sCO_2 Power Cycles with Integrated Thermochemical Energy Storage Using an MgO-Based sCO_2 Sorbent in Direct Contact with Working Fluid for Grid Energy Storage Applications

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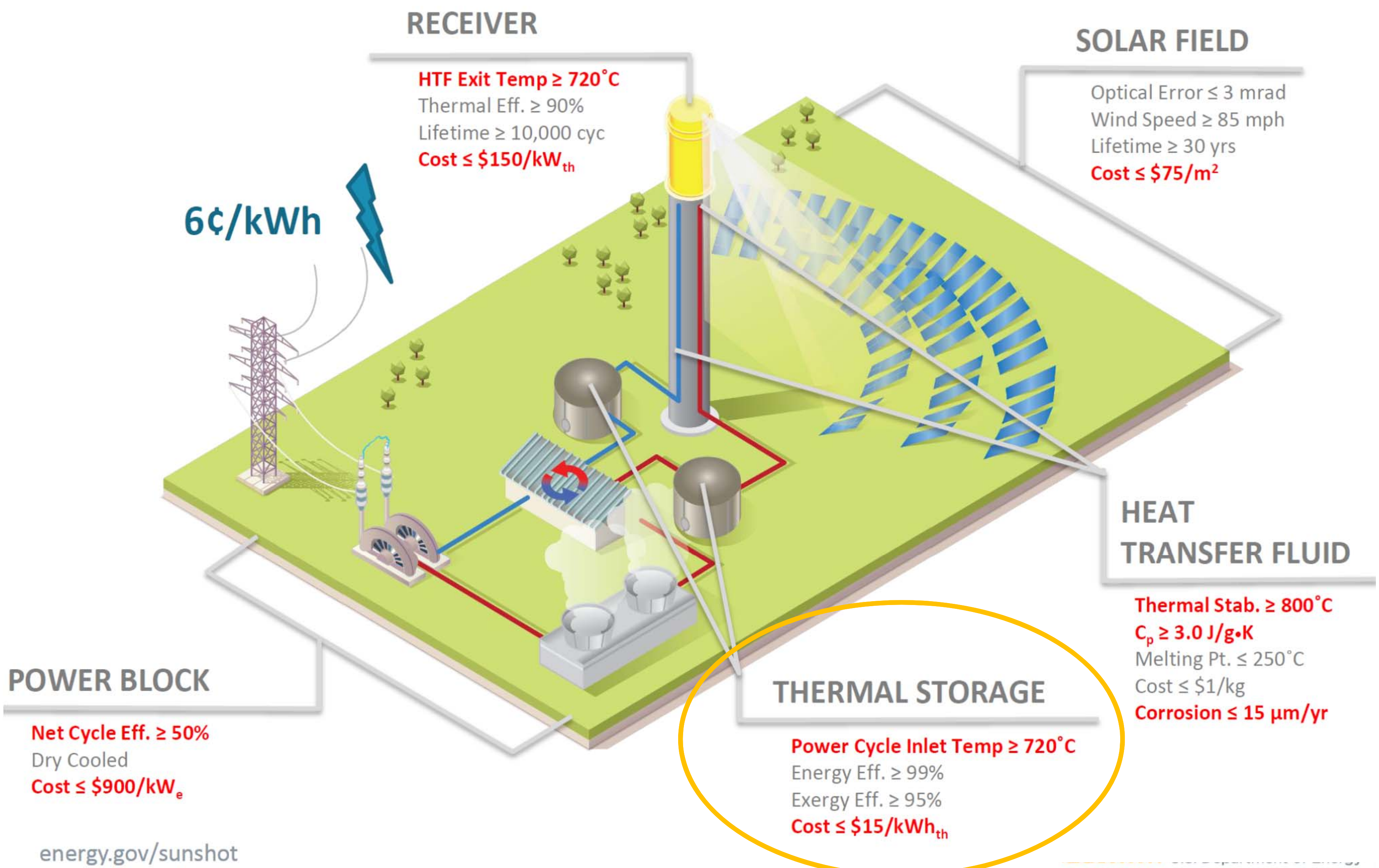
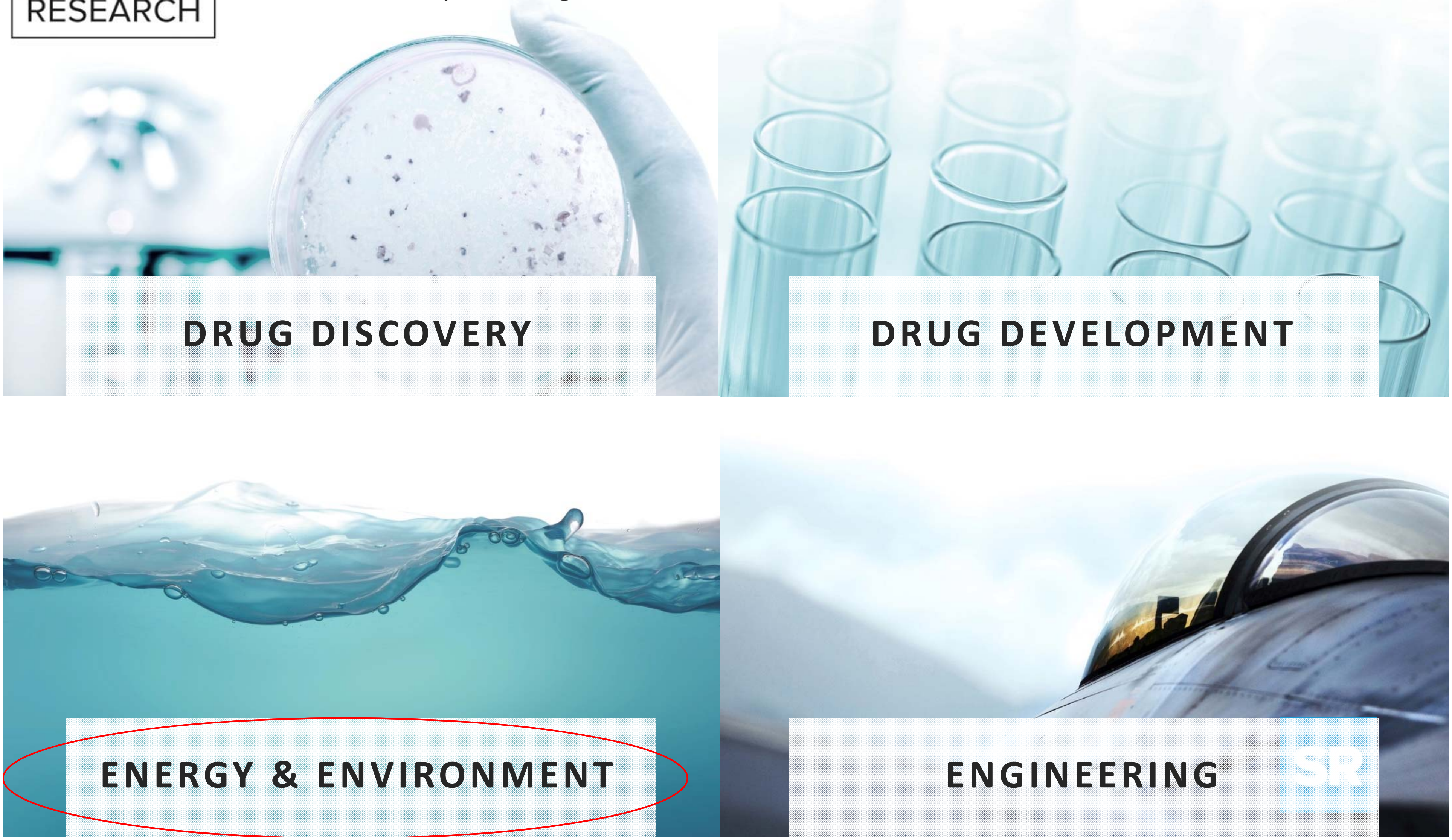
Presentation Outline

