Components' and Materials' Performance for Advanced Solar Supercritical CO_2 Powerplants

COMPASsCO$_2$

General Project Presentation

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German Aerospace Center (DLR)

sCO2-Flex Final Event
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This project has received funding from the European Union's Horizon 2020 Research and Innovation Action (RIA) under grant agreement No. **958418.**

Presentation Structure

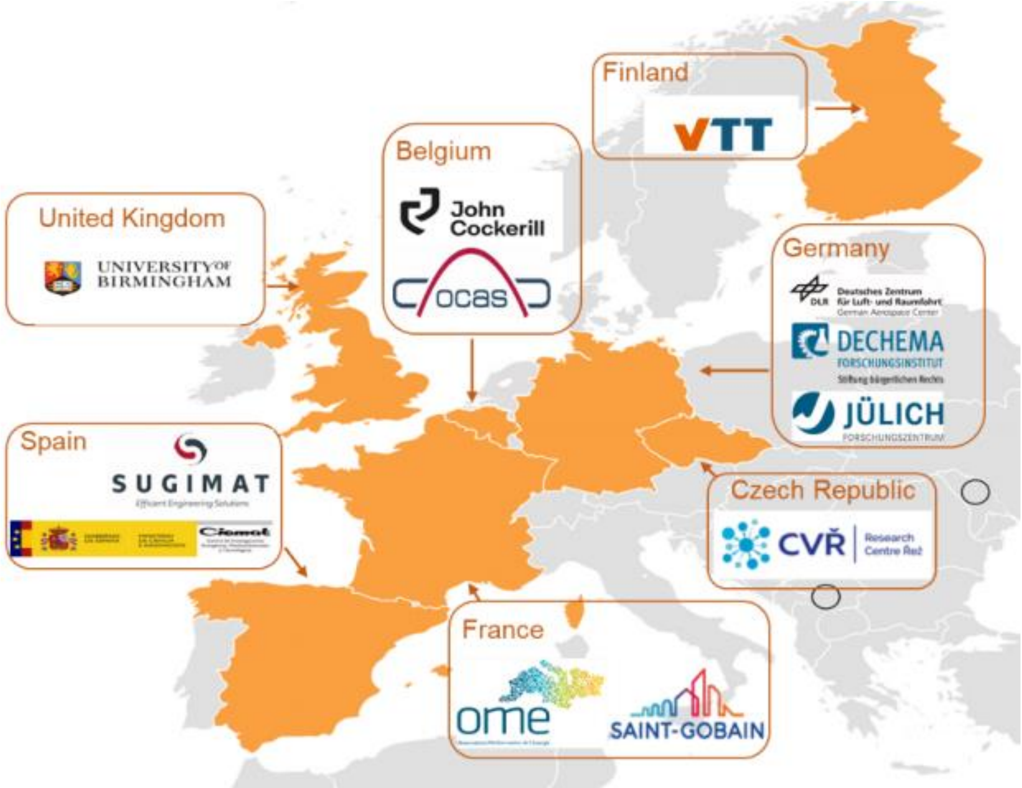
- About COMPASsCO2
- Technical Description
- Current results
- Cooperation potential

About COMPASsCO2

The project “**Components’ and Materials’ Performance for Advanced Solar Supercritical CO2 Powerplants**” is funded by the EU’s H2020 Research and Innovation Action supported by the “Sustainable Process Industry through Resources an Energy Efficiency” [(spire2030.eu)](spire2030.eu) association.

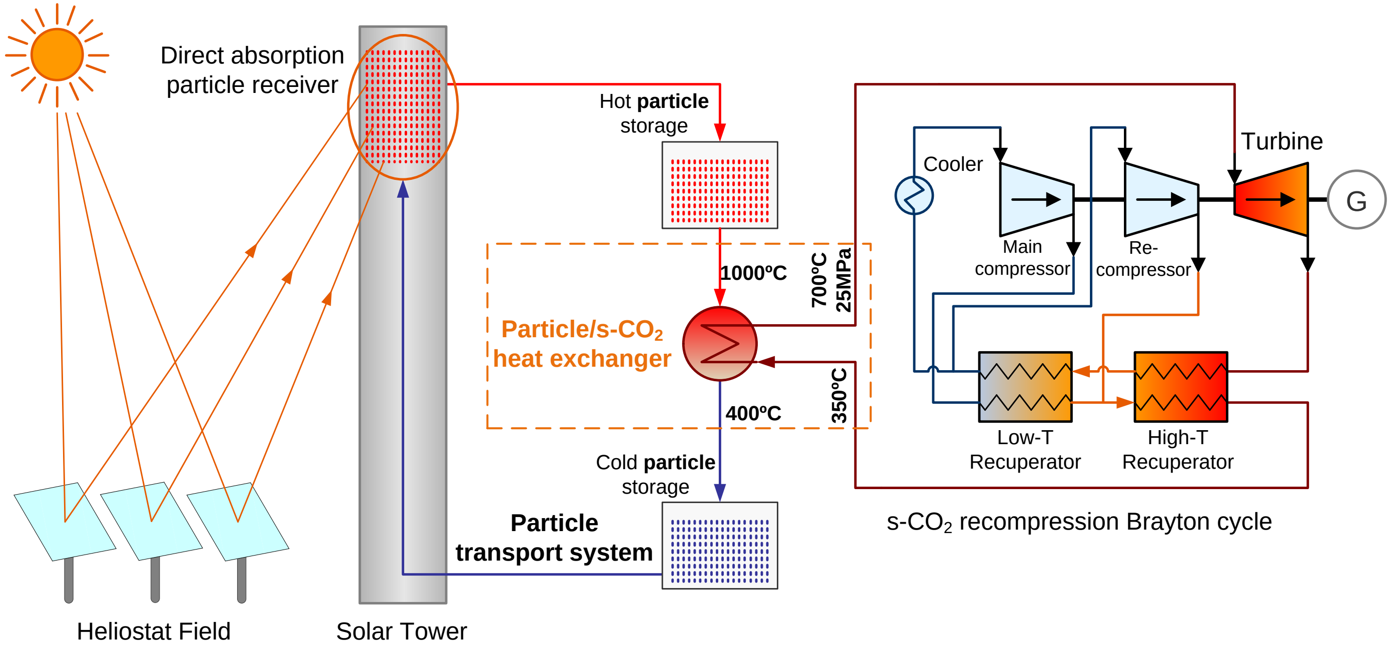
Project start: November 2020

Duration: 4 years



About COMPASsCO2

The main goal is to integrate two innovative systems:
CSP plants with particles and sCO2 Brayton power cycles



→ Project's focus is development of materials under harsh conditions

Project Objectives

- Develop highly durable and efficient particles for CSP plants
- Develop optimized structural materials for heat exchanger tubes in contact with particles and sCO2
- Demonstrate material lifetime by measuring and modeling the degradation of the materials
- Design, construct and operate a particle/sCO2 heat exchanger section in order to validate the degradation and heat transfer models
- Evaluate the economic benefits of a CSP-sCO2 plant using the materials and components developed in COMPASsCO2 and compare it with state-of-the-art CSP plants

Brayton cycle selection – Approach

1) Literature study to identify most suitable sCO2 cycle and process parameters
   - Non-conclusive (see Del1.1)

2) Simplified annual yield model to estimate levelized cost of electricity for a large number of sCO_2 cycle configurations
   - 10 cycle layouts
   - 6 parameters

sCO2 cycles
01_simple
02_simple_RH
03_simple_IC
04_simple_RH_IC
05_recomp
06_recomp_RH
07_recomp_IC
08_recomp_RH_IC
09_partC_RH_IC
10_partC_IC

Parameter	Unit	Range
Turbine inlet temperature	[°C]	550…700
Compressor inlet pressure	[bar]	45…100
Recuperator TTD	[K]	5…
$(U*A)_{cooler/IC}$	$[MW_{th}/K]$	…18
Recompression fraction	[%]	25…44
TTD PHX,high-pressure	[K]	5…300

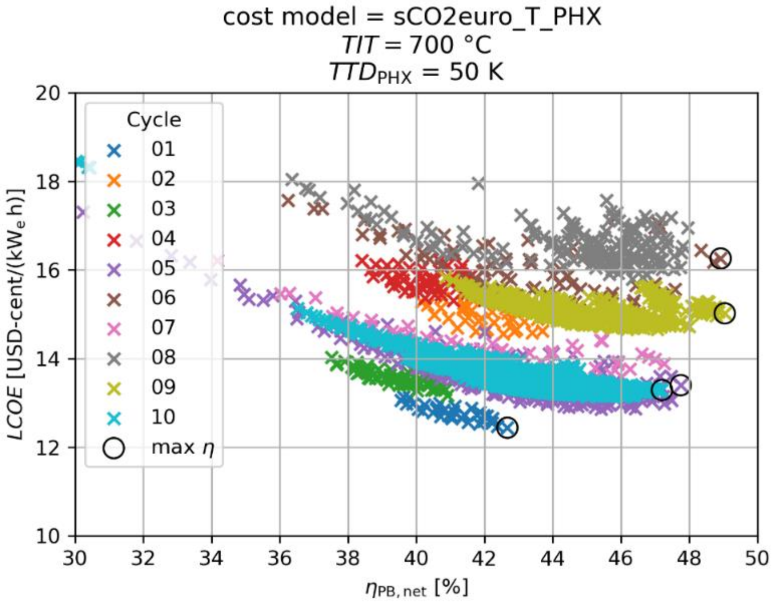
RH: reheat
IC: intercooler
partC: partial cooling

TTD: terminal temperature difference
*U*A*: conductance-area product
PHX: primary heat exchanger

[1] Heller, L., S. Glos and R. Buck (2021)

Brayton cycle selection – Results

sCO2 cycles
01_simple
02_simple_RH
03_simple_IC
04_simple_RH_IC
05_recomp
06_recomp_RH
07_recomp_IC
08_recomp_RH_IC
09_partC_RH_IC
10_partC_IC



