# Development of an innovative thermal energy storage (TES) solution for middle-size concentrated solar power (CSP) plant


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# OUTLINE

Introduction

Objectives

Experimental work

- Selection of the storage material
- Structural characterization
- Thermophysical properties
- Mechanical properties
- Corrosion and compatibility study

Conclusions

Perspectives

# Background of the project

## The CSP-ORC (1 MWel) commercial power plant characteristics:

| Plant location | Benguerir, Morocco |
|---|---|
| Direct Normal Irradiance | 2100 kWh/m²/year |
| Solar field (SF) heat transfer fluid | Delcoterm Solar E15 (Mineral oil) |
| SF inlet/outlet temperature | 180 - 300 °C |
| ORC working fluid | Cyclopentane |
| ORC Gross output | 1 $MW_{el}$ |
| ORC design point efficiency | 20 % |
| Storage | No |

*Power block of the plant*

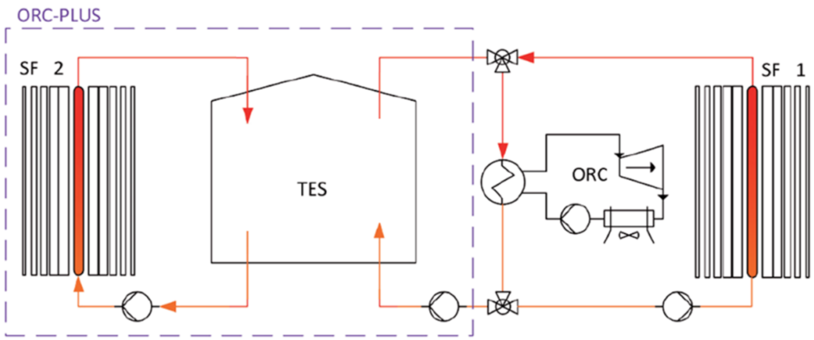
*Overview of the Green Energy Park*

*North side of the solar field*

# The aim of the ORC-Plus project

## Develop a TES solution adapted to 1 – 5 MWel CSP plants:

- Extension of the solar field to feed the storage system.
- Validation of thermocline TES Prototype of 200 $kWh_{th}$ at laboratory scale.
- Construction of commercial TES system of 20$MWh_{th}$ (4 hours of storage) for the CSP-ORC power plant at Green Energy Park in Ben-Guerir, Morocco.

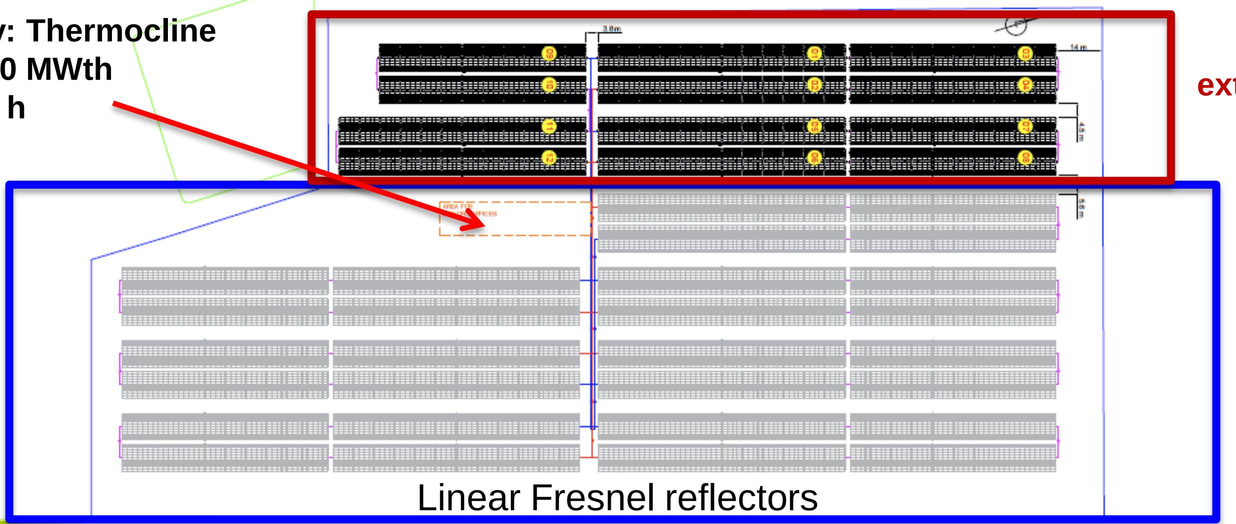



SF1: 7 loops to feed ORC
SF2: 3 loops to charge TES

## Integration of a novel thermal storage system

- Technology: Thermocline
- Capacity: 20 MWth
- Duration: 4 h

HTF: mineral oil
$T_{min}$: 180 ºC
$T_{max}$: 300 ºC




extension of the solar field

1MW commercial CSP-ORC plant located in Green Energy Park Benguerir, Morocco)

