# Receivers for Solar Tower Systems

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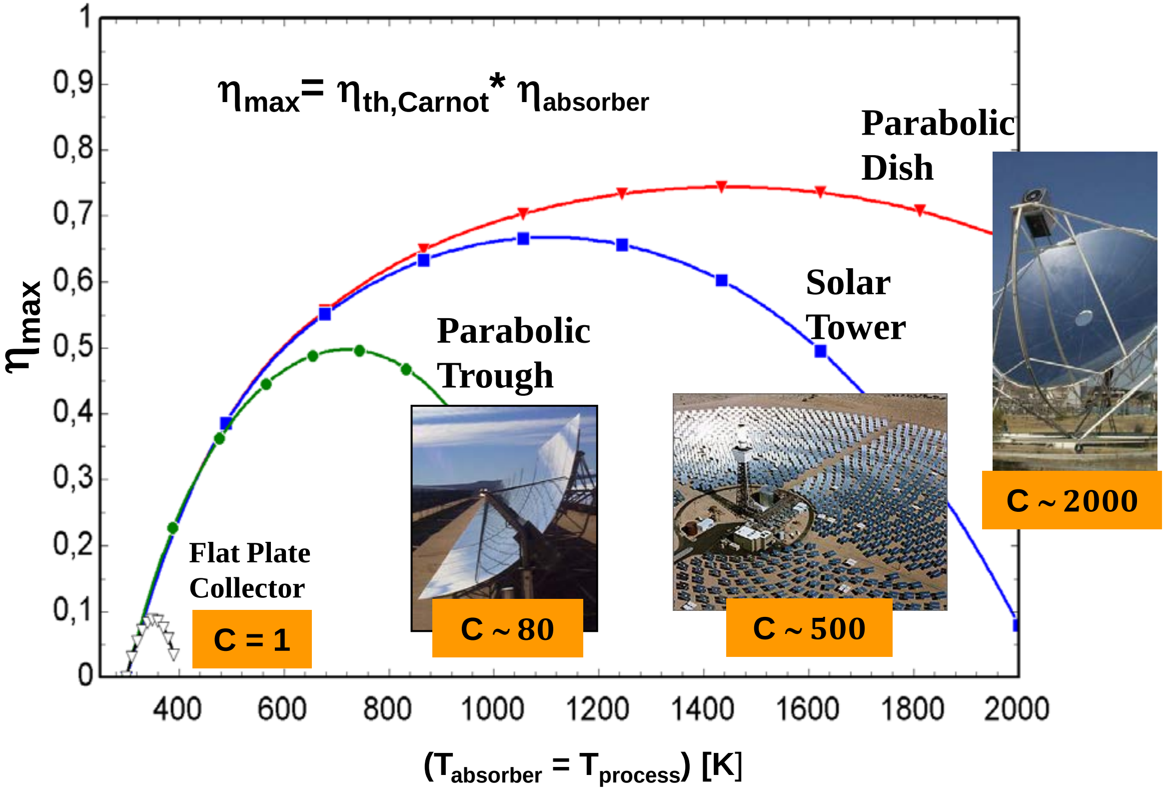
June 25-27, 2014
Font Romeu, France


DLR

# CSP Characteristics




Solar tower systems:

⇒ higher concentration

⇒ higher process temperature

⇒ higher solar-to-electric efficiency

⇒ reduced collector area

⇒ **lower cost**

# Introduction: Solar Tower Technology

**Solar Tower Technology:**

- ascending renewable power technology
- **high conversion efficiency**
- **added value:**
  - high capacity factor (storage)
  - firm capacity
- **significant cost reductions expected**
  - technological development
  - improved manufacturing
  - increased maturity (financing)
- **high local content achievable**
- also suitable for HT process heat

# Receiver Classification

**Classification by**
**Heat Transfer Medium**:

- molten salt
- water/steam
- Air open/closed
- liquid metals
- solid particles
- other gases

**Classification by maturity**

**State of the art technology:**

- molten salt
- water/steam

**First of its kind technology**

- Open volumetric air receiver

**Technology in pilot phase**

- Pressurized Air Receivers

**Technology under development**:

- liquid metals
- solid particles

# Combination of Receiver and Storage

**Receiver/Heat Transfer Medium is relevant for selection of storage system**

**Storage type**:

- sensible
- latent
- (thermochemical)

**Storage concepts:**

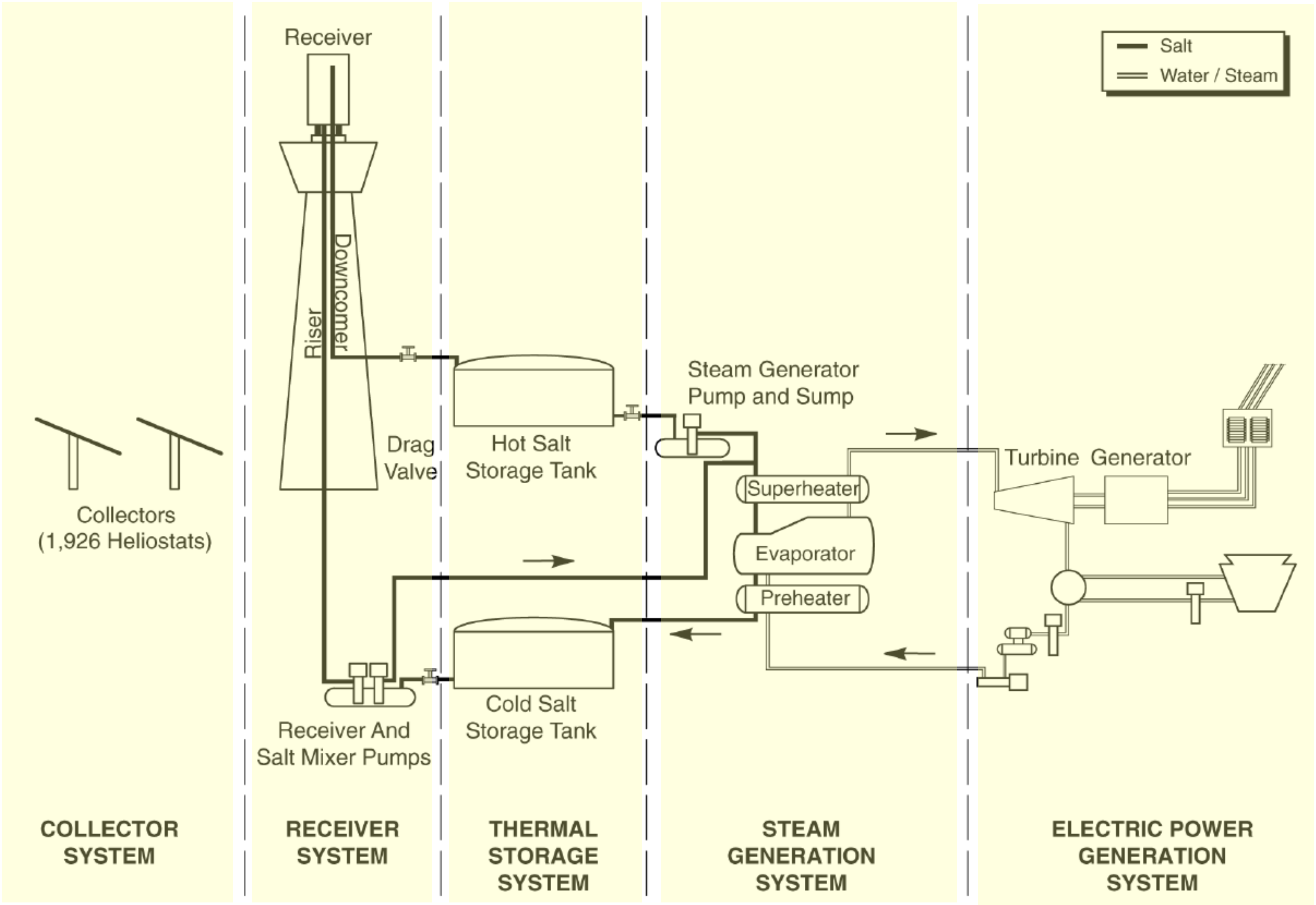
- direct: receiver HTM is also used as storage medium
  - molten salt, particles, (water)
- indirect: a different storage medium is used
  - air/gases, liquid metals