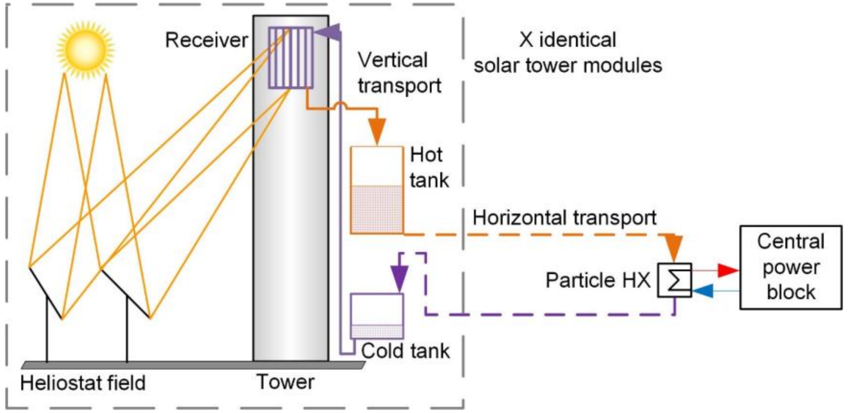
Cycle	*LCOE* [USD-cent/kWe h]	$\eta_{PB,net}$ [%]	$T_{PHX,sCO2,in}$ [°C]	$T_{PHX,sCO2,in,RH}$ [°C]
01	12.4	42.7	442	-
05	13.4	47.8	504	-
06	16.3	48.9	577	620
09	15.0	49.0	533	583
10	13.3	47.2	438	493

Parameter	Unit	Value
Pre-compressor inlet pressure	[bar]	45
Main compressor inlet pressure	[bar]	80
Recuperator TTD	[K]	5
Pre-cooler U*A	[MW_{th}/K]	3.5
Intercooler U*A	[MW_{th}/K]	6.2
Recompression fraction	[%]	44

COMPASsCO2 focuses on an increased thermal efficiency and on lowering the cost of high-temperature, high-efficiency systems.

Solar particle loop- Boundary conditions

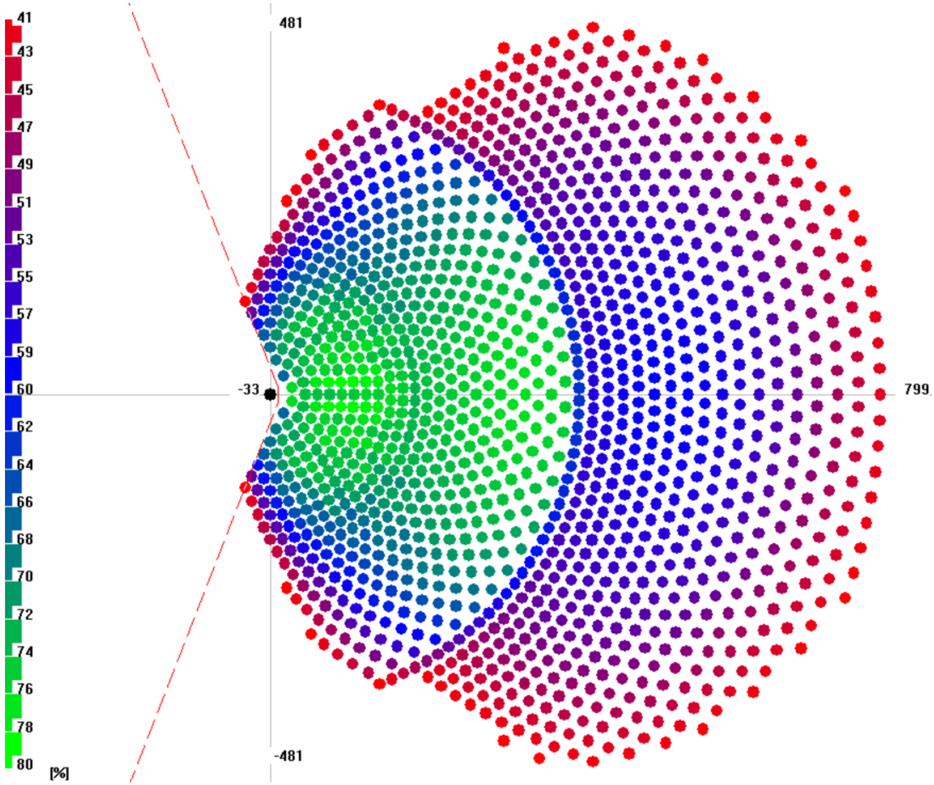
Parameter	Value	Comment [Source]
Location	Postmasburg, South Africa	Good solar resource
Power block net rating	112.8 MW_e	Based on cycle chosen in Deliverable 1.1
Particle inlet temperature to the HX	900 °C	
Max. particle temperature	~1000 °C	Due to inhomogeneous temperature distribution
Receiver thermal power @ design point	96.23 MW_t	Per unit
Number of towers and receivers	6	multi-tower system
Thermal storage capacity	12 h	hours of discharging at full load



Solar particle loop - Field optimization

LCOE-optimized solar field design

Parameter	Unit	Value
Height of receiver center above ground	[m]	133.6
Heliostat aperture area (per tower)	[m^2]	170 000
Particle inventory (per tower)	[t]	5172
Field efficiency, annual average	[-]	54.2 %
Receiver efficiency, annual average	[-]	87.4 %



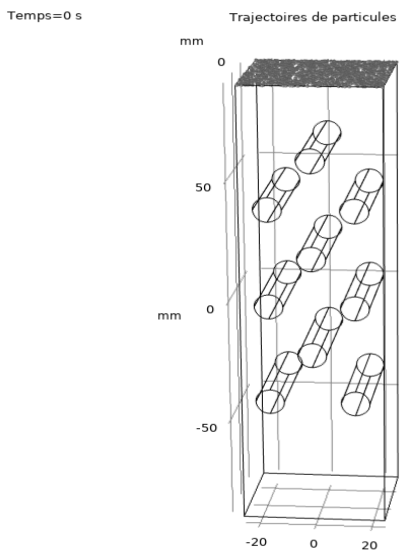
Heliostat field layout showing average annual efficiency per heliostat (color code)

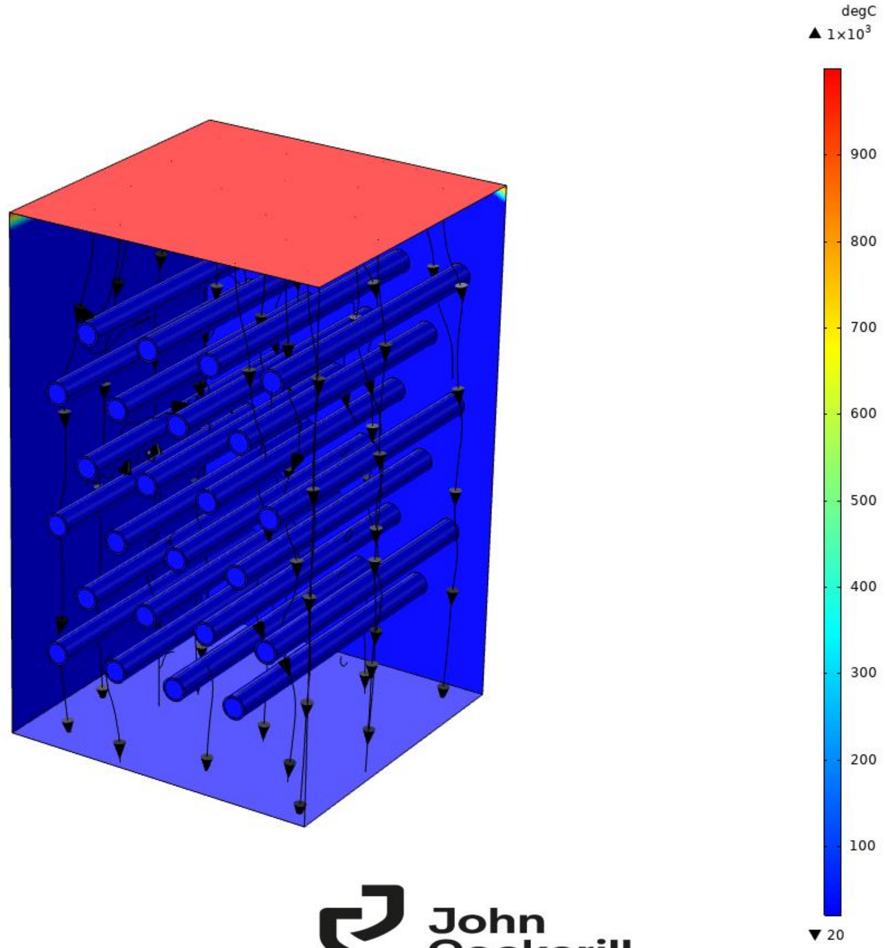
dp: design point

Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center

Preliminary particle heat exchanger design

- Principle → moving bed of hot particles crossing bundles of horizontal tubes containing sCO_2
- Simulations performed with Comsol Multiphysics



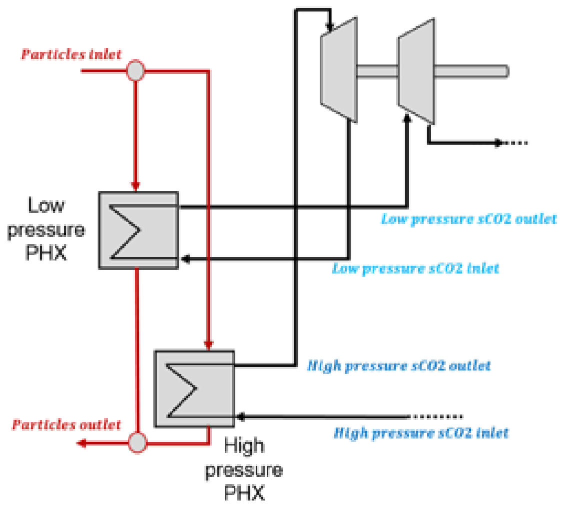


John Cockerill

Preliminary particle heat exchanger design

- Different alloys were considered for the tubes

- Calculations based on the ASME code highlighted two alloys to withstand the operating conditions ($P_{sCO_2} = 265\ bars$ and $T_{\mathrm{tube,avg}} = 725°C$)
  - Alloy 740
  - Haynes 282