- **Introduction to SunShot program and Southern Research**
- **Thermochemical energy storage fundamentals and system design**
- **Heat exchange reactor design**
- **Quasi steady state and Transient modeling**
- **Technoeconomic analysis**
- **CO_2 sorbent material engineering**
- **Summary and technical challenges**

SunShot CSP Performance and Cost Targets



- Non-profit, established in 1941
- Headquarters in Birmingham Alabama
- 450 Scientists, Engineers and Technicians
- Four operating divisions



Energy Storage Projects at Southern Research

SunShot thermochemical energy storage projects

CaO-based CO_2 sorbent

1) ELEMENTS (2 yrs): "Regenerative Carbonate-Based Thermochemical Energy Storage System for Concentrating Solar Power**", DE-EE0006535**

2) APOLLO (3 yrs): "Demonstration of High-Temperature Calcium-Based Thermochemical Energy Storage System for use with Concentrating Solar Power Facilities**", DE-EE0007116**

MgO-based CO_2 sorbent

3) EERE, Combined water gas shift/CO_2 capture process for integrated gasification combined cycle systems, **DE-FE0026388**

4) SunShot Technology to Market (2 yrs): "sCO_2 power cycle with integrated thermochemical energy storage using an MgO-based sCO_2 sorbent in direct contact with working fluid**", DE-EE0008126**

Types of Thermal Energy Storage

Sensible Heat

- Energy stored in vibrational modes of molecules (molten salts, sand, etc.)