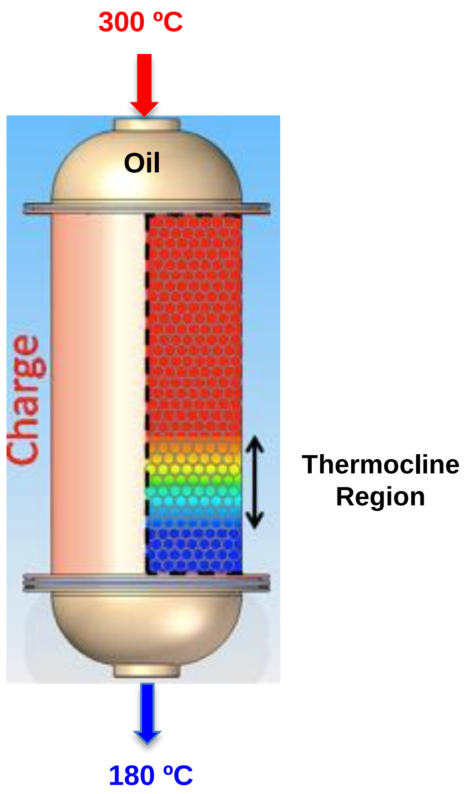
# The aim of the ORC-Plus project

## TES prototype of 200 kWth (1/100 industrial scale) to validate the technology:

**Solid packed-bed thermocline system is under development and testing at laboratory scale.**

- **Storage based on natural stratification of temperature.**
- **Two materials in direct contact in the same tank:**
  - **Filler (packed bed): ceramic material**
  - **Heat transfer fluid: liquid (oil or molten salt) or gas (Air)**

| Developer | CIC EnergiGUNE |
|---|---|
| Technology | Packed-bed thermocline |
| Total energy capacity ($kWh_{th}$) | 200 |
| Storage volume | 2 $m^3$ |
| Filler material | Solid material |
| Heat Transfer Fluid (HTF) | Delcoterm Solar E15 (mineral oil) |
| Temperature range | 180°C-300°C |



# Selection of the storage material

## Valorisation of different classes of ceramic materials:

- To obtain a viable and cost-effective TES material,
- To reduce the industrial environmental impact.

BOF-Slag
(by-product)

Magnetite
(mineral)

River Rock
(local natural rock)

## Material requirements for TES:

- Low cost  ceramic materials,
- Appropriate thermophysical properties,
- Good thermal stability,
- Good mechanical behaviour,
- Good thermomechanical stability,
- Compatible with the heat transfer fluids.

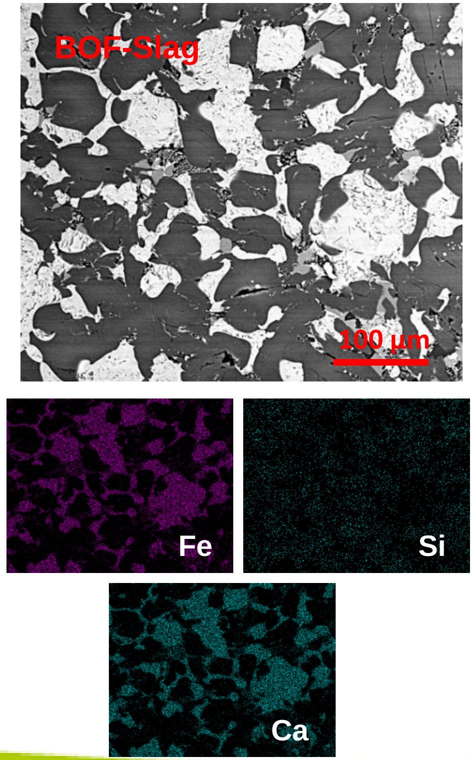
# Structural characterization

## Chemical Composition (ICP - OES)

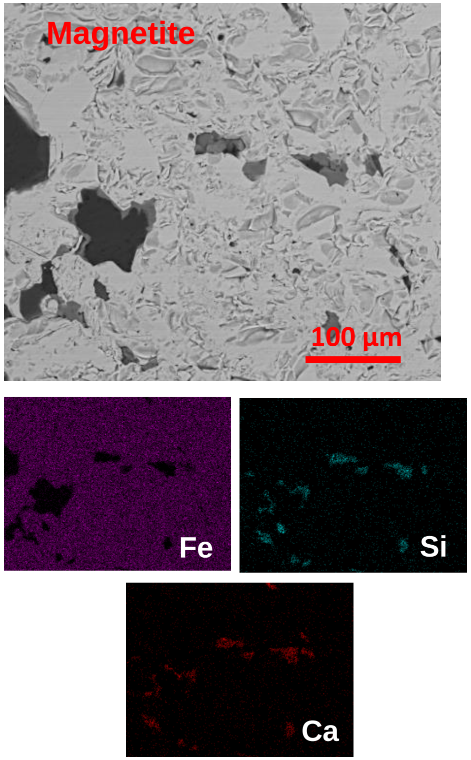
| Material | Element (wt.%) | | | | | |
|---|---|---|---|---|---|---|
| | Al | Ca | Fe | Mg | Si | Mn |
| **BOF-Slag** | 1.2 | **26.6** | **20.9** | 3.7 | **8.3** | 3.6 |
| **Magnetite** | 0.2 | 2.1 | **57.5** | 0.2 | 1.0 | 0.1 |
| **River Rock** | **3.44** | **23.5** | 1.6 | 1.1 | **11.3** | - |