# State of the Art: Molten Salt Receivers

- „solar salt“: 60% $NaNO_3$ / 40% $KNO_3$
- **low salt cost** allow use as heat transfer and storage medium
- salt temperatures **up to 565°C** for superheated steam generation
- **good heat transfer** characteristics
- critical: salt **freezing below 220°C**
- **heat tracing required**, draining of receiver and other system components during night
- **salt degradation** at temperatures higher than **600°C**
- **corrosion** issues on metallic components (depends on salt quality)

| Storage Medium | Temperature Cold (°C) | Temperature Hot (°C) | Average density (kg/m³) | Average heat conductivity (W/mK) | Average heat capacity (kJ/kgK) | Volume specific heat capacity ($kWh_t/m^3$) | Media costs per kg (US$/kg) | Media costs per $kWh_t$ (US$/$kWh_t$) |
|---|---|---|---|---|---|---|---|---|
| **Liquid media** | | | | | | | | |
| Mineral oil | 200 | 300 | 770 | 0.12 | 2.6 | 55 | 0.30 | 4.2 |
| Synthetic oil | 250 | 350 | 900 | 0.11 | 2.3 | 57 | 3.00 | 43.0 |
| Silicone oil | 300 | 400 | 900 | 0.10 | 2.1 | 52 | 5.00 | 80.0 |
| Nitrite salts | 250 | 450 | 1,825 | 0.57 | 1.5 | 152 | 1.00 | 12.0 |
| Nitrate salts | 265 | 565 | 1,870 | 0.52 | 1.6 | 250 | 0.50 | 3.7 |
| Carbonate salts | 450 | 850 | 2,100 | 2.0 | 1.8 | 430 | 2.40 | 11.0 |
| Liquid sodium | 270 | 530 | 850 | 71.0 | 1.3 | 80 | 2.00 | 21.0 |

# Molten Salt Systems

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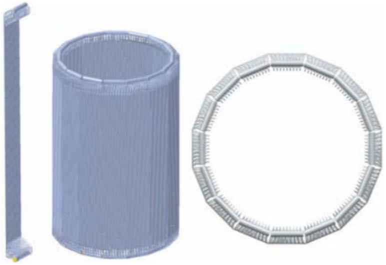
# Molten Salt Systems

- **GEMASOLAR**:
  - 20MW el.
  - External tube receiver
  - operation since 2011
  - 290°C – 565°C
  - 120 $MW_{th}$ @DP
  - $eta_{rec,DP}$ ~88%



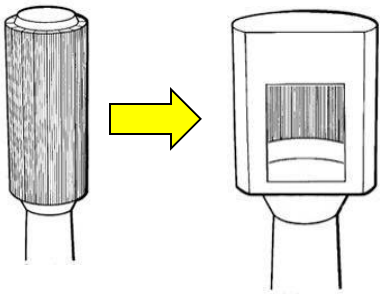
# Molten Salt Systems

- **Crescent Dunes** (SolarReserve)
  - Molten salt
  - 110MW$_{el}$
  - External tube receiver
  - Receiver outlet temperature: 565°C


# Strategies improving Molten Salt Systems

- **Higher temperature molten salt**:
  - Higher steam parameters
  - Smaller heat exchanger
  - Smaller storage
  - Less critical operation (over temperature receiver)

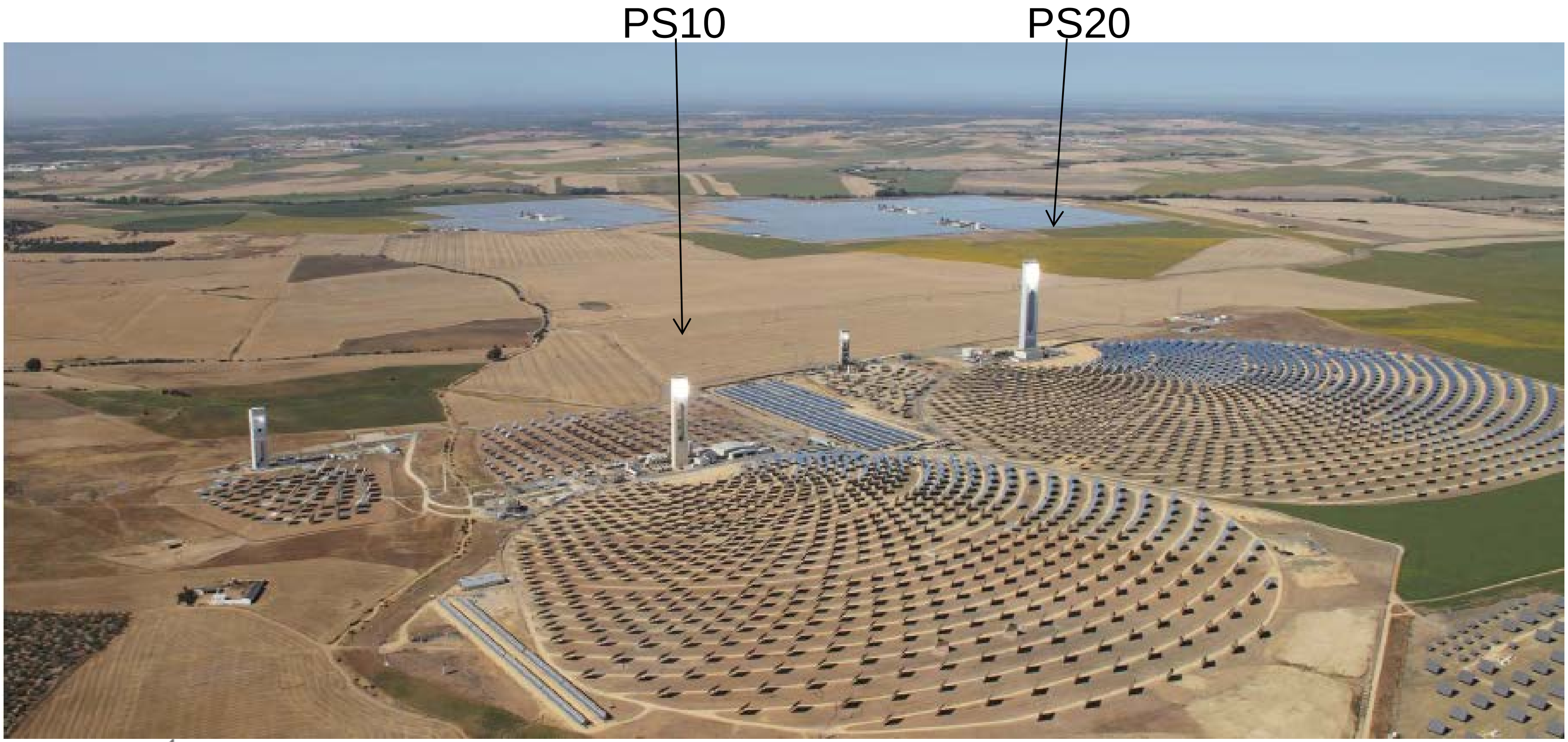
- **Higher receiver efficiency** by:
  - Reduction of thermal losses
  - Cavity arrangement
  - Face down (can design)
  - Using standard vacuum absorber for first temperature step
  - Higher absorption of solar radiation ((selective) coatings)



- **Optimization of operation**
  - Real time aim point strategy for homogenous receiver temperature (→life time!)
  - Solar pre-heating of receiver
  - Faster start-up
  - Avoiding draining of receiver during clouds

# State of the Art: Saturated Steam

- **PS10/PS20**
  - direct irradiated absorber tubes (250°C@40Bar)
  - 11/20 $MW_{el}$
  - cavity receiver



# Superheated Steam Systems

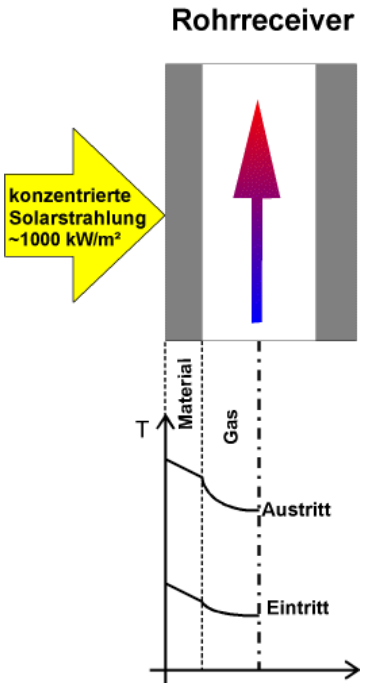
- **Brightsource**:
  - Ivanpah 377MW
  - direct Steam (550°C)
  - external tube receiver