Latent Heat

- Energy stored in media as it changes phase from solid to liquid (molten salts, Al-Si alloy)

Thermochemical Energy

- Reversible chemical reactions involving gases. Gases can be compressed and allow for a temperature swing, pressure swing or combination thereof to drive reaction.

Too Hot

Metal oxides

Decomposing gases (Hydrocarbons, Ammonia)
Carbonates
Metal hydrides
Hydroxides

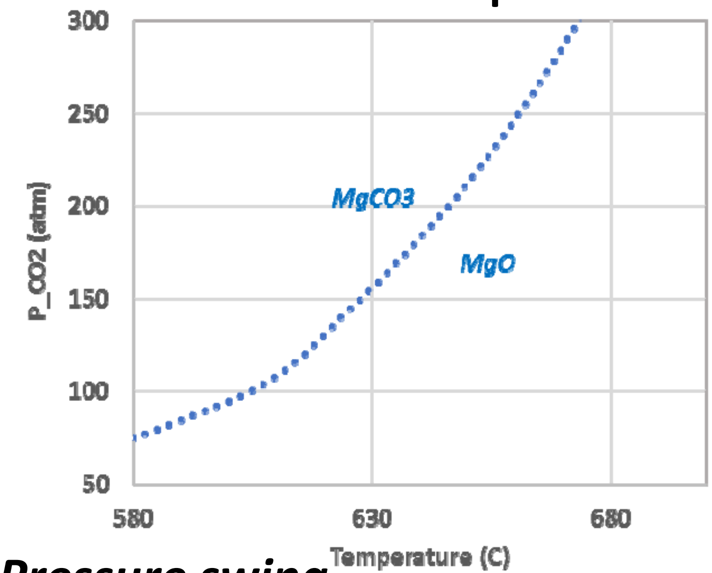
Ammoniates
Hydrates

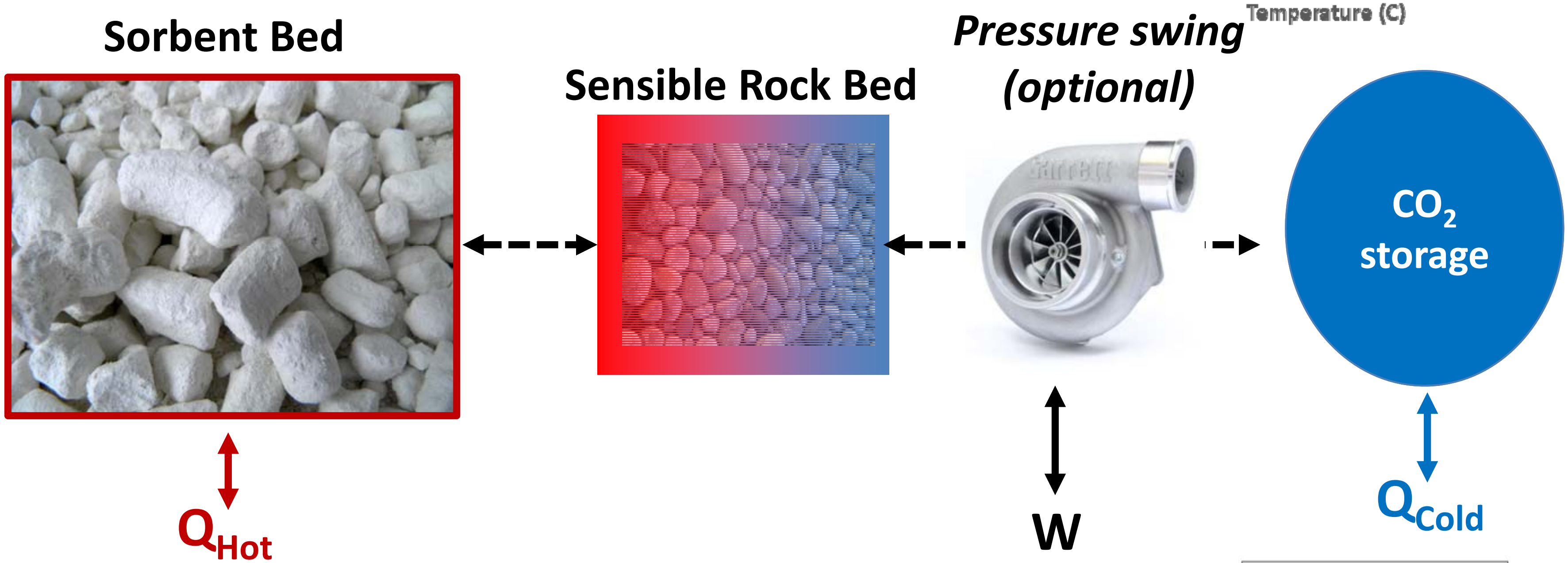
Too Cold

Thermochemical Energy Storage Operation and Components

(sorbent) (sorbate)