SEM & EDX analyses

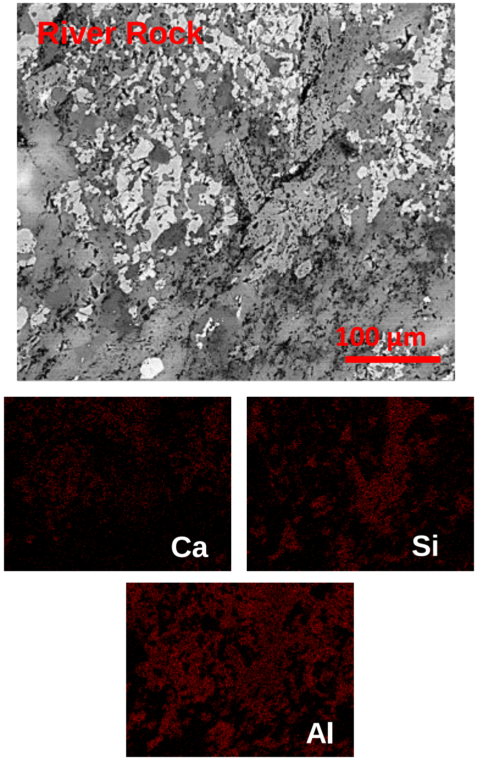
**multi-phases**




**mono-phase**




**multi-phases**

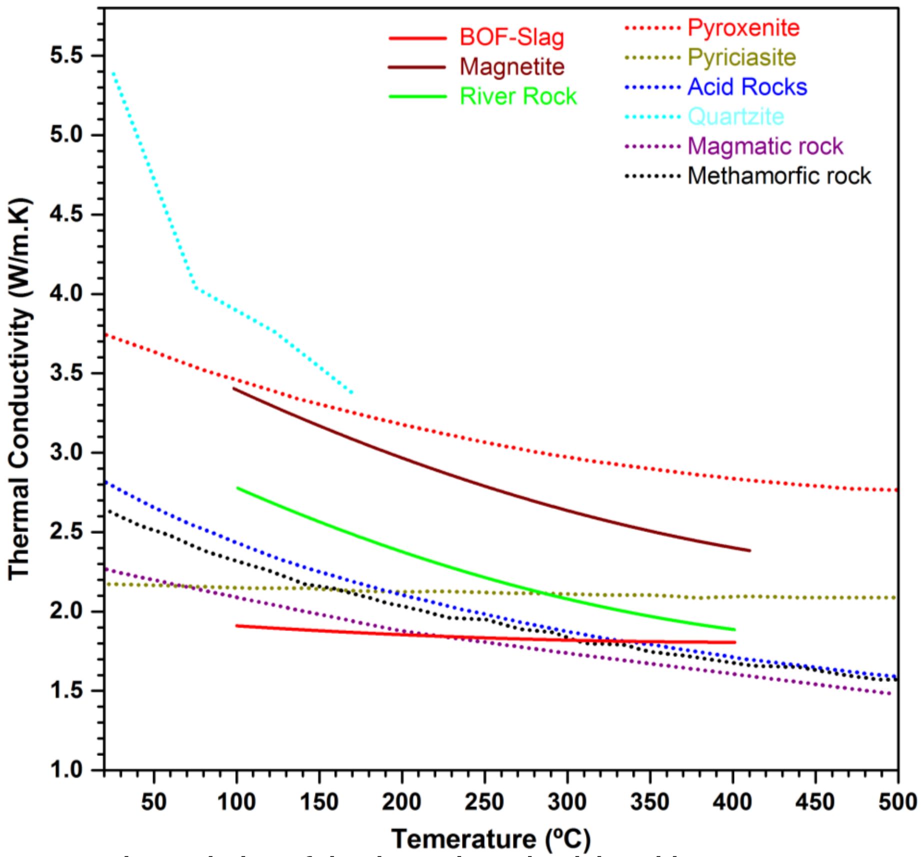


# Thermophysical properties

## Thermal conductivity

➢ **The thermal conductivity at 100ºC is around 1.9, 2.8 and 3.4 W/m.K for BOF-Slag, River rock and Magnetite, respectively.**

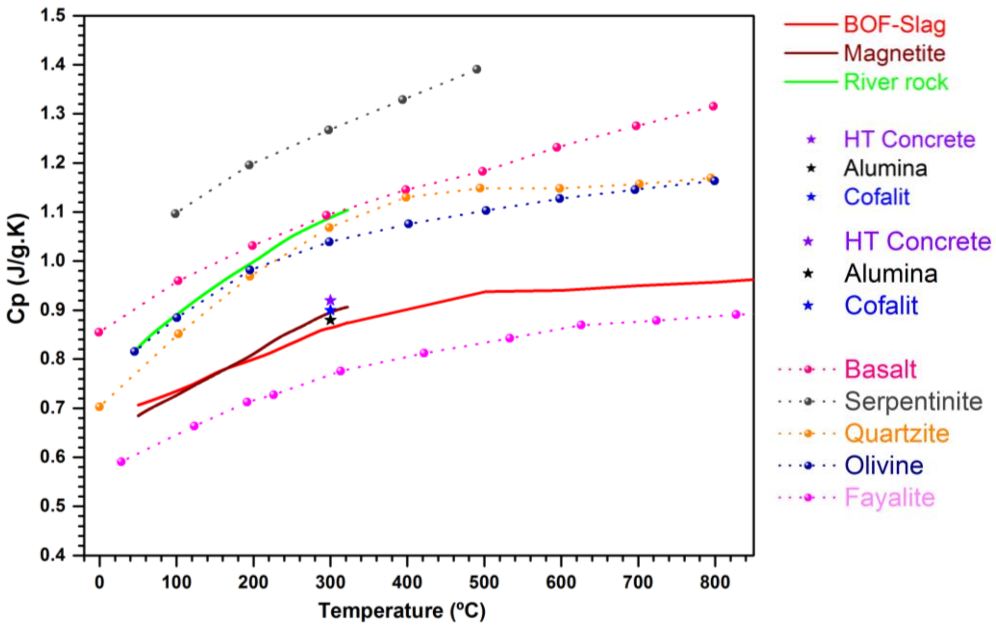
➢ **Slight decrease with temperature is obtained.**