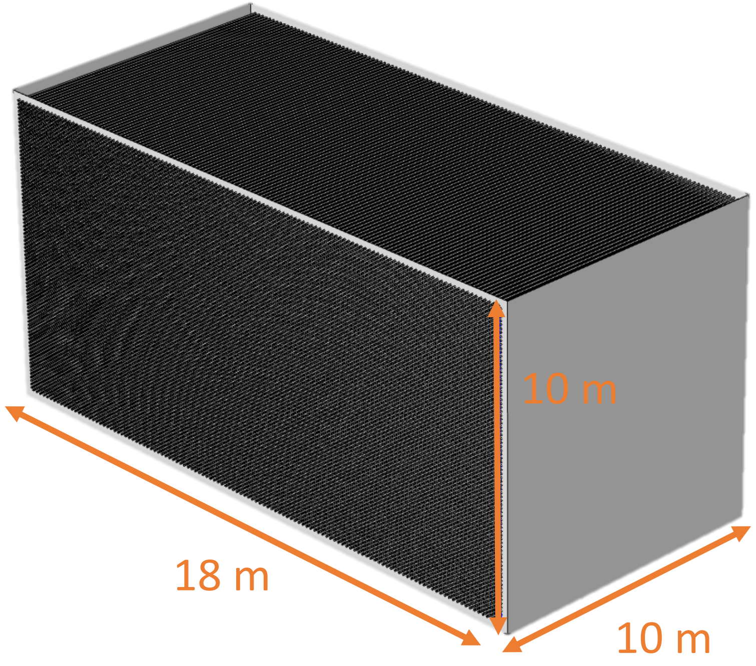


Parameters	Particles (high pressure PHX)	Particles (low pressure PHX)	sCO2 (high pressure PHX)	sCO2 (low pressure PHX)
Inlet temperature [°C]	900	900	532.8	583.4
Outlet temperature [°C]	582.8	633.4	700	700
Inlet pressure [bar]	/	/	265.3	110.4
Outlet pressure [bar]	/	/	260	108.2
Mass flowrate [kg/s]	355.9	288.3	632.6	632.6

Preliminary particle heat exchanger design

- The main geometric variables of the HEX were calculated

Design parameter	Unit	High pressure PHX	Low pressure PHX
Tube external diameter	[mm]	30.8	30.8
Tube wall thickness	[mm]	2.6	2.6
Number of tubes in parallel	[-]	208	500
Tube length per row	[m]	10	4
Number of rows	[-]	33	22



- 66.5 tons of 30.8mm diameter tubes made of alloy 740

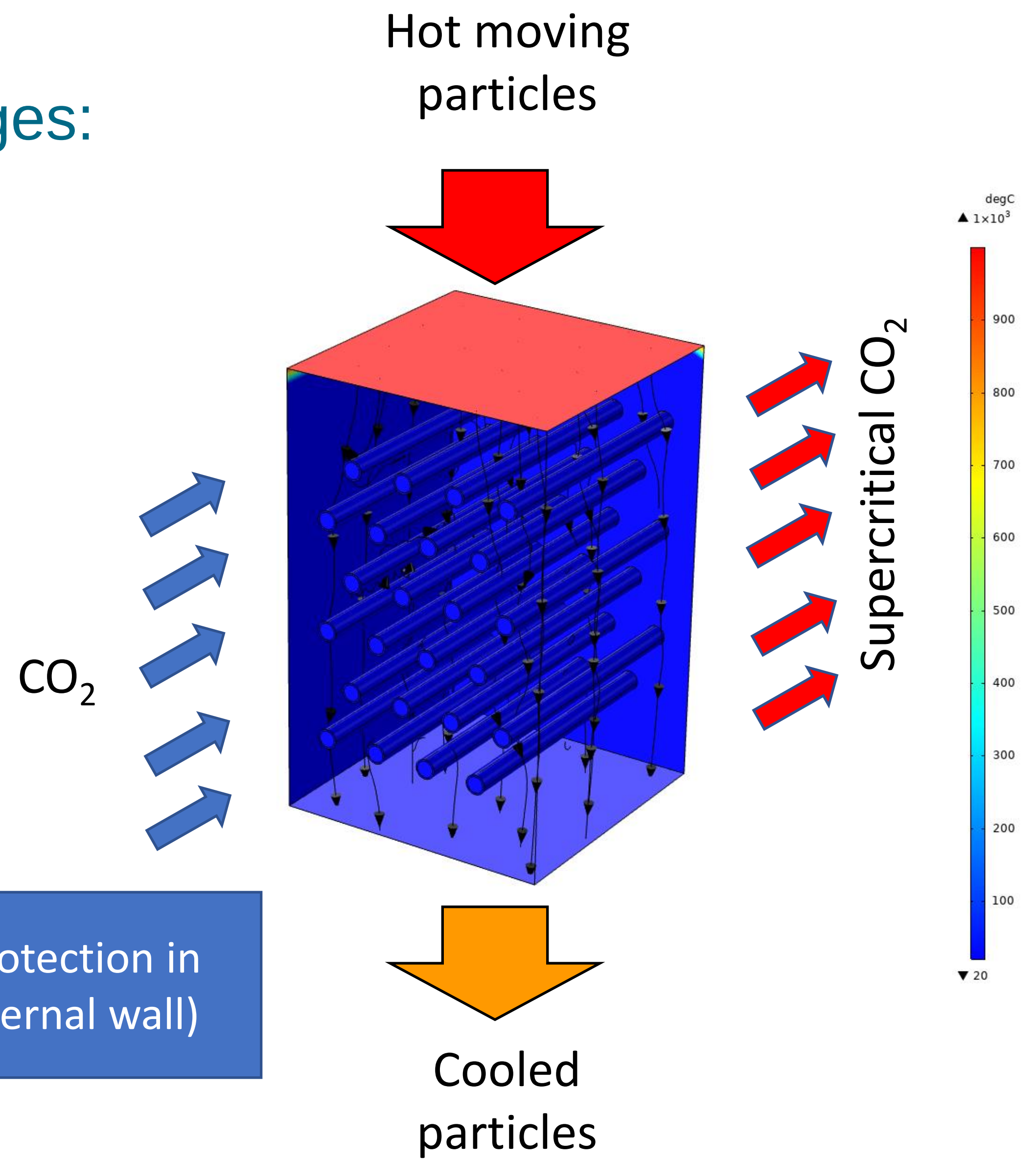
Heat Exchanger's tubes

Particles and sCO2 give us several challenges:

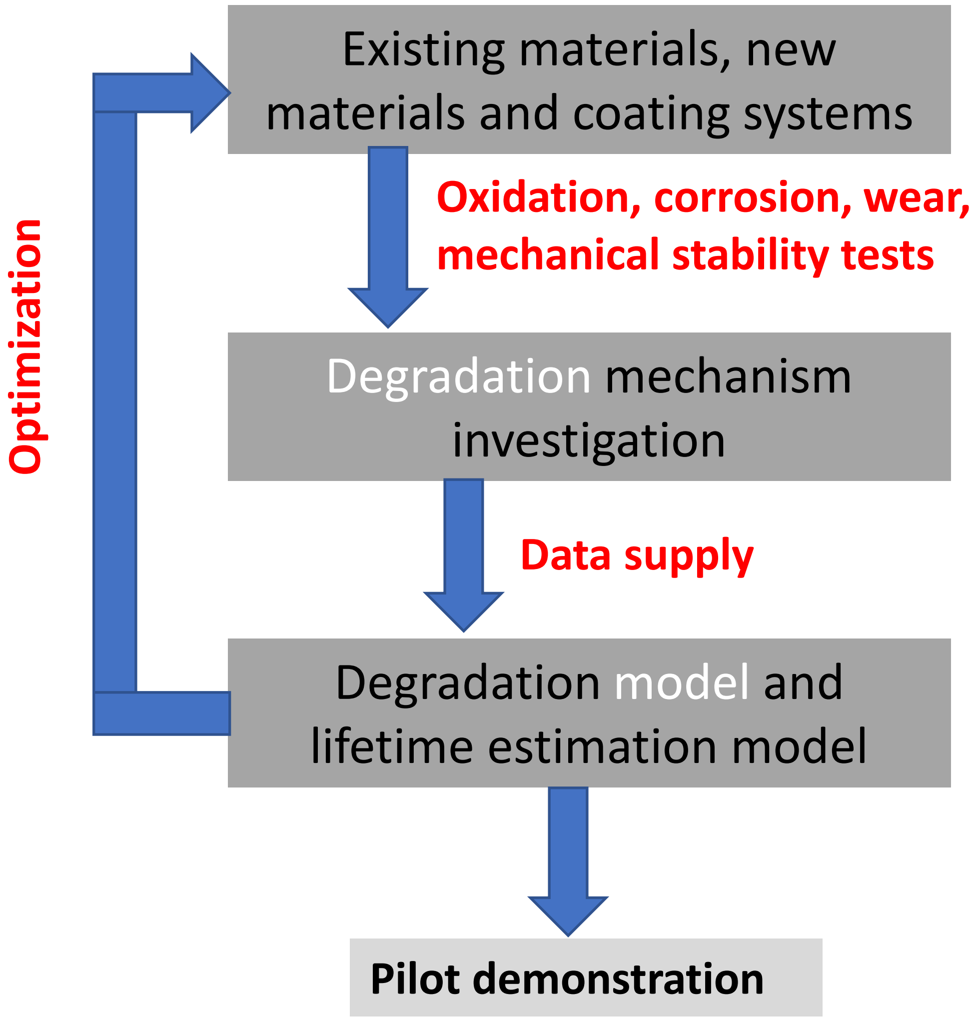
Mechanical stability in supercritical conditions (inner wall)