# Strategies improving Superheated Steam

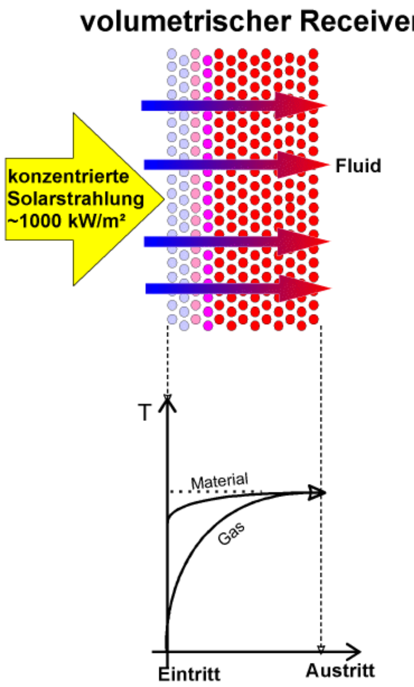
- **Higher steam temperatures** and pressures for higher efficiency at the power block
- **Higher loads for absorber tubes** (pressure and temperature)
- **Three zones in receiver** with different heat transfer coefficients:
  - pre-heating
  - evaporation
  - superheating

# First-of-its-Kind: Open Volumetric Air Receivers

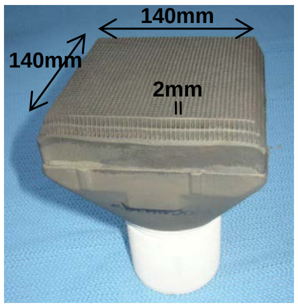
## Volumetric Receiver Principle



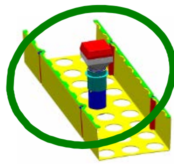

**drastic increase of heat transfer surface area**



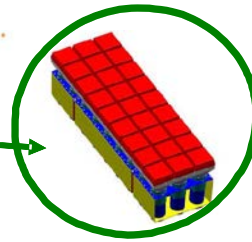
# First-of-its-Kind: Open Volumetric Air Receivers



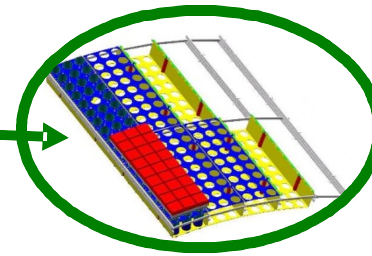

0.02 m²
Absorber



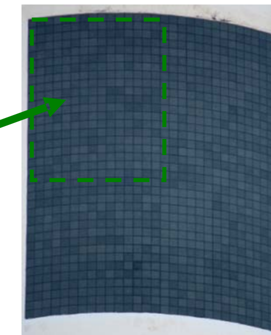
0.57 m²
Submodul

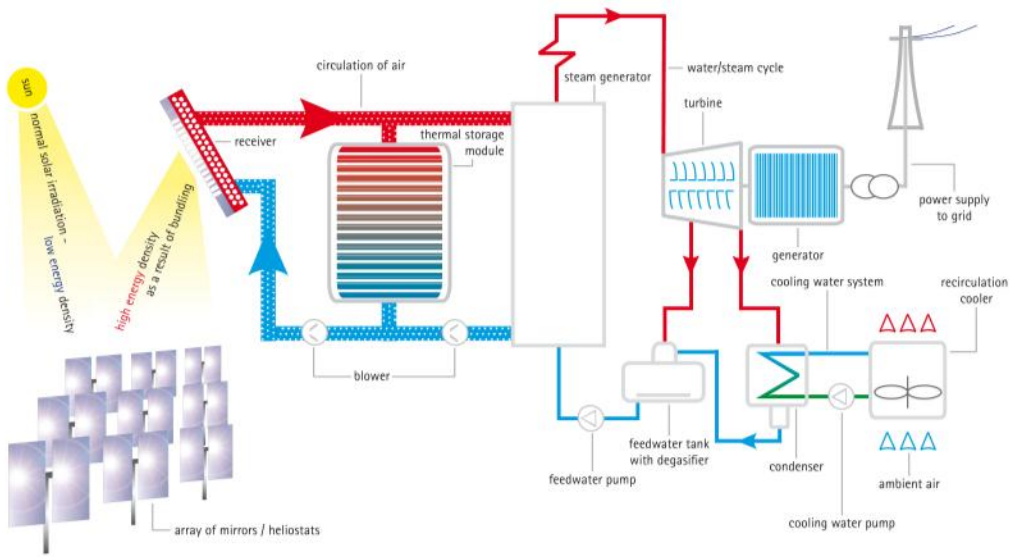


5.7 m²
Solair Receiver (PSA)



22.7m²
Receiver (Jülich)



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# First-of-its-Kind: Open Volumetric Air Receivers

## Power Plant Jülich (DLR)

**process parameters**:
- pressure: ambient
- return air: 120°C
- receiver air outlet: 680°C

**material load parameters**:
- max. temp.: 1100°C (front)
- max. load: 1000kW/m²
- temp. gradient: ~100K/cm
- average mass flow: 0.55 kg/m²-s

**dynamic operation**:
- air outlet temp. of single cup: max. temp. change ≈3.3K/sec

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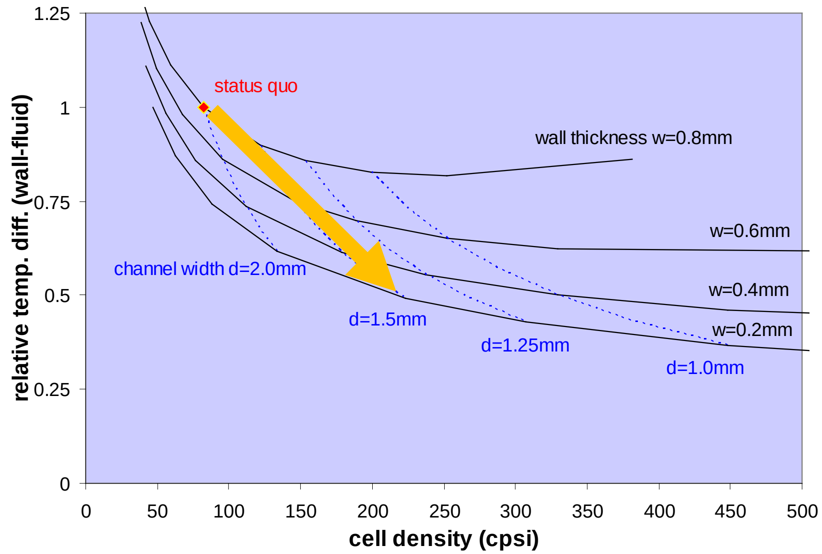
# First-of-its-Kind: Open Volumetric Air Receivers Strategies for Improving

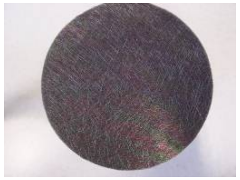
**Improve of Absorber**

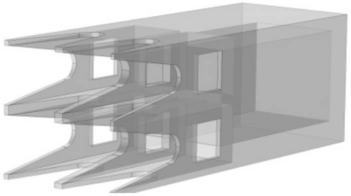
- Higher Porosity
- Higher heat transfer surface per volume
- Stable mass flow
- Extension of durability

**Improve of System**:

- Less auxiliary energy
    - Decrease of pressure drop
- Online aiming point strategy
- Cavity receiver
    - Increase of air return ratio
- Operator assistence system





# Technology in Pilot-Phase: Pressurized Air Receivers

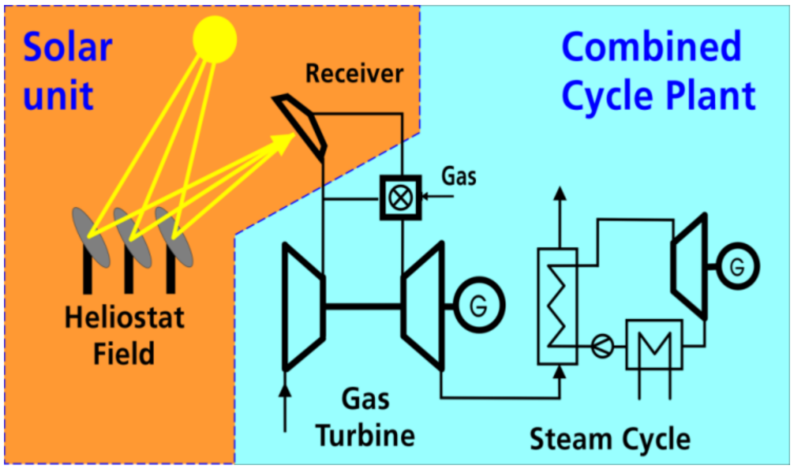
- **pre-heating of the compressed** air of a Brighton cycle
- **currently two power levels** are under development:

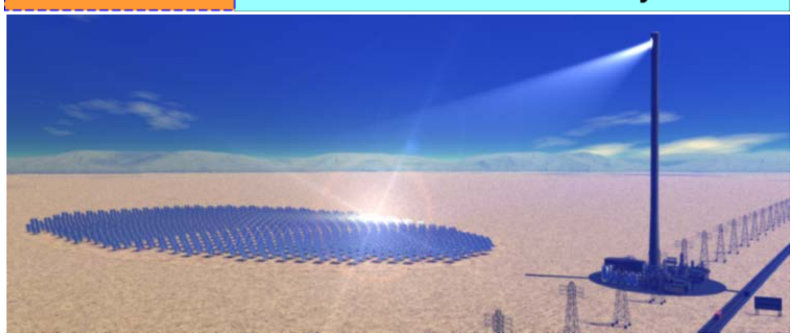
**<u>large systems:</u>**

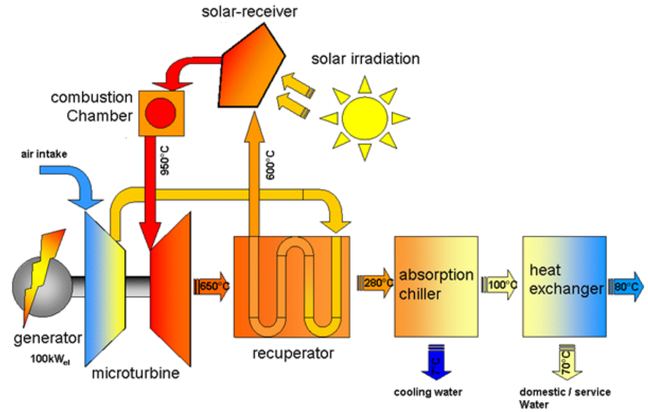
- 5-150 MW el.
- combined with steam cycle

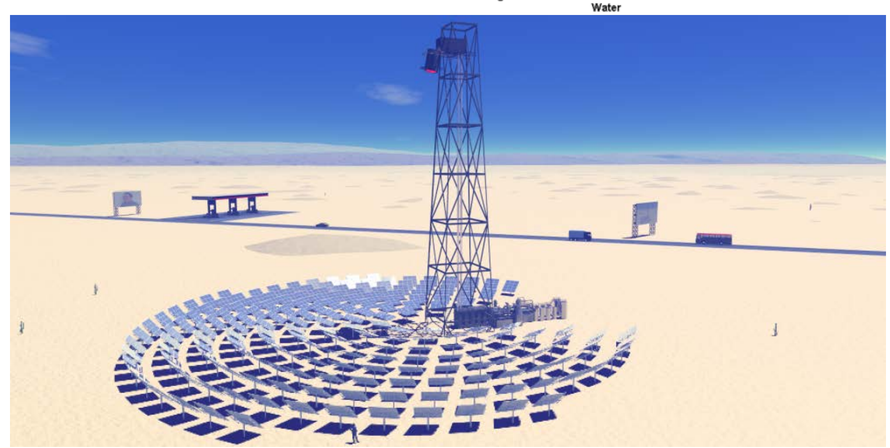
**<u>small systems:</u>**

- 0.1-5 MW el. (recuperated turbine)
- combined with cooling/heating (desalination)





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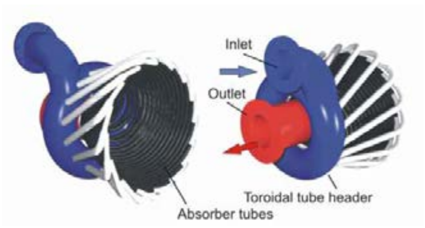
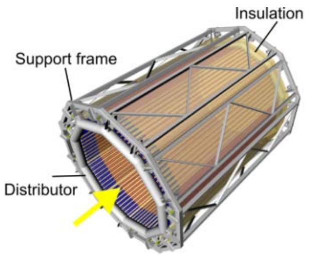
# Technology in Pilot-Phase: Receiver Development

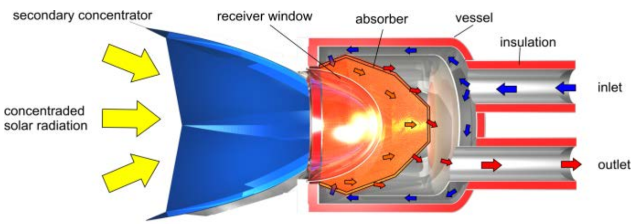
- air outlet temperature: 800-1000°C
- pressure: 4-16 $\text{Bar}_{abs.}$
- pressure drop: 100-400mBar
- materials: high temperature alloy, ceramics, fused silica

tube receivers

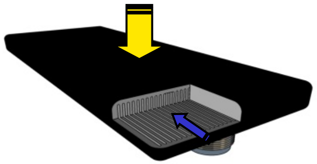


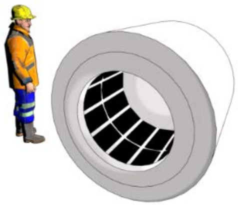



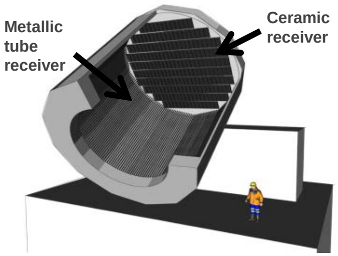

volumetric receivers




ceramic plate receiver

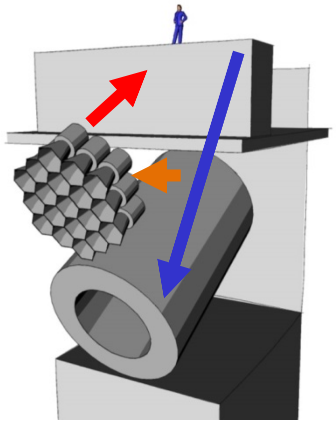


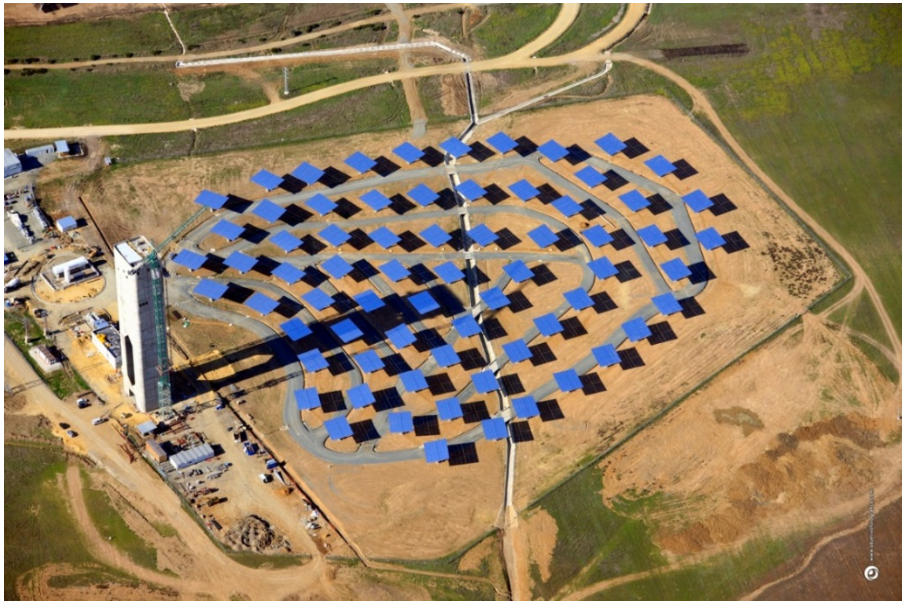


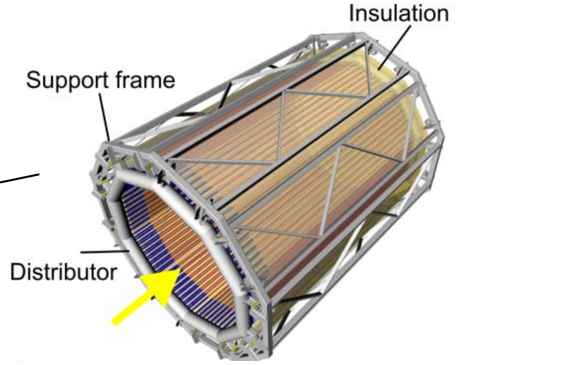


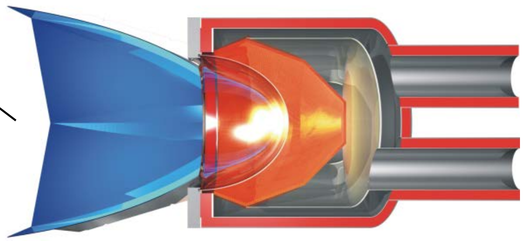
# Technology in Pilot-Phase: First Pilot (SOLUGAS)