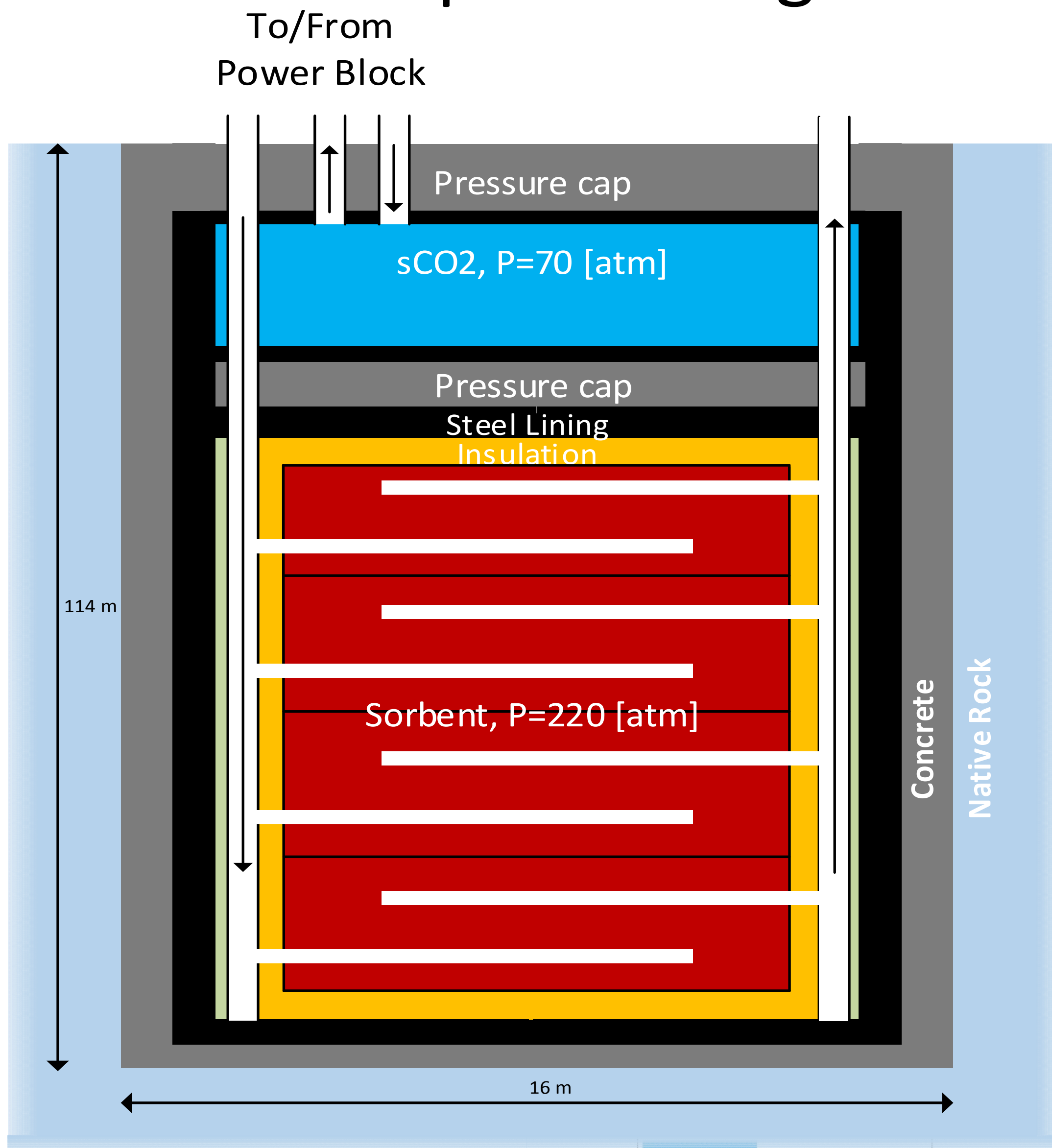
$$MgO + CO_2 = MgCO_3 + 106\ kJ$$





Heat Exchange Reactor Conceptual Design