Corrosion protection in supercritical conditions (inner wall)

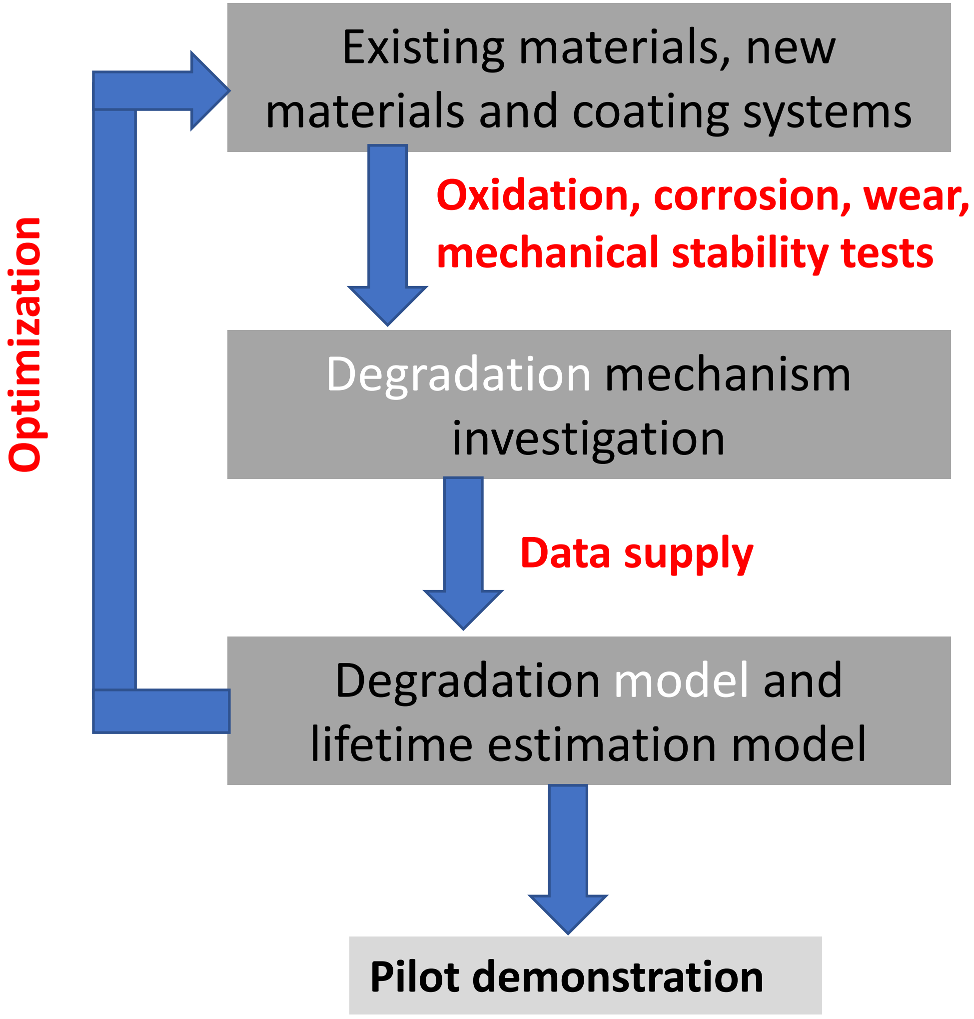
Erosion and oxidation protection in oxidative conditions (external wall)