- EU- project under leadership of ABENGOA SOLAR NT
- Test of a 3MW$_{th}$ metallic tubular receiver
  - Inlet temperature: 330°C
  - Outlet temperature: 800°C
  - Pressure: 10Bar$_{abs}$
- Since summer 2012: more then 700h of solar operation
- Design values reached and simulation models validated
- Next step: Integration of Volumetric Pressurized receiver (1MWth /1000°C)





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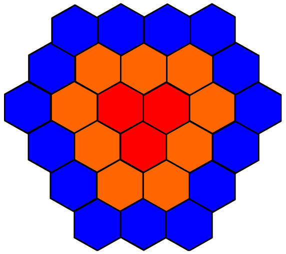
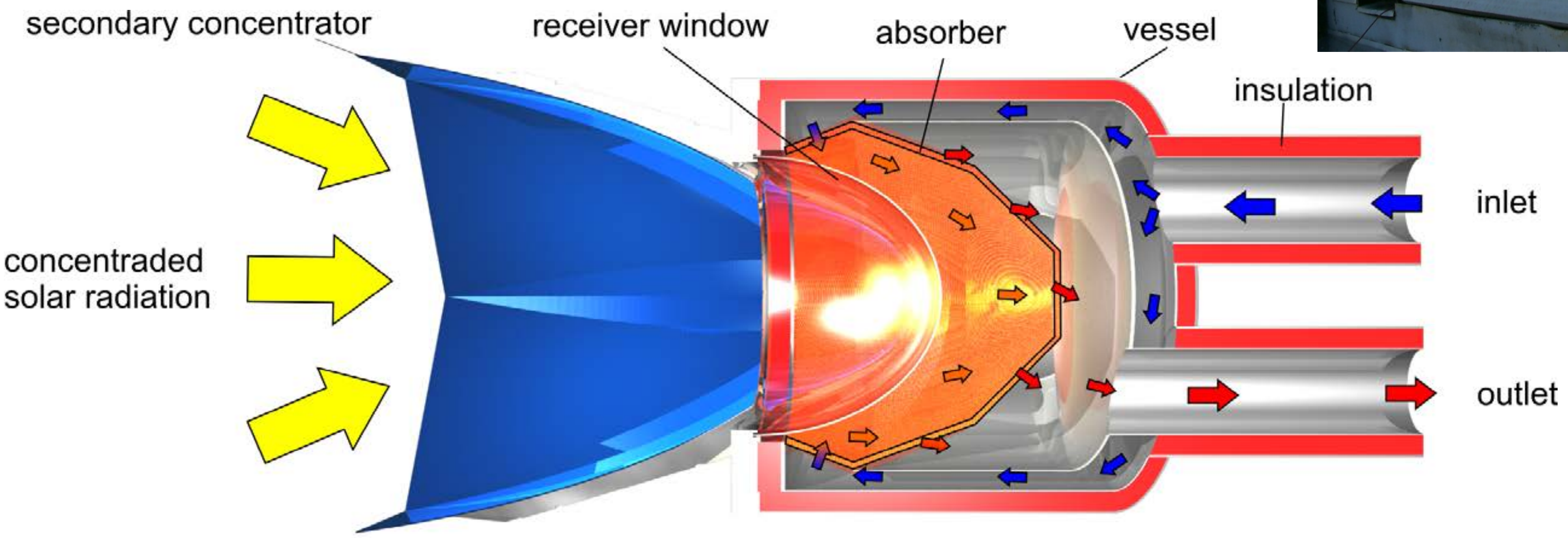
# Technology in Pilot-Phase: Receiver Development
# Closed Volumetric Receiver

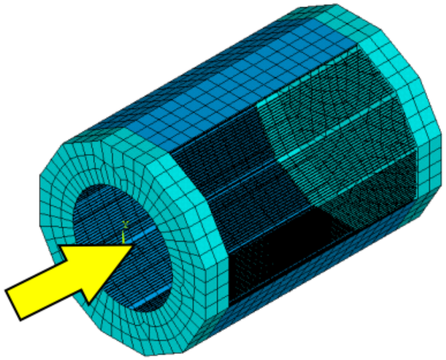
- **high efficiency** (>80%) caused by…
  - „volumetric“ absorption of radiation
  - relatively low absorber temperatures
  - low thermal reradiating
- **low pressure drop** (< 30mbar)
- high possible outlet temperatures (>1000°C)
- **proven technology**



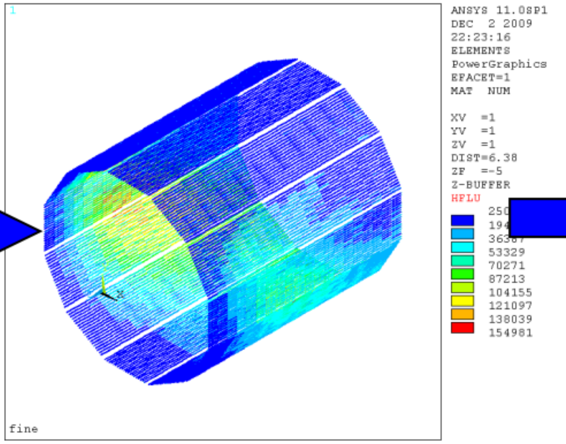


# Technology in Pilot-Phase: Receiver Development
# Tube Receiver and Design methods

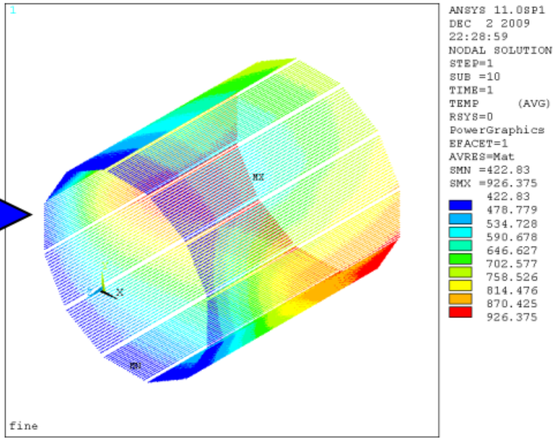
- **using commercial FEM/CFD** codes for the thermal and mechanical layout
- **using** the raytracing code **SPRAY**
- **thermal field** can be used for mechanical simulation (**strain, stresses**)
- **parametric approach allows** easy variations (geometry, load cases) and **optimization**



