parabolic trough collectors ARCHIMEDE type, E/W oriented
Working conditions	Working fluid: molten salts mixture (KNO3/NaNO3 at 40/60%) Power: up to 300 kWth Mass Flow: up to 10 kg/s Temperature: up to 550°C Pressure range: atmospheric (except for head losses)

Special features in relation to the storage interface
Hydraulic circuit: for saturated steam in charge tests: up to 6.0 MPa Preheater: to preheat water during tests

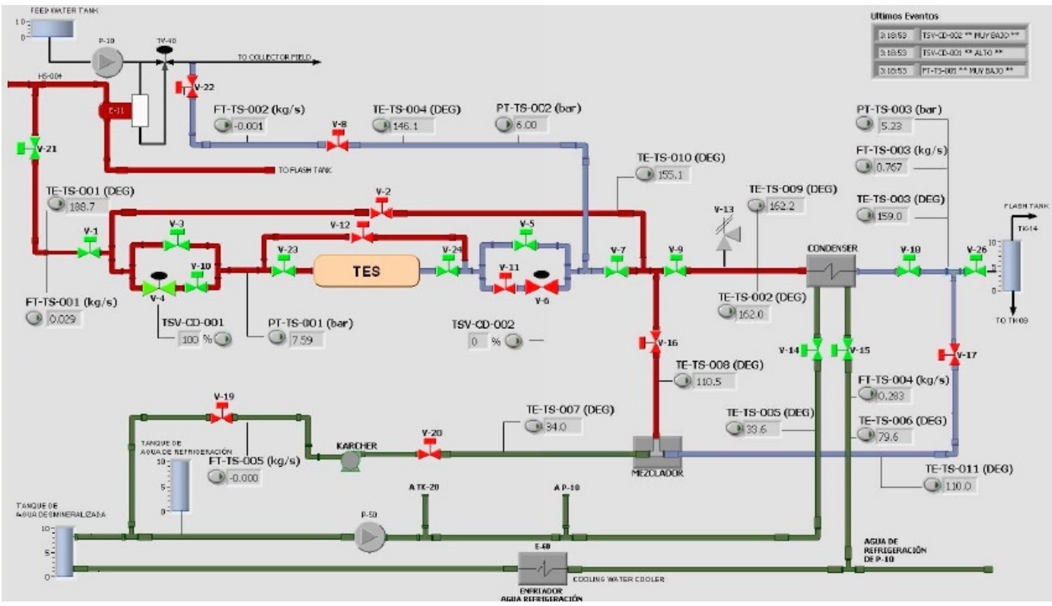
Scheme of test facility



PSA-DSG/TES loop	
Location	PSA - Almería (Spain)
Main features of heat source	
Type	Parabolic trough collectors with direct steam generation (DISS)
Components	Parabolic trough collectors both LS3 and ET-I type (N/S oriented), plus a balance of plant
Working conditions	Power: up to 3 MW_{th} Mass flow: up to 1kg/s Temperature range: up to 400ºC Pressure range: up to 100 bar

Special features in relation to the storage interface	
Hydraulic circuit	For saturated steam used in charge tests up to 60 bar
Mixer (“MEZCLADOR”)	Mixes cold water with the steam/water flow leaving TES prototype. Allows to perform a heat balance for calculating outlet flow enthalpy and obtaining steam quality
Preheater	Provides hot saturated water for discharge tests

Scheme of test facility



PSA-HTF loop		
Location		PSA - Almería (Spain)
Main features of heat source		
Type	Parabolic trough collectors with Syltherm 800 as HTF	
Components	Parabolic trough collectors LS3 type (E/W oriented), plus a balance of plant	
Working conditions	Power: Mass flow: up to 8.3 l/s Temperature range: up to 420ºC Pressure range: up to 16 bar	

RHTS test system		
Location	WIS - Rehovot (Israel)	
Main features of heat source		
Type	electrical heater	
Components	6 kW HTF electrical heater	

Special features in relation to the storage interface	
Hydraulic circuit	Water pump loop including both preheater and control system. For pumped water used in discharge tests, up to 100 bar Water mass flow: up to 0.5 kg/min
Mixer: (To be installed)	Mixes cold water with the steam flow exiting the steam generator Allows to perform a heat balance for calculating outlet flow enthalpy and obtaining steam quality
Preheater	Provides hot water for steam generation in discharge tests

Scheme of the test facility for 25 kWh thermal storage capacity