*The evolution of the thermal conductivity with temperature*

# Thermophysical properties

## Specific heat $C_p$




*Specific Heat Cp of BOF-Slag, Magnetite and River rock*

| Material | ρ(kg/m³) | Cp(J/g.K) | Volumetric Storage Capacity (KJ/m³.K) |
|---|---|---|---|
| BOF-Slag | 3806 | 0.91 | 3446 |
| Magnetite | **4962** | 0.89 | **4416** |
| River rock | 2616 | **1.08** | 2825 |
| Alumina | 3953 | 0.88 | 3478 |
| Cofalit | 3120 | 0.90 | 2808 |
| HT Concrete | 2250 | 0.92 | 2070 |

# Mechanical properties

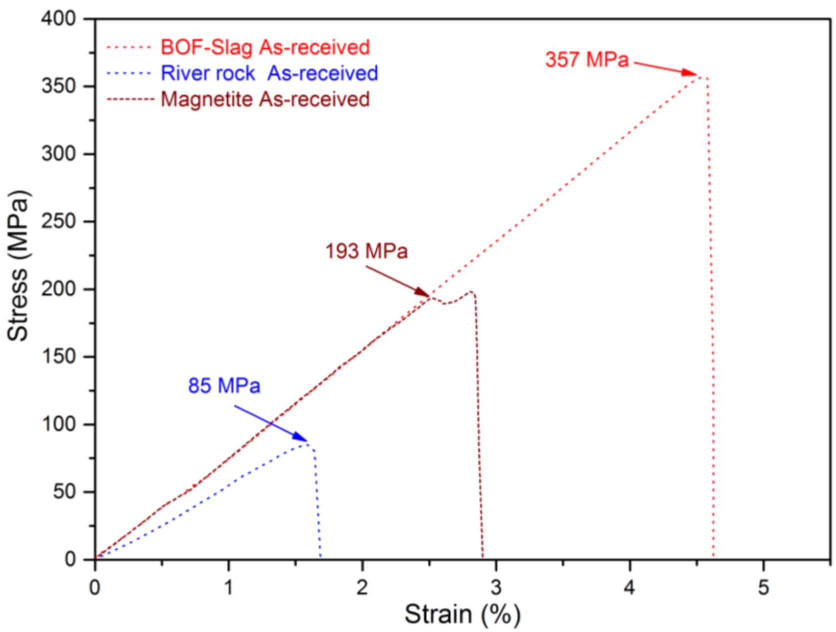
## Compressive Strength

- The compression tests were carried out using a test speed of **3 mm/min** and load cell of **100 KN**.
- The compressive yield strength (σ) was calculated by:

$$\sigma = {}^{F}/_{A}$$

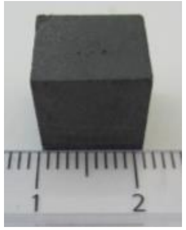
F: Load at yield,
A: Cross-section area.

- The maximum compressive strength at RT are 357, 193 and 85 MPa for BOF-Slag, Magnetite and River rock, respectively.




| | BOF-Slag | Magnetite | River rock |
|---|---|---|---|
| Compressive Strength (MPa) | 357 | 193 | 85 |

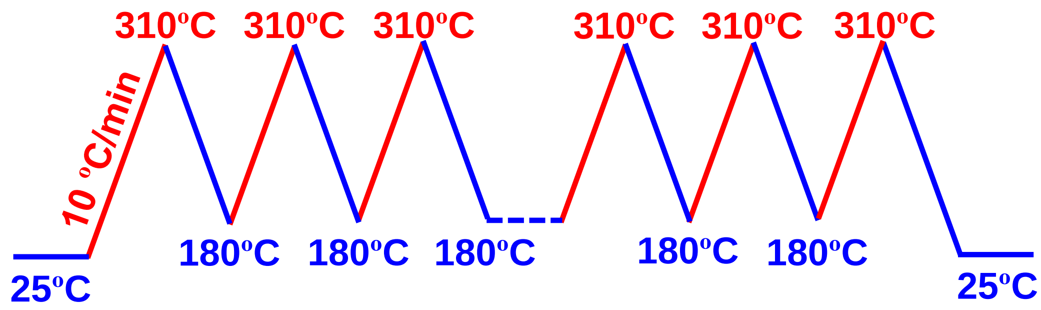
10x10x10 mm.