Heat Exchanger's tubes - Methodology



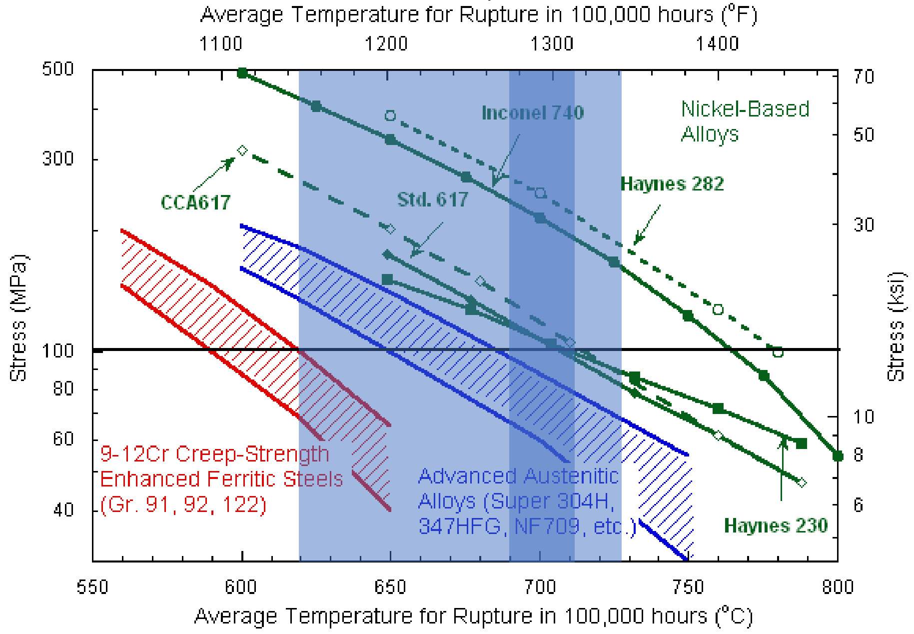
Heat Exchanger’s tubes

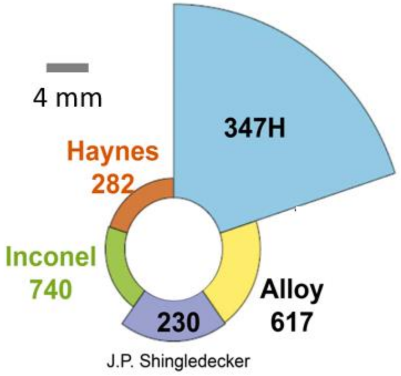


Mechanical properties

700°C Haynes 282, IN 740

650°C IN 617, Sanicro 25



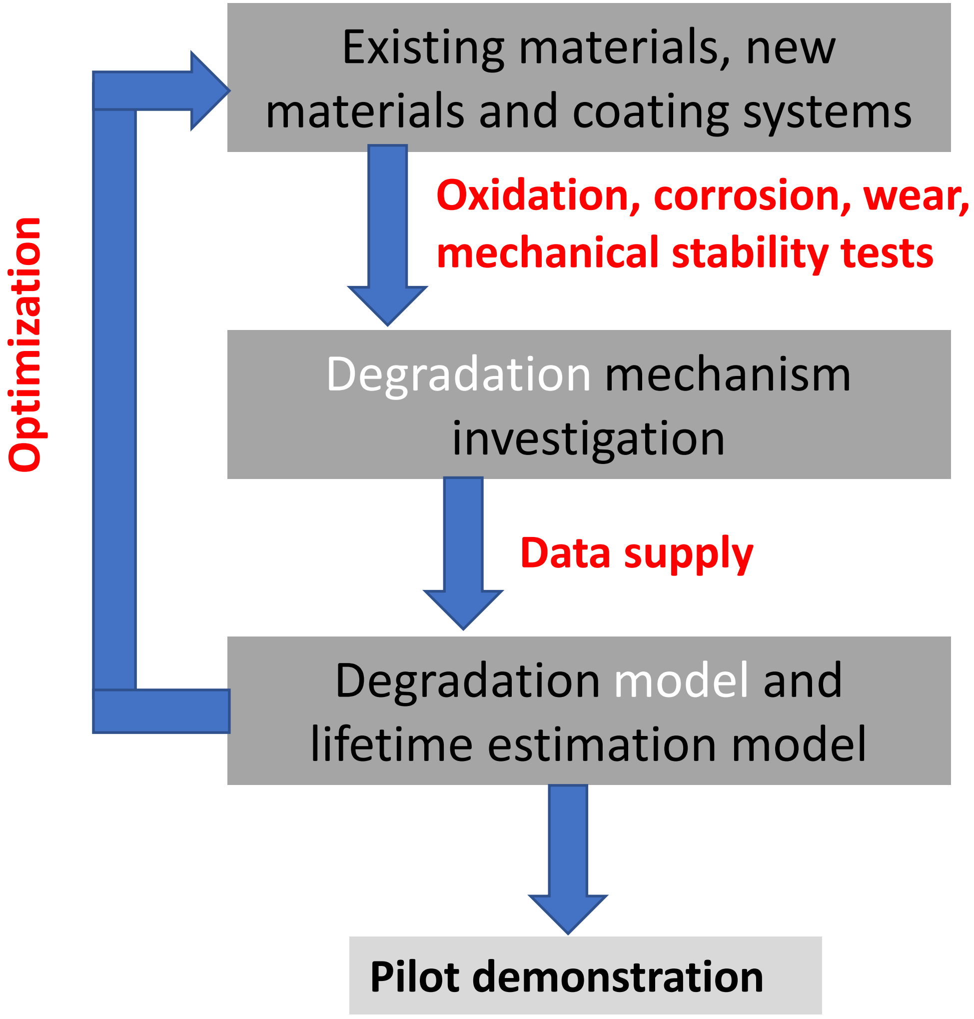


Wall thickness calculated for sCO2 at 760°C and 34.5 MPa

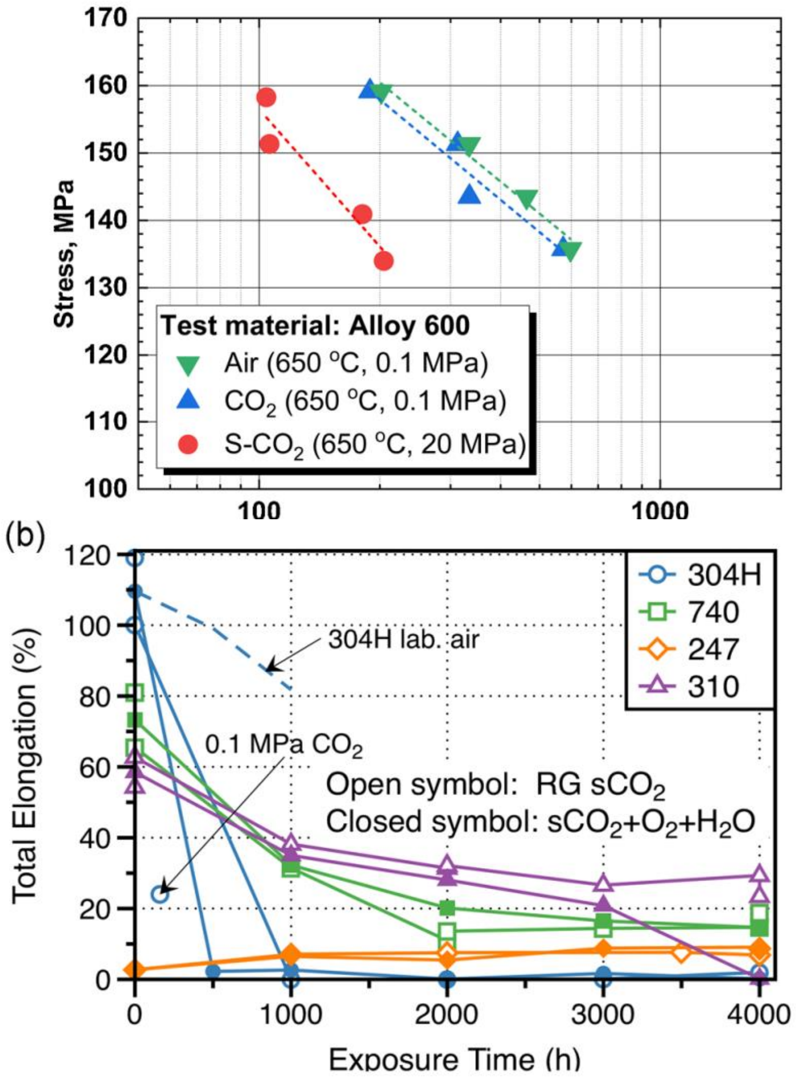
Clifford K. Ho et al “Evaluation of Alternative Designs for a High Temperature Particle-to-sCO2 Heat Exchanger” Journal of Solar Energy Engineering APRIL 2019, Vol. 141
Clifford K. Ho, Sandia National Laboratories «*High-Temperature Particle Heat Exchanger for sCO2 Power Cycles”* SAND2016-3639PE https://www.osti.gov/servlets/purl/1365201

John A. Siefert, Cara Libby, and John Shingledecker, “Concentrating solar power (CSP) power cycle improvements through application of advanced materials, AIP Conference Proceedings” 1734, 070030 (2016); https://doi.org/10.1063/1.4949177

Heat Exchanger’s tubes



Corrosion+ mechanical degradation combined



Heat Exchanger’s tubes

Corrosion (due to pressure and thermic cycles)

Optimization

Existing materials, new materials and coating systems

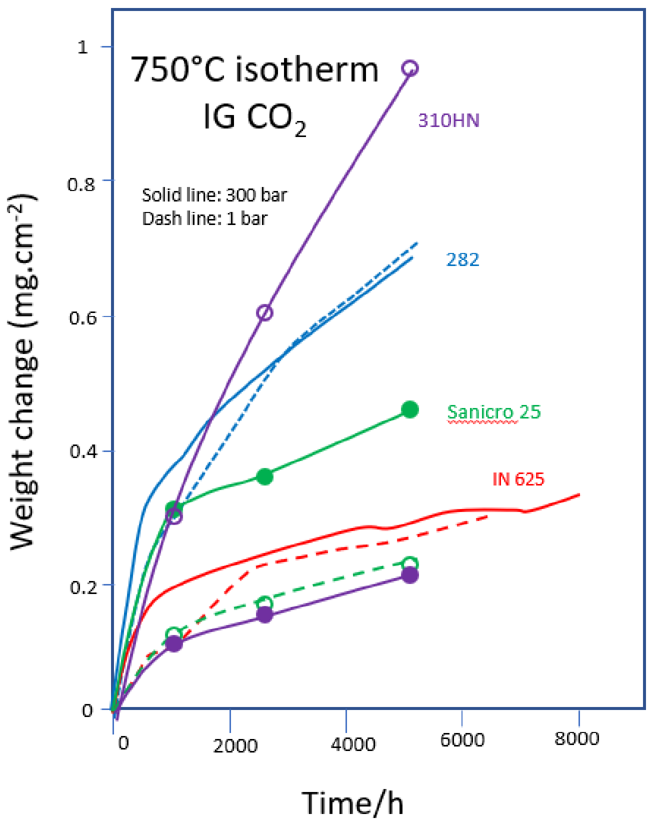
Oxidation, corrosion, wear, mechanical stability tests

Degradation mechanism investigation

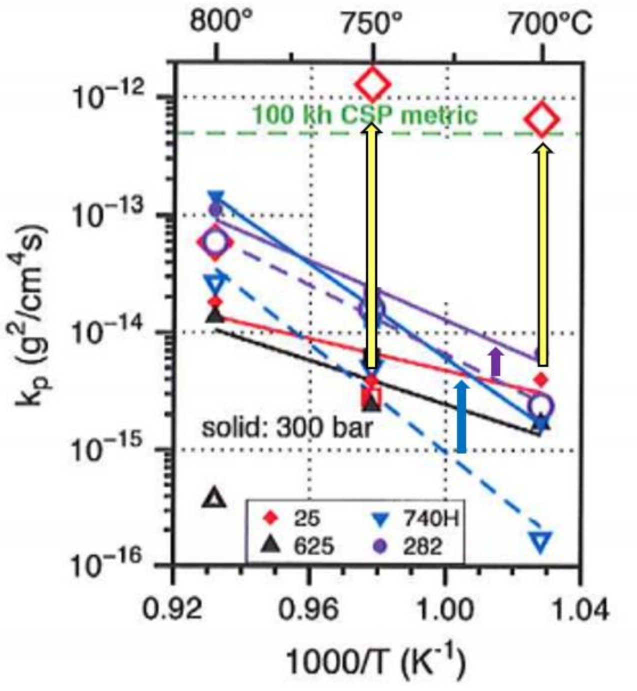
Data supply

Degradation model and lifetime estimation model

Pilot demonstration



B.A. Pint, J. Lehmusto, M.J. Lance, J.R. Keiser, “Effect of pressure and impurities on oxidation in supercritical CO_2”, Materials and Corrosion 70 (2019) 1400–1409



B.A. Pint, K.A. Unocic, „The Effect of CO_2 on Chromia Scale microstructure at 750°C“, JOM 70 (8) 2018 https://doi.org/10.1007/s11837-018-2963-4

Heat Exchanger’s tubes

Existing materials, new materials and coating systems

Oxidation, corrosion, wear, mechanical stability tests

Degradation mechanism investigation

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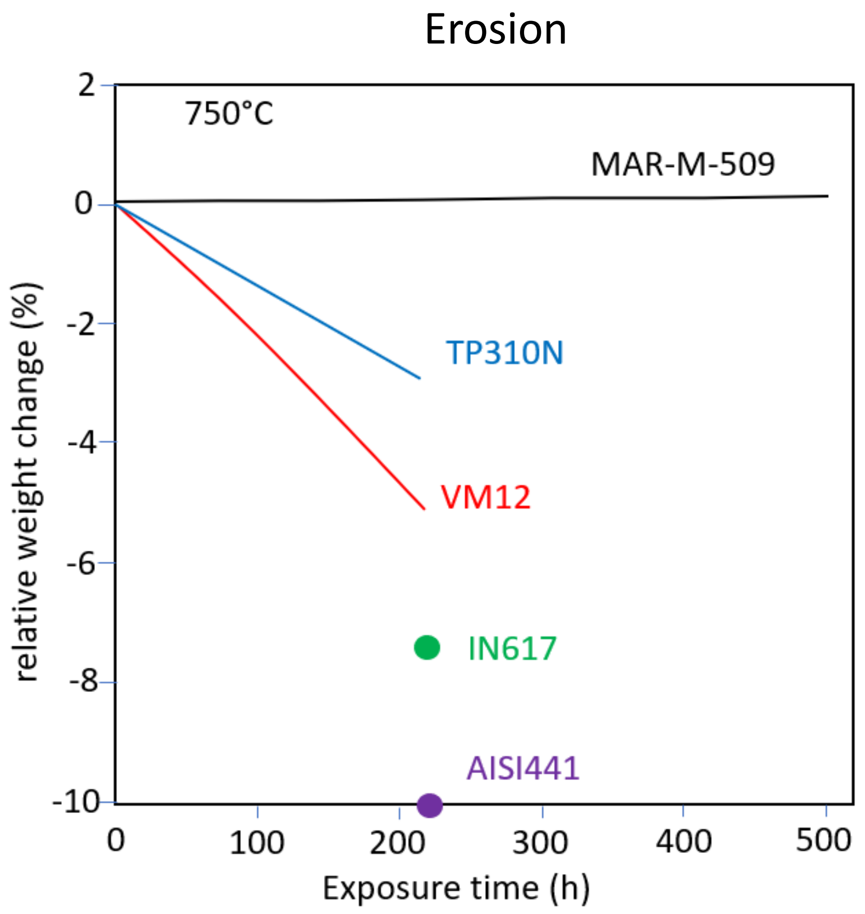
Pilot demonstration