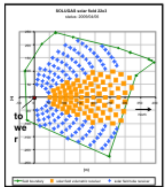
FE- Model




Solar heat fluxes




Temperature distribution

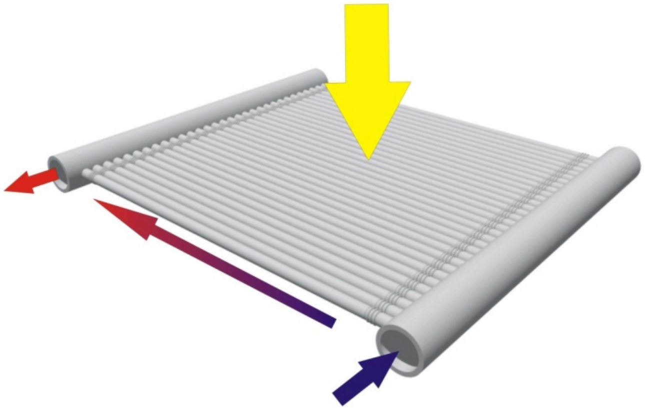


Raytracing using
- FE- Model
- Heliostat field data
- Time point

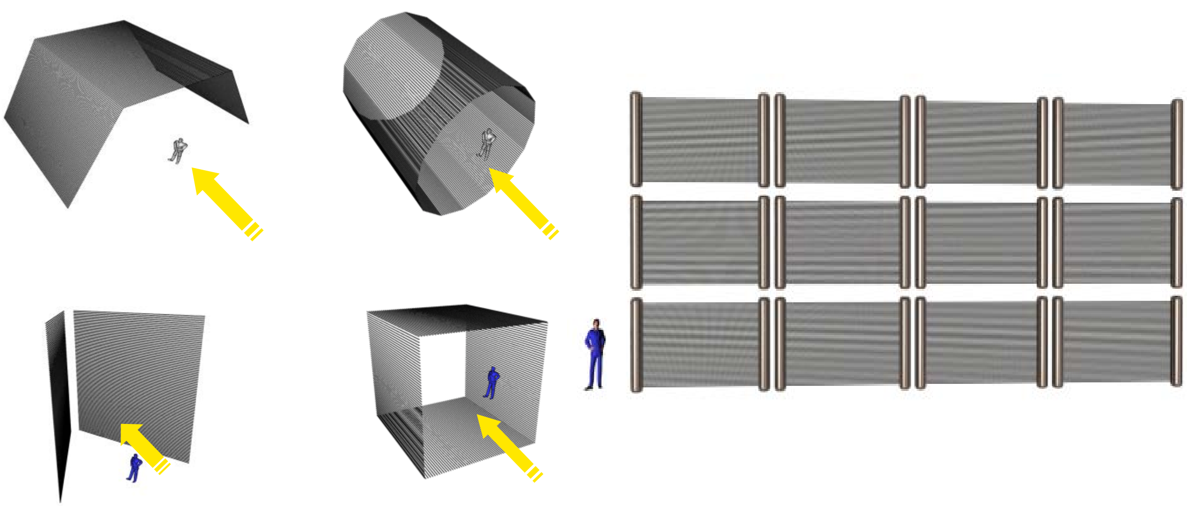
Other thermal boundaries
- Radiation exchange
- Forced convection to fluid

# Technology in Pilot-Phase: Receiver Development
# Ceramic Plate Receiver

- mass flow is distributed to **several parallel absorber** tubes by a tubular header
- absorber **tubes** should have **small diameters** for best heat transfer.
- the **thermal strain** of each absorber tube has to be **compensated**.
- tubular collector collects the heated fluid.
- design of receiver has to fulfil thermodynamic, hydraulic and economic needs.



Different Panel Arrangements

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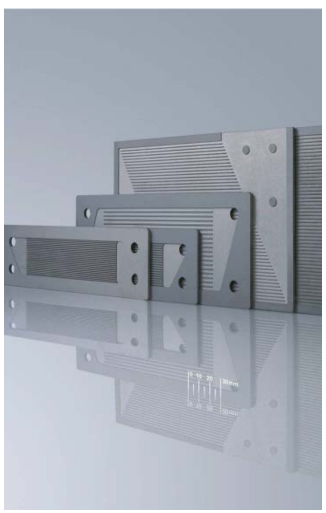
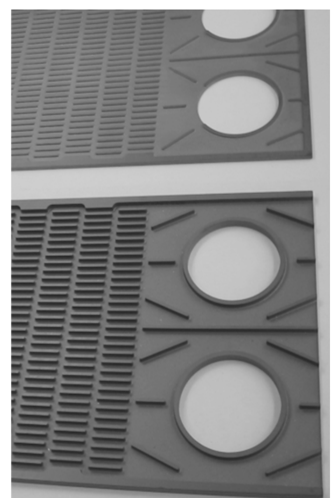
# Technology in Pilot-Phase: Receiver Development Ceramic Plate Receiver

Material benefits of SiC ceramic

- **High** thermal **conductivity**
- Very low thermal expansion coefficient
- Temperature **stability up to 1500°C** (in air)
- Gas-tight
- **High strength**
- “Black without coating”
- Design of inner structure

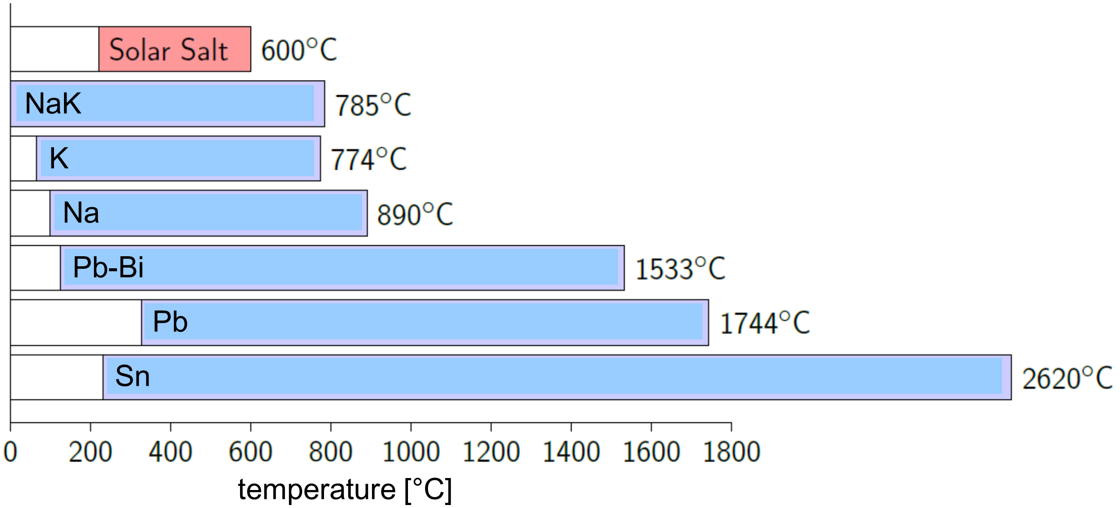




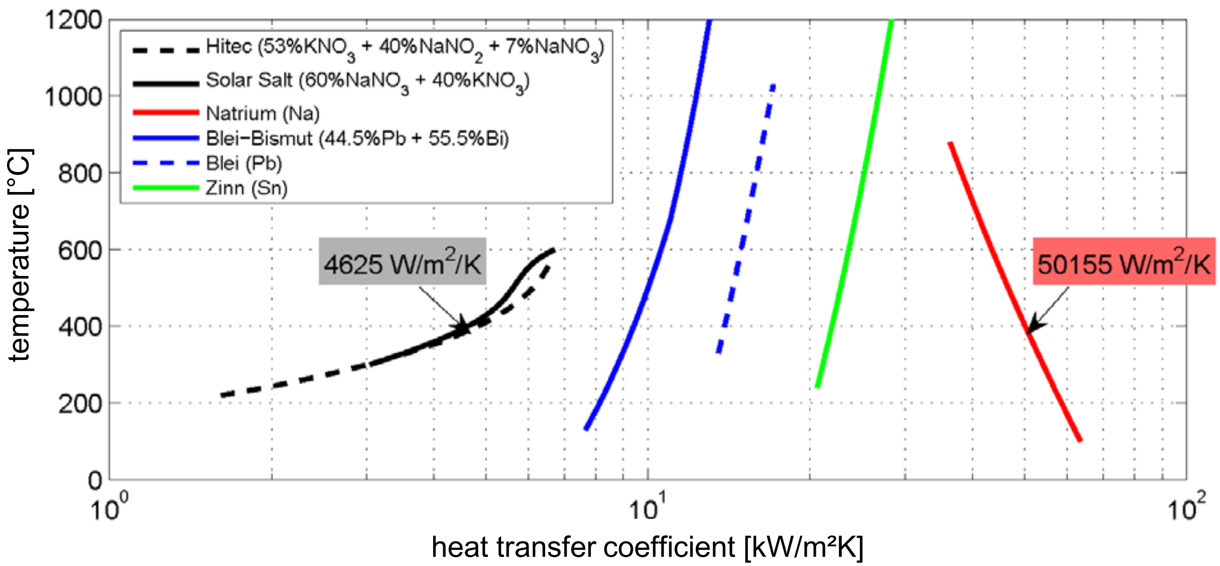
ESK a ceradyne company DLR

# Technology under development: Liquid Metal Receivers

large temperature range




high heat transfer coefficients

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# Technology under development: Liquid Metal Receivers
# Experiences in solar power systems