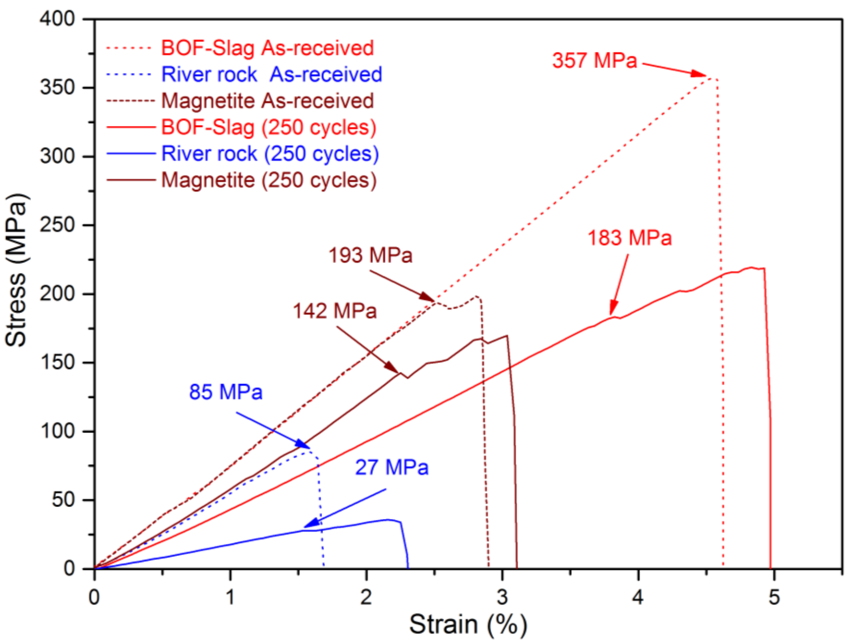
# Mechanical properties

## Compressive Strength

Compressive Strength after thermal cycling




250-1000 cycles

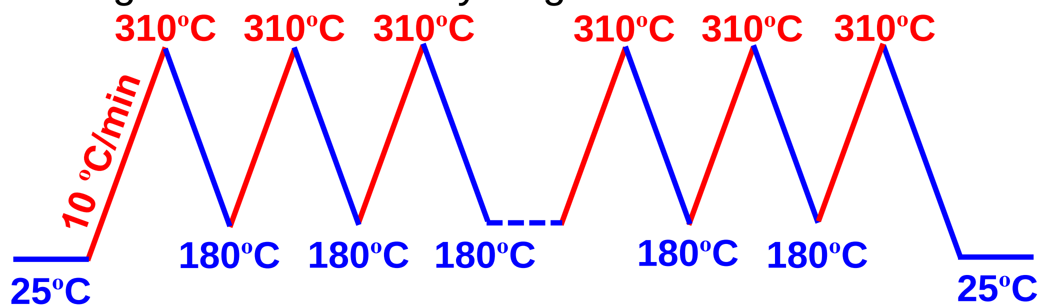



| | | BOF-Slag | Magnetite | River rock |
|---|---|---|---|---|
| Compressive Strength (MPa) | As-received | 357 | 157 | 85 |
| | After 250 cycles | 183 | 142 | 27 |
| Decrease | | 48% | 9% | 62% |

# Mechanical properties

## Compressive Strength

Compressive Strength after thermal cycling

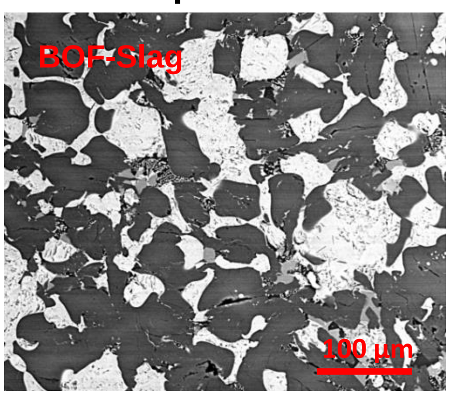



250-1000 cycles

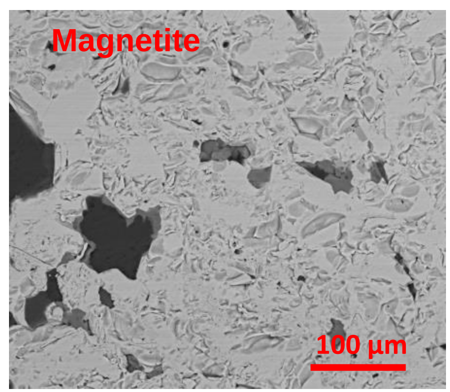
The reasons:

- The gradient of the temperature due to the limited thermal conductivity,
- The multi-phases constitutions with different thermal expansion coefficients.