Optimization



T. Galiullin, B. Gobereit, D. Naumenko, R. Buck, L. Amsbeck, M. Neises-von Puttkamer, W.J. Quadakkers, „High temperature oxidation and erosion of candidate materials for particle receivers of concentrated solar power tower systems”, Solar Energy 188(2019) 883-889

Heat Exchanger's tubes

Existing materials, new materials and coating systems

Oxidation, corrosion, wear, mechanical stability tests

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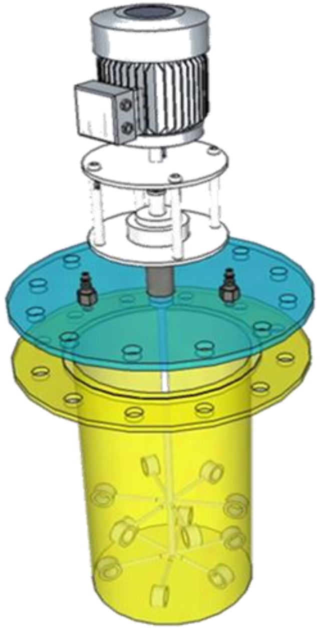
Pilot demonstration

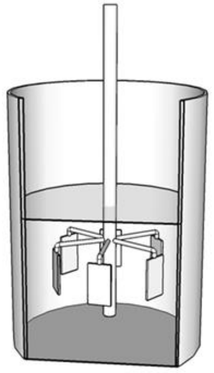
Optimization

Autoclaves for **erosion tests** at high T with a rotating multisample holder (specimen´s movement)

Ciemat

JÜLICH FORSCHUNGSZENTRUM





Heat Exchanger's tubes

Optimization

Existing materials, new materials and coating systems

Oxidation, corrosion, wear, mechanical stability tests

Degradation mechanism investigation

Data supply

Degradation model and lifetime estimation model

Pilot demonstration

Ciemat

Oxidation tests at 700 ^{0}C **atmospheric CO_2**

Heat Exchanger’s tubes

Optimization

Existing materials, new materials and coating systems

Oxidation, corrosion, wear, mechanical stability tests

Degradation mechanism investigation

Data supply

Degradation model and lifetime estimation model

Pilot demonstration

Ciemat

27 creep machines to perform uniaxial creep tests at temperatures **below 1000 º C in air**

Heat Exchanger's tubes

Optimization

Existing materials, new materials and coating systems

Oxidation, corrosion, wear, mechanical stability tests

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Degradation model and lifetime estimation model

Pilot demonstration

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Thermocyclic testing in **CO_2**

Heat Exchanger's tubes

Optimization

Existing materials, new materials and coating systems

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Pilot demonstration

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Creep at 700 ^{0}C in atmospheric CO_2

Heat Exchanger’s tubes - Alternative ways

- Develop new BCC materials
  - Corrosion and erosion resistant Cr-NiAl alloys
  - Corrosion and erosion resistant Cr-Si alloys

- Apply coatings of newly developed materials
  - Deposit the coatings by cost effective methods
    - ⇨ *Slurry*
    - ⇨ *Pack cementation*

- **Bcc superalloys microstructure:**

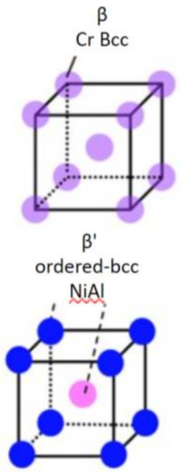
β (bcc) matrix with ordered β’ precipitates

Cr T_m=1,907°C greater than Ni T_m=1,455°C

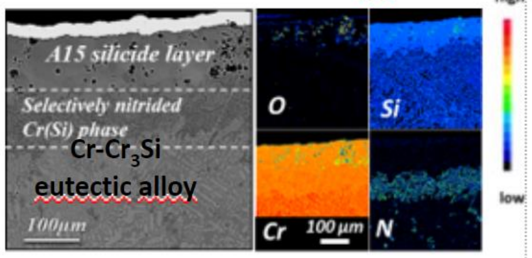
How to design?

Strong and tough?

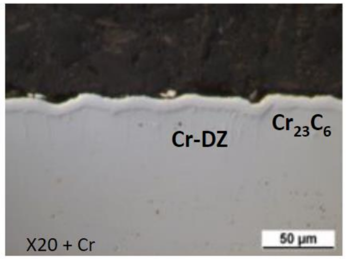
Balance of properties?



1000 h @ 1200°C in air



Alloy	Ni	Cr	C	Mn	Si	P	S	Mo	V	Al
X20CrMoV12-1 [wt.%]	0.60	11.30	0.22	0.63	0.33	0.02	< 0.01	1.01	0.26	< 0.01



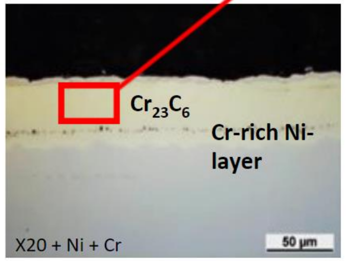
Cost-efficient base material

Diffusion

Coatings

Highly alloyed materials

Properties of Cr in surface layer



Alloy	Ni	Cr	C	Mn	Si	P	S	Cu	N	Nb
DMV310N [wt.%]	20.93	25.18	0.06	1.21	0.45	0.02	< 0.01	0.09	0.28	0.46

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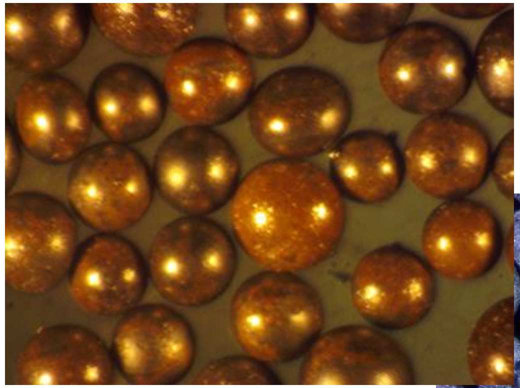
Particle materials

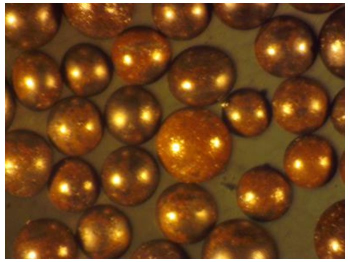
Develop new ceramic particles exhibiting properties and shape features with improved performance in CSP application vs state-of-the-art media (*ie* Sintered Bauxite/Proppants)

State-of the art particle

New particle candidates



Particle materials




- Explore new compositions and surface textures:
  - *Two process platforms are investigated to get spherical particles: granulation and electrofusion*
  - *Various compositions investigated to maximize density and heat capacity (Cp)*
  - *Use of recycle raw materials to optimize cost position*
  - *Possibility to produce size ranges from ~300µm to several mm depending on needs*
- Particles will be produced in lab scale to pilot scale volumes (40 to 600kg batches)
- Particle evaluation and benchmarking vs state-of-the-art:
  - *Extensive physicochemical and optical characterizations*
  - *Basic mechanical tests and attrition / impact resistance through in-house equipment*
  - *Cost estimation*
- Expected results:
  - *Improved performance with solar absorptance >95%, heat capacity > 1.2 J/gK and thermal stability >900°C*
  - *Increase lifetime (particle mass loss by attrition < 0.5 kg/MWh$_{thtransferred}$, useable lifetime > 10 years)*
  - *Low cost ~1 €/kg*

Main results/outcome

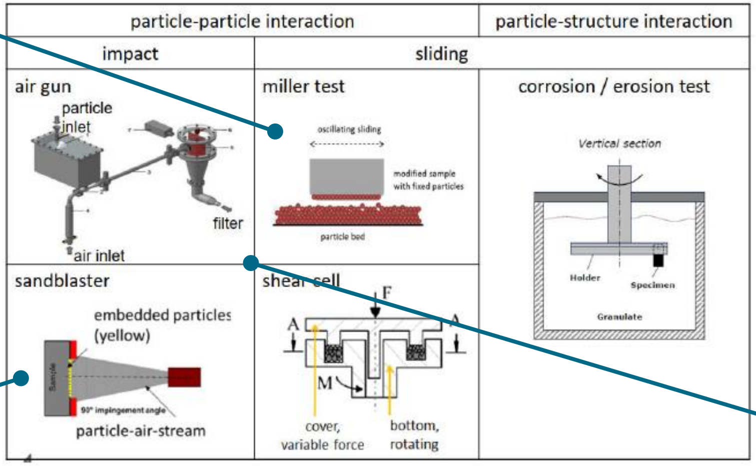
Mechanical characterizations

SAINT-GOBAIN

Impact test / blasting device

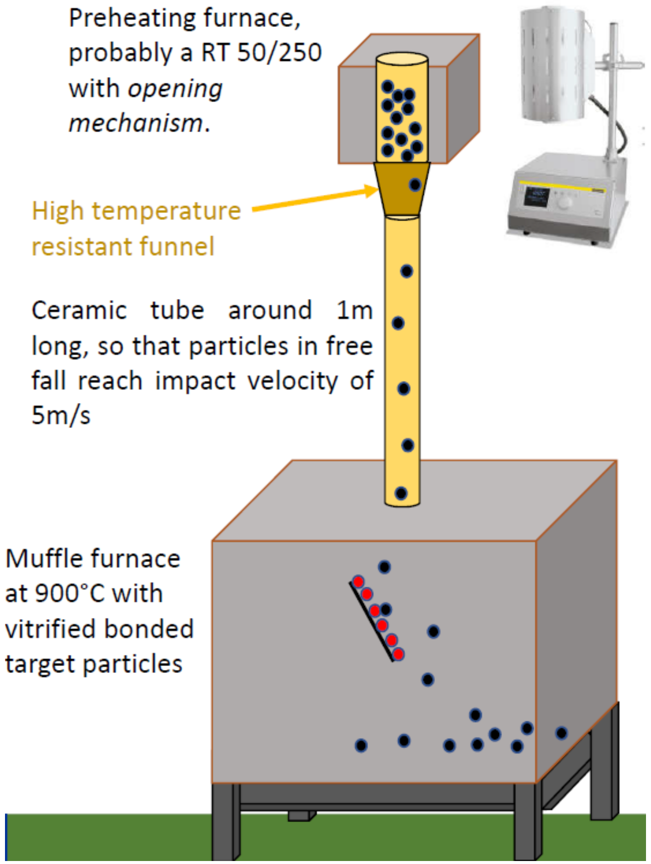
Planetary mill

DLR Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center



For all tests: identify conditions most representative to the actual CSP application (T°, impact velocity, duration, etc…)