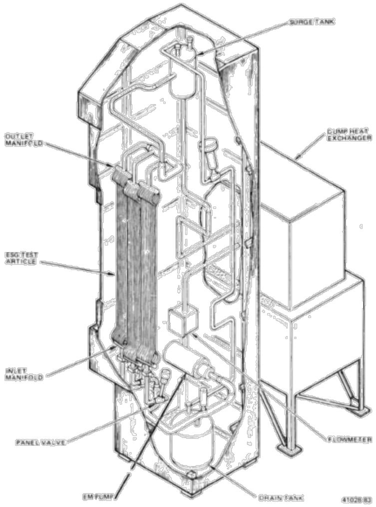
First receivers tested in the 80's with sodium as HTF achieved high efficiencies

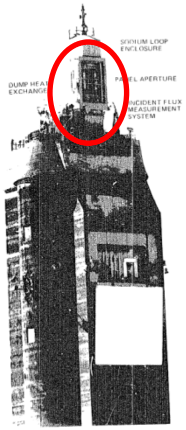
Receiver test in the USA: Sandia CRTF

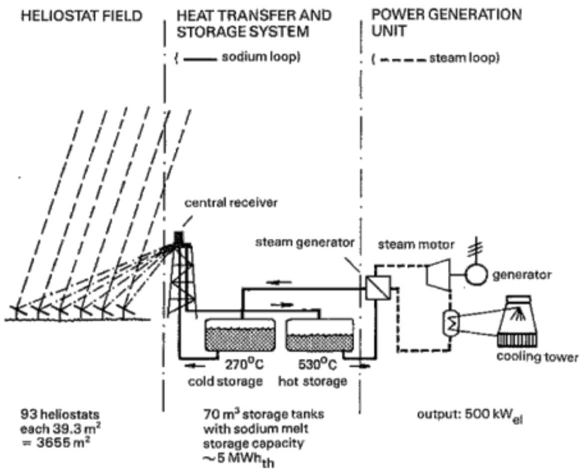
- 750 litres, 70 hours

Plant test in Spain: PSA

- 70,000 litres, 5 years




After a sodium fire in 1986 in Almeria, investigation of liquid metals in solar power systems was stopped!

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# Technology under development: Liquid Metal Receivers Ongoing Research

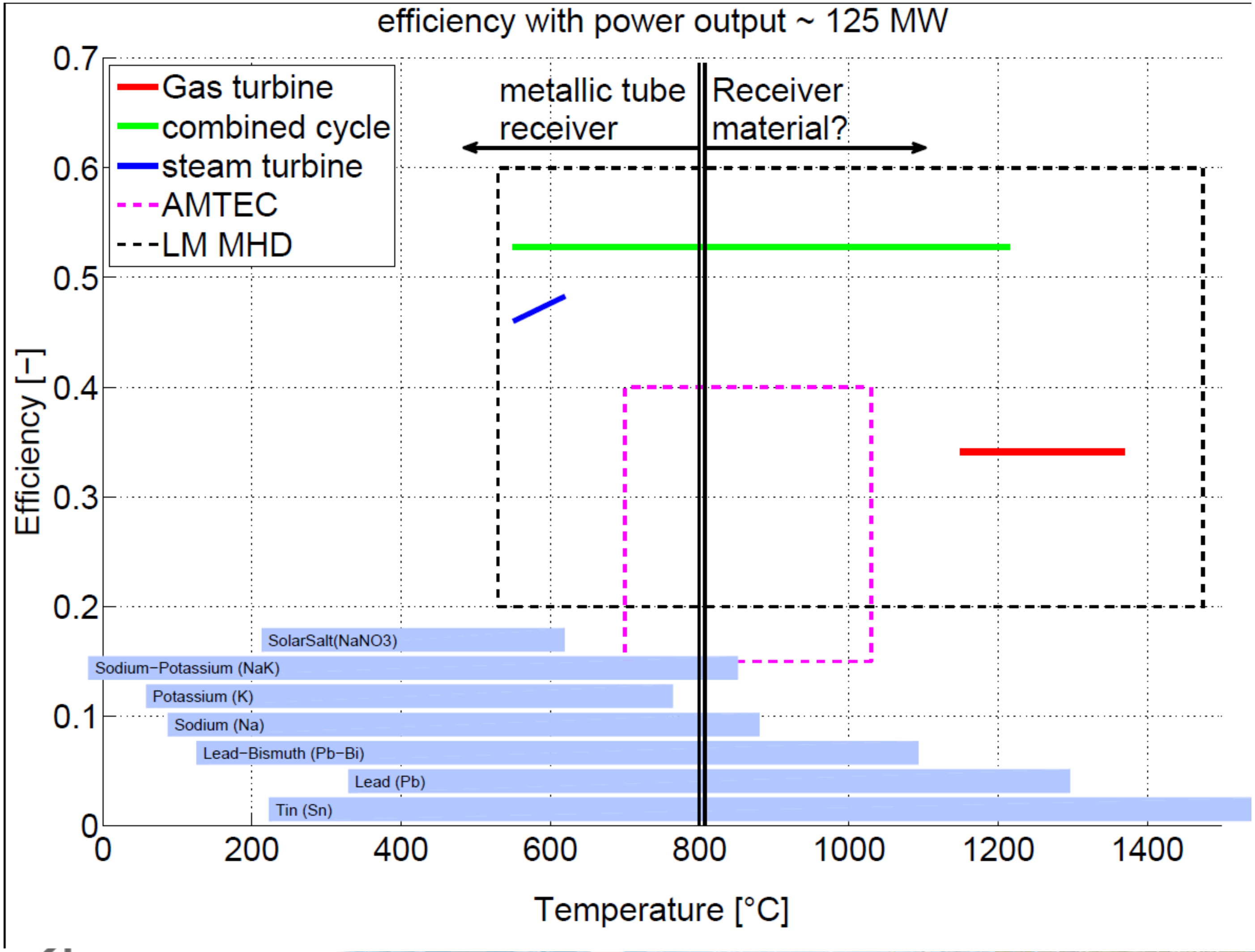
## Conventional technologies

- Steam turbine (η ≈ 45%)
- Gas turbine (η ≈ 40%)
- Gas- and steam turbine (η ≈ 55%)

## Innovative technologies

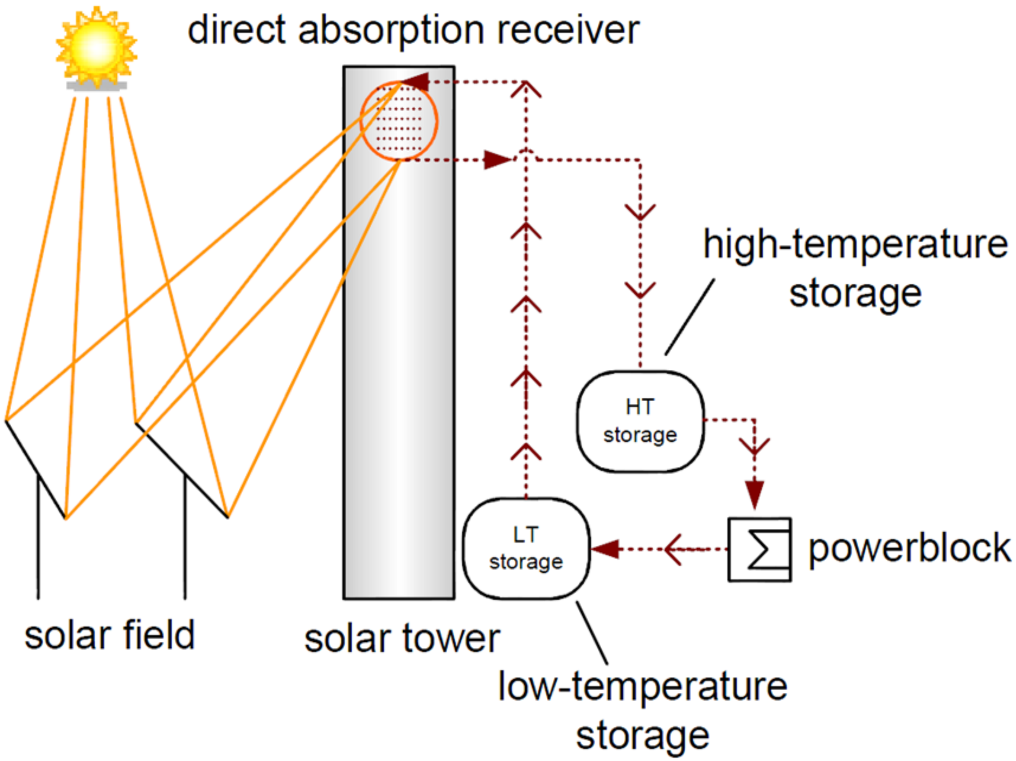
- Thermo-electrical Generator (TEG: Seeback-Effect) (η ≈ 5%)
- Thermionic Power Generator (Edison-Richard-Effect) (η < 5%)
- **Alkali-Metal Thermal Electric Converter (AMTEC),** Electrochemical device for direct conversion of heat to electricity (η ≈ 15...40%)
- **Liquid Metal Magneto-hydrodynamic Generator (LM MHD),** energy conversion: heat → kinetic energy → electricity (η ≈ 20...60%)