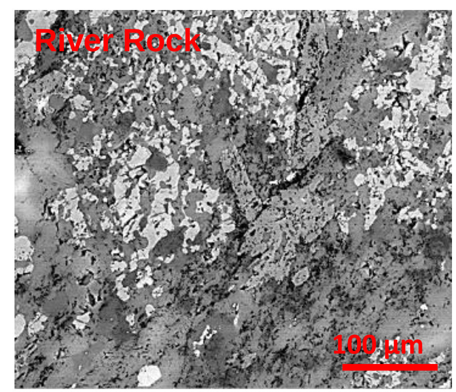
**multi-phases**




**mono-phase**




**multi-phases**



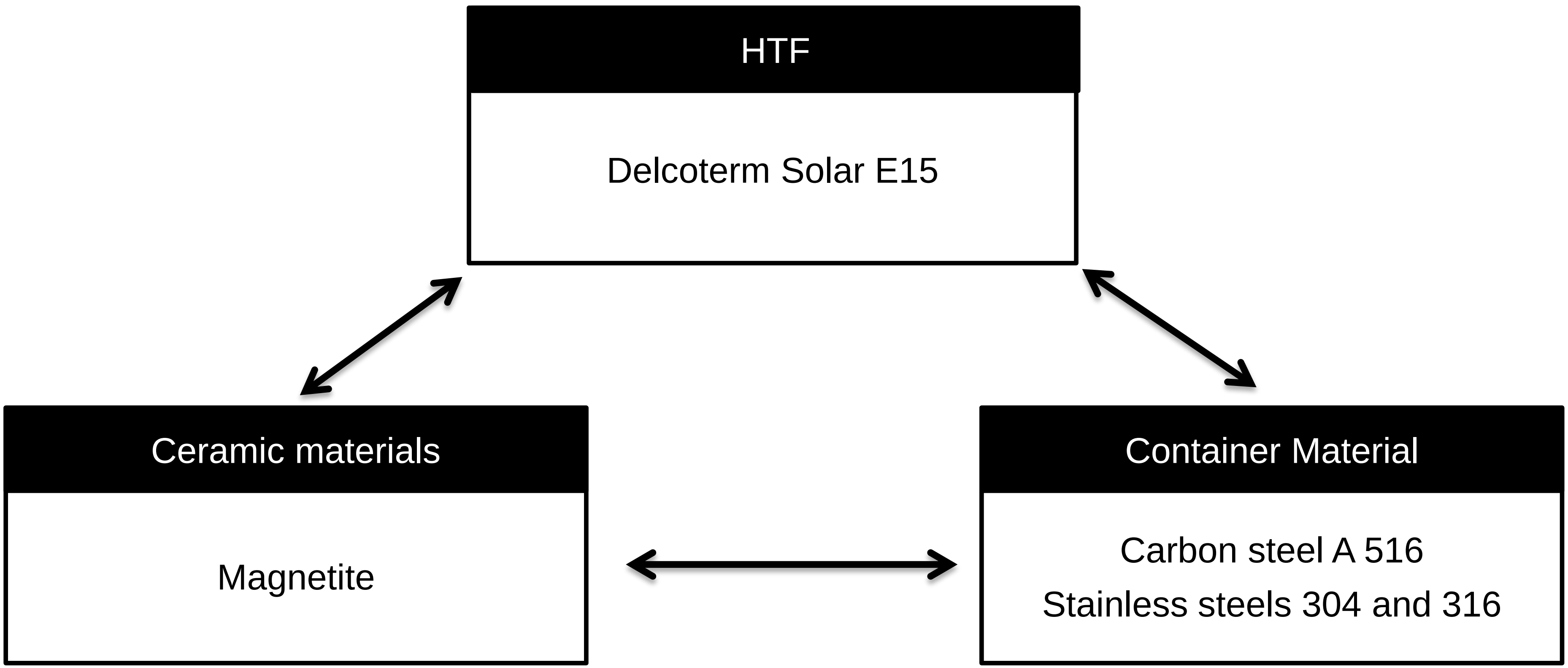

***SEM images of BOF-Slag, Magnetite and River rock***

The magnetite presents high thermal conductivity and mono-phase constitution which may responsible of its good thermomechanical behaviour.

# Corrosion & compatibility study

## Systems and conditions

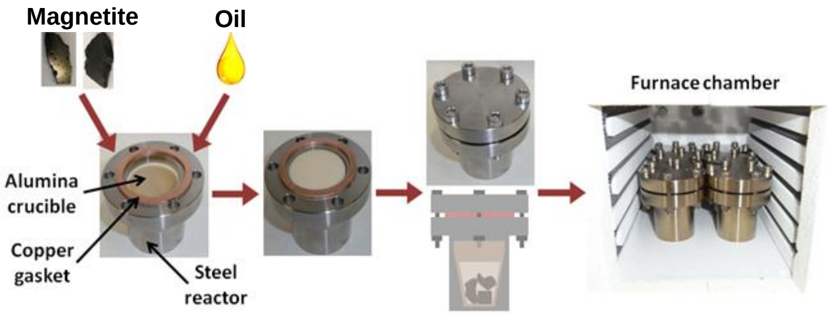
- Isothermal mode: at 310 ºC for 500h, 1000, 1500 and 3000 hours
- Cycling mode: between 180ºC and 310ºC with heating rate of 10ºC.min-1
- Time: 500, 1000, 1500 and 3000 hours