Particle chute test

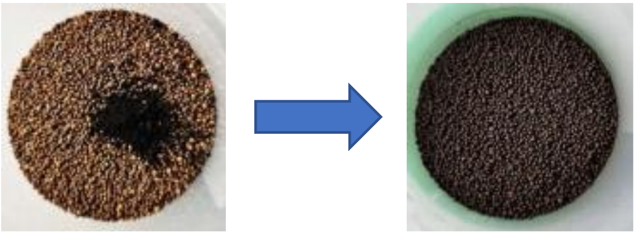


Main results/outcome

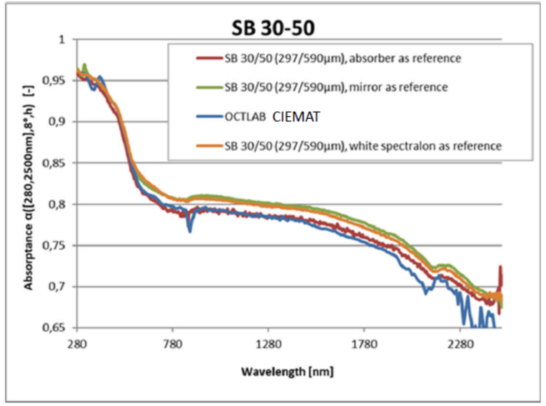
➢ Optical characterizations and particle coatings

- Particle color stability (T° and time) is a potential issue to ensure optimum solar absorption during operation
  → propose to apply coatings on particle surface
  → different strategies investigated (DLR, CIEMAT): pigment vs slurry; post sintering T°…

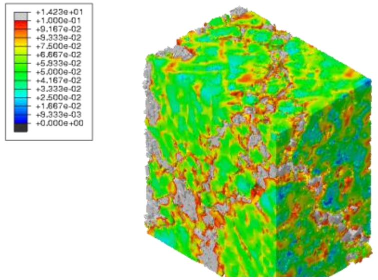
Before *After*

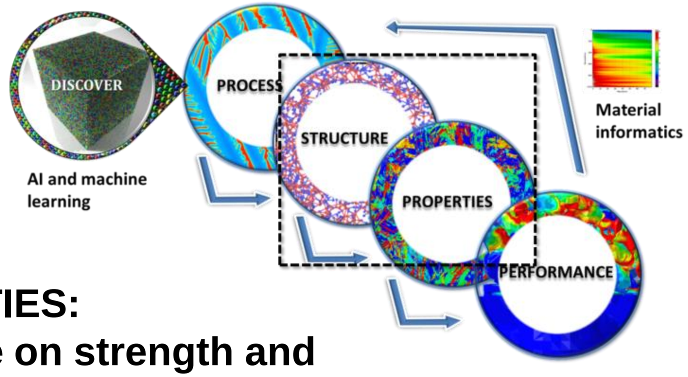


- Absorptance (α) and emittance (ε) measurement through UV-VIS-NIR spectrophotometer (CIEMAT, DLR)
  - Check impact of particle composition, coating, aging, etc…
  - First measurements done on state-of-the art particle for calibration

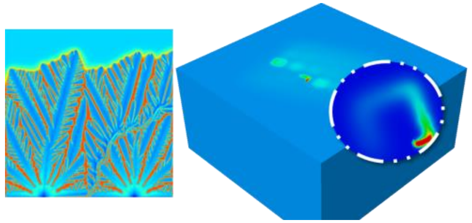


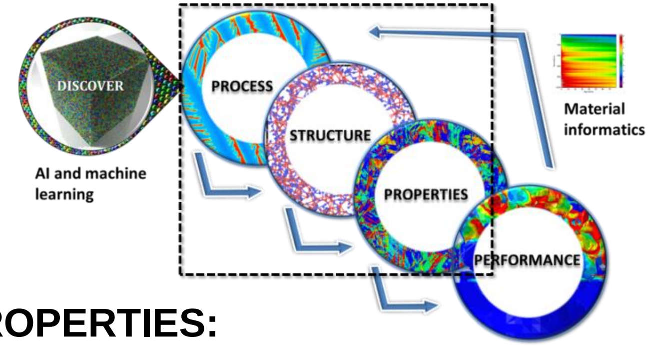
Design Optimization and Degradation Modelling



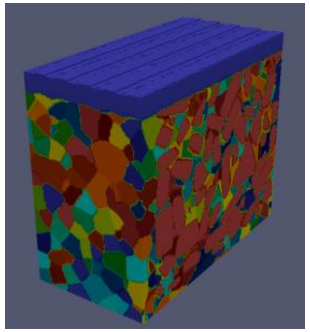


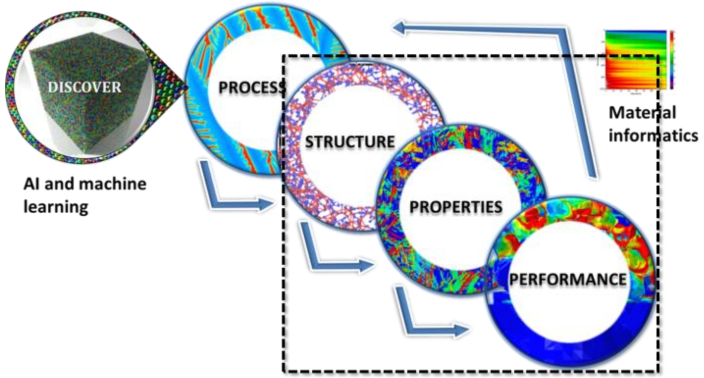
STRUCTURE-PROPERTIES:
Effect of microstructure on strength and engineering material properties





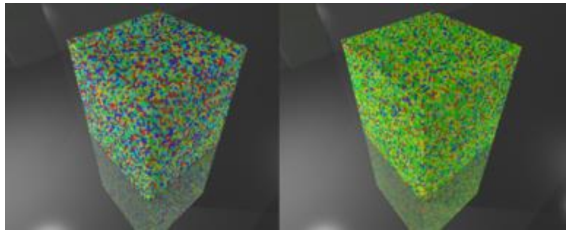
PROCESS-STRUCTURE-PROPERTIES:
Alloy and manufacturing process design for targeted material properties

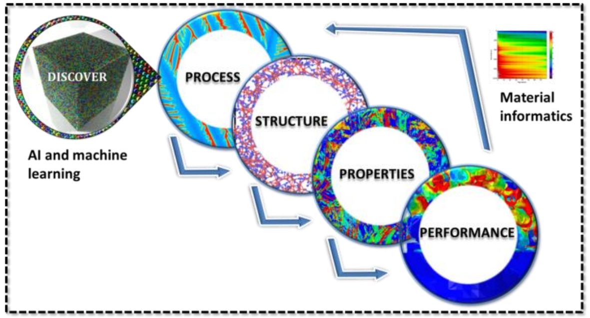




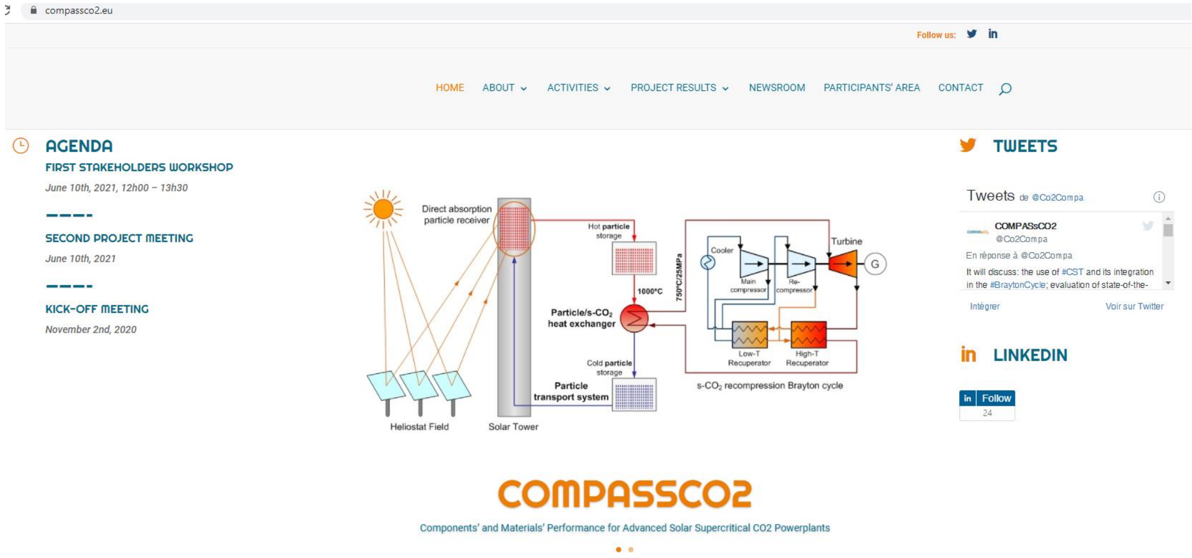
STRUCTURE-PROPERTIES-PERFORMANCE:
Effect of microstructure and micromechanics on fatigue, thermomechanical and wear performance and product lifetime