# Technology under development: Liquid Metal Receivers Conceptual study



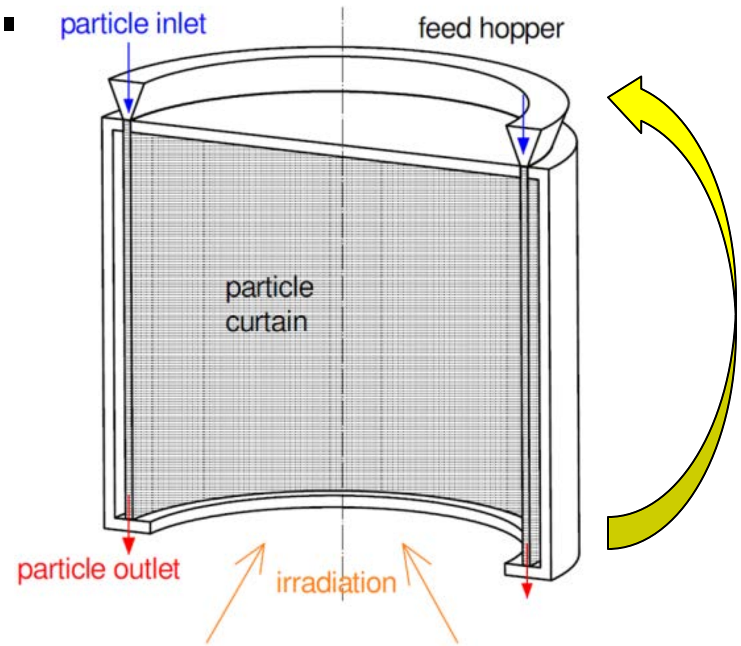
# Technology under development: Direct Absorbing Particle Receiver

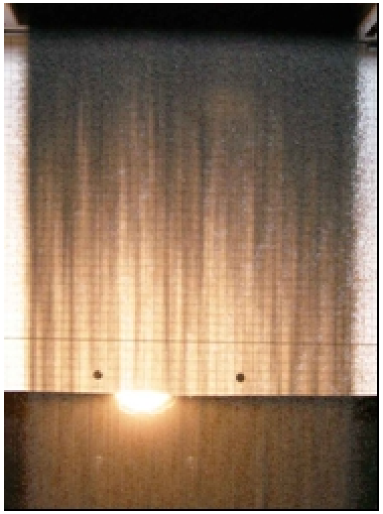
- **direct absorbing** of solar radiation at **small ceramic particles**
- ceramic **particles as heat transfer** and **storage** medium
- **high temperature capability (>900°C)** for power generation and process heat
- **no limits in flux densities** (no wall between heat absorption and heat transfer medium)

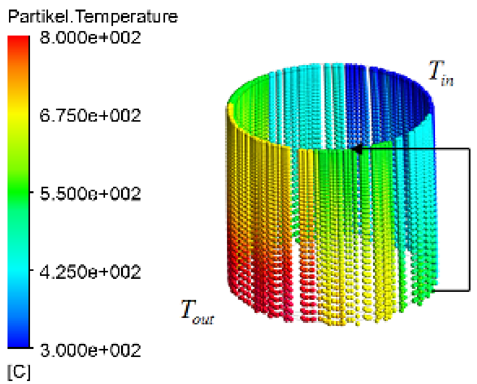



# Technology under development: Direct Absorbing Particle Receiver: 1. Approach – Falling Particle Curtain

- **optically dense particle film** near the inner surface of a cylinder/box
- **gravitation forces give falling** speed and duration of particle in solar radiation
- **re- circulating of the particles** necessary to obtain design outlet temperature
- concentrated solar radiation through the opening at the bottom
- **high level models developed** (coupling of CFD, raytracing and particle movement)

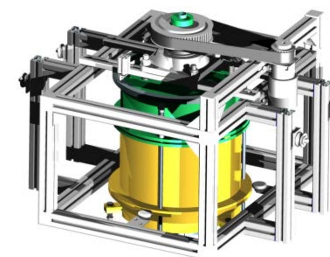


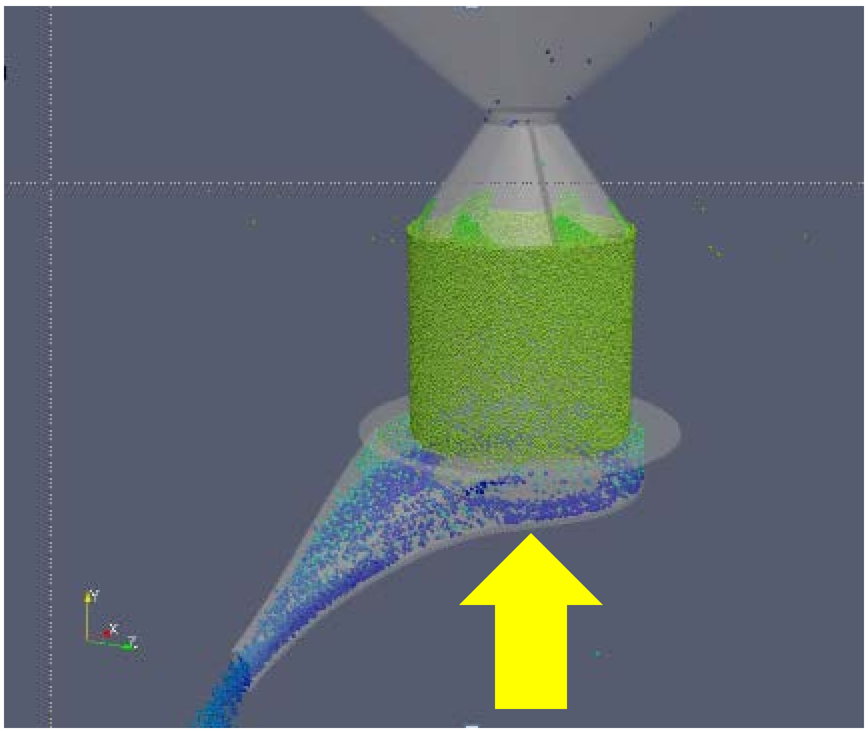





# Technology under development: Direct Absorbing Particle Receiver: 2. Approach – Centrifugal Particle Receiver

- **optically dense moving particle film** on the inner surface of a rotating cylinder
- **gravitation and centrifugal forces → particle retention time can be controlled** by rotation speed
- Prototype (10kW) successfully **tested up to 900°C**





DLR

# R&D Outlook on Technologies (plus Trough Tech.)

- **State of the art technologies**
  - Trough with thermo oil
  - Tower with steam
  - Tower with salt
  - Fresnel with steam

**Field of R&D**

Methods on qualification, operation optimization, degradation, side evaluation

- **First-of-its-Kind technologies**
  - DSG in trough
  - Open vol. Receiver
  - Industrial process heat

Optimization of components
Adaptation of conventional components for solar applications

- **Technology in pilot phase**
  - Salt in Trough/Fresnel
  - GT + Tower

Pilot plants and Development

- **Technology under development**
  - Particle (Tower)
  - Liquid metal (Tower)
  - Development of new HTF (Tower/Trough/Fresnel)
  - Solar Fuels

Prototype testing (lab scale) / Scale-up / Modeling / materials and properties / system evaluation / basic research on effects, kinetics, conversion rates ….

# Thank you for your attention!

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