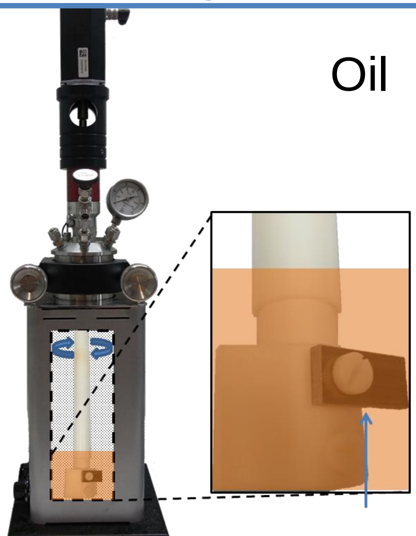
# Corrosion & compatibility study

## Methods

### Static

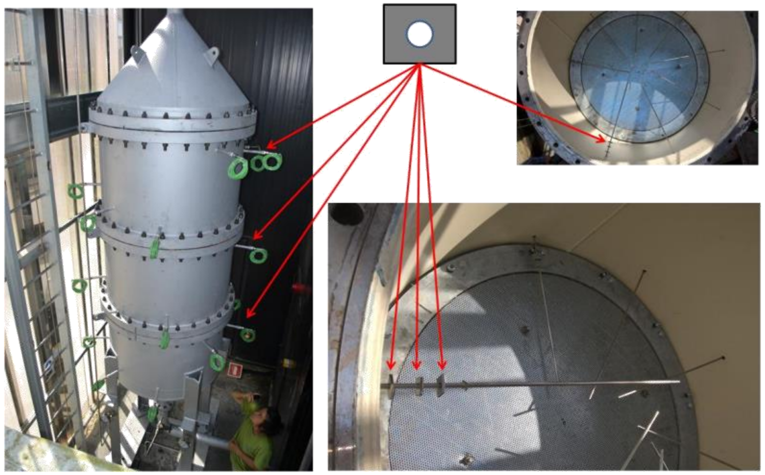



### Dynamic




**High-pressure reactor**

### In-situ

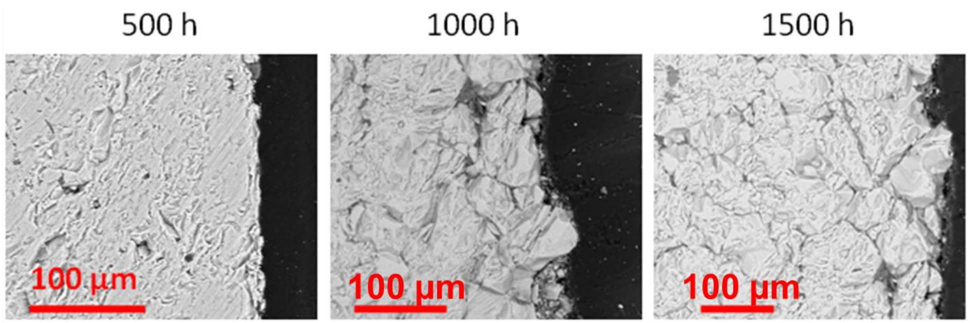


# Corrosion & compatibility study

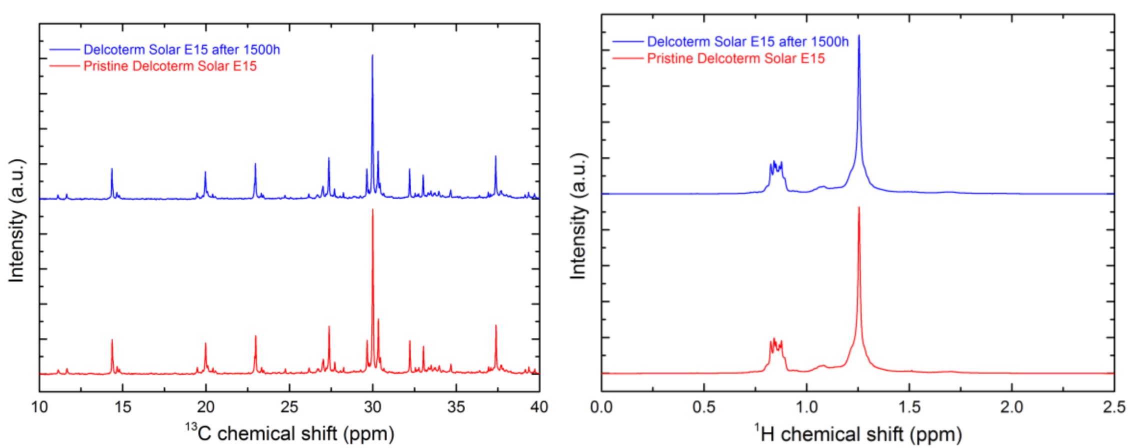
## Results: Magnetite + Delcoterm Solar E15 Oil at 310ºC

- **Magnetite: no significant modifications were detected**
- **Oil: no structural changes and no thermophysical properties modifications were observed**

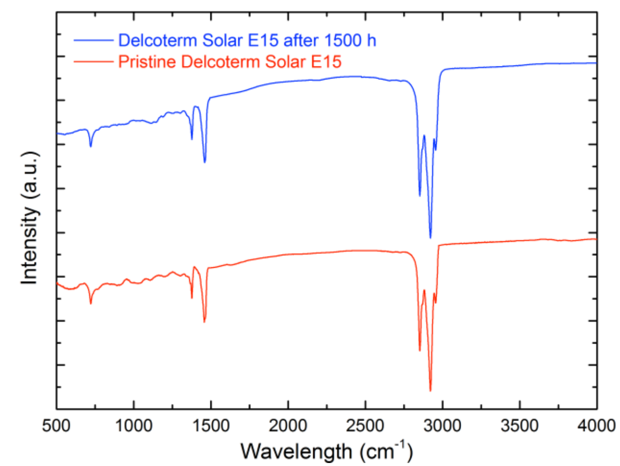
➯ **The Magnetite and Delco Term oil are fully compatible to operate in direct contact up to 310ºC**




**SEM cross section images of the Magnetite after 500,1000 and 1500 hours of direct contact with Delcoterm E15 oil**




**13C and1H liquid state NMR spectra of the pristine and 1500 hours tested Delcoterm E15oil.**




**FTIR spectra of the pristine and 1500 hours tested *Delcoterm E15* oil.**

# Conclusions

The **Magnetite** is very promising material:

- **High volumetric** energy storage capacities: **4416 kJ/m$^3$.K**,
- High values of the **thermal conductivity**: **>2.5 W/m.K**,
- Good **thermo-stability** in the operation temperature range,
- **Good mechanical** properties of **as-received materials** at room temperature.
- **Good thermo-mechanical** stability up to 250 cycles in the operation temperature range
- **Fully compatible** with the HTF (DelcoTem Oil) in the operation temperature range.