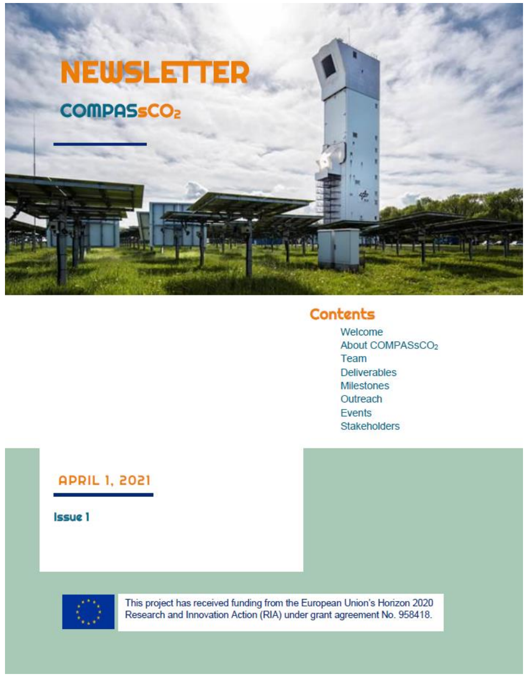
AI/Machine learning:
Material discovery, design, and optimization





Dissemination of Results





Data Management Plan

Deliverable: 7.5

Version: 1.0

WP7: Communication, dissemination and exploitation

Date: February 28th 2021

Deliverable type: Report

Dissemination level: Confidential

Lead participant: OME

confidential

Process parameters of solar sCO_2 Brayton cycle

Deliverable Number 1.1

WP1 "Materials operation conditions and their feasibility studies"

Date: January 13rd, 2021

Deliverable type: Report

Dissemination level: Public

Lead participant: John Cockerill

Process Parameters of Solar Particle Cycle

Deliverable 1.2

WP1: Materials operation conditions and their feasibility studies

Date: January 31st 2021

Deliverable type: Report

Dissemination level: Public

Lead participant: DLR

Material candidates for solar sCO_2 Brayton cycles

Deliverable Number 1.3

WP1 "Materials operation conditions and their feasibility studies"

Date: January, 2021

Deliverable type: Report

Dissemination level: Confidential

confidential

Lead participant: DECHEMA-Forschungsinstitut

Communication and Dissemination Plan

Deliverable: 7.2

Version: 1.0

WP7: Communication, dissemination and exploitation

Date: April 30th, 2021

Deliverable type: Report

Dissemination level: Public

Lead participant: OME

Cooperation potential

- Optimization of sCO2 Brayton cycles for CSP applications
- Development of particles as heat carriers for high temperature processes (>1000°C)
- Development of structural materials for harsh conditions regarding temperature, pressure, erosion, oxidation, corrosion, thermal cycling, etc.
- Testing and modelling of material degradation
- Scientific publications, joint dissemination events, etc.

Thank you for your attention!

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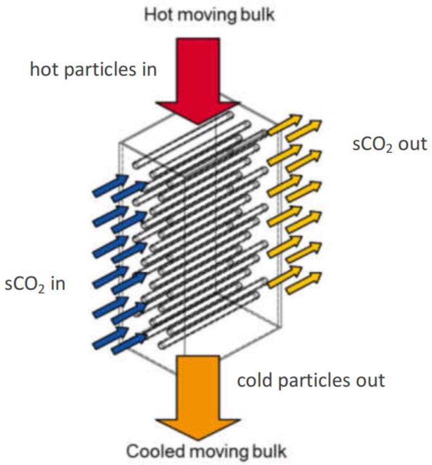
Technical Description (backup)

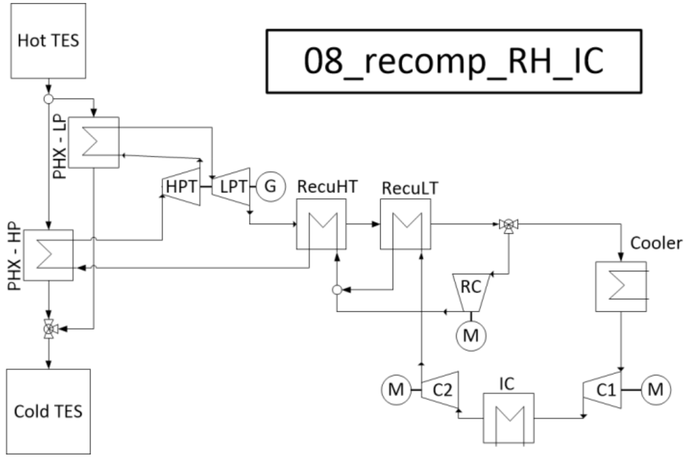
CentRec™ receiver

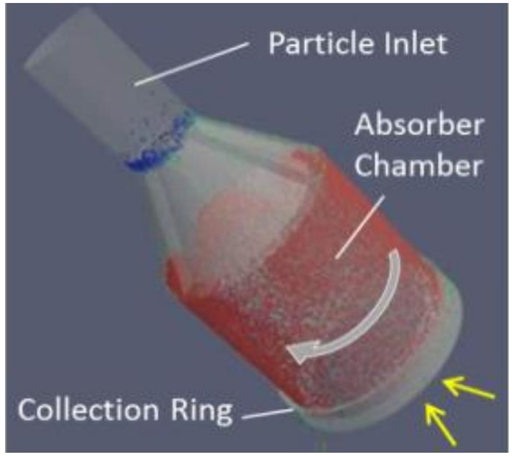
Ceramic particles

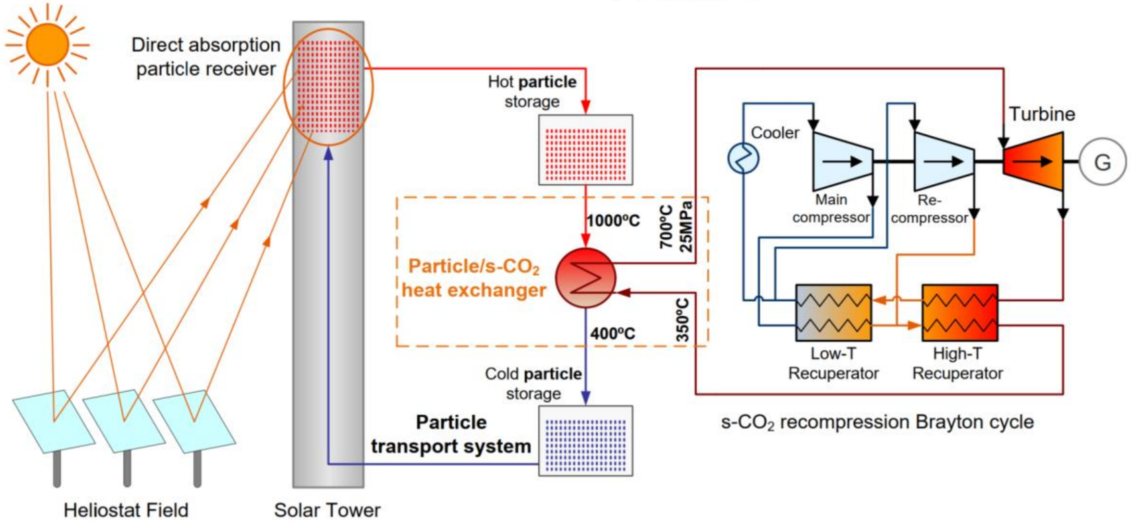
Particle heat exchanger



sCO_2 cycle







Technical Description (backup)

CentRec™ receiver

- Very high outlet temperatures (1000 °C)
- High thermal efficiency (≈ 90 %)
- Fast ramping
- Low cost
- Not yet commercially demonstrated

Ceramic particles

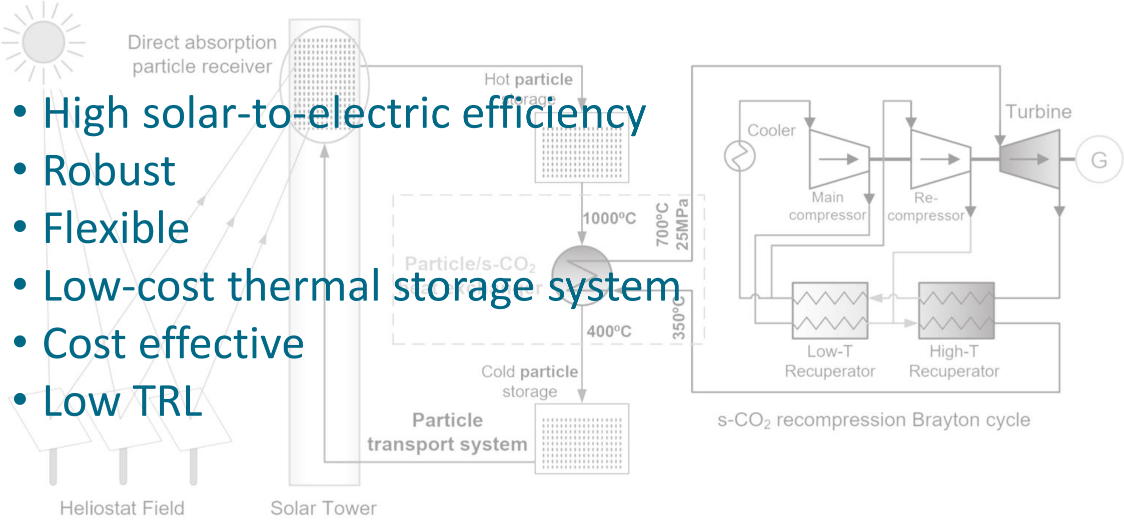
- No practical temperature limitations
- Low cost
- Medium distance transport feasible
- Long-term durability unknown

Particle heat exchanger

- Rather conventional design
- Low TRL
- challenging operating conditions

sCO_2 cycle

- Very high thermal efficiency
- Compact, cost effective
- Fast ramping
- Low TRL



- High solar-to-electric efficiency
- Robust
- Flexible
- Low-cost thermal storage system
- Cost effective
- Low TRL