This material can be considered as the most promising candidate for effective thermal energy storage.

# Perspectives

**Design, realization and commissioning of the trial TES system**

The construction of the system based on Magnetite pebbles as storage media is already constructed and under testing.

- Useful volume for storage: 2.07 $m^3$
- Aspect ratio = 2 (H/D)
- Useful dimensions: D=1.097 m & H =2.194 m
- Void fraction = 0.37

**<u>Storage material: Magnetite</u>**

Density: 4962 kg/$m^3$
Mass: 6468 kg
Cp:0.85 J/g.K
$\Delta T$=120 K
Energy stored in Magnetite: 119 kWh

**<u>Oil:</u>**

Density: 675 kg/$m^3$
Cp: 2.68 kJ/(kg.K)
Energy stored in the oil: 80 kWh

**TOTAL: 199 $kWh_{th}$**

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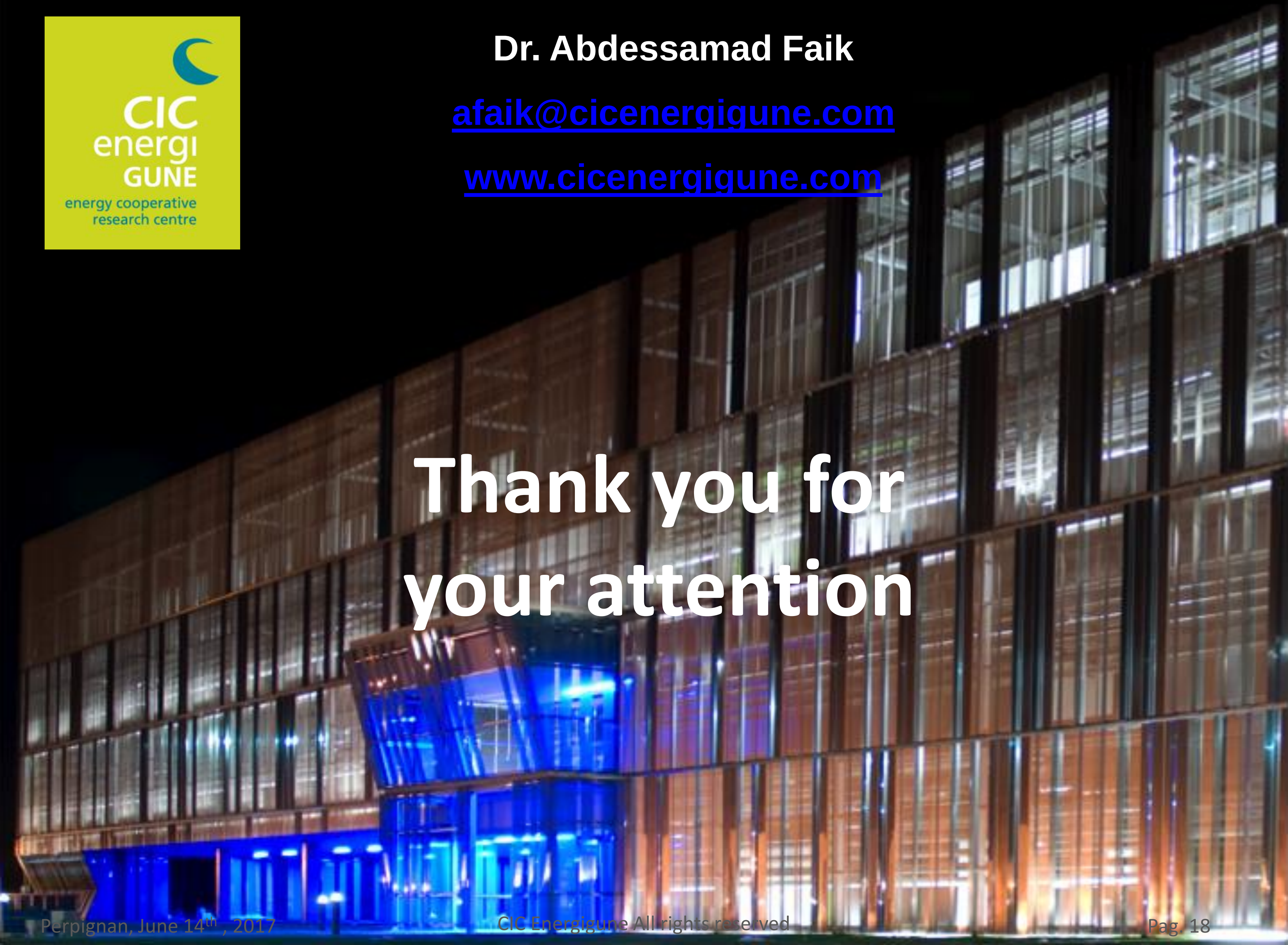

# Thank you for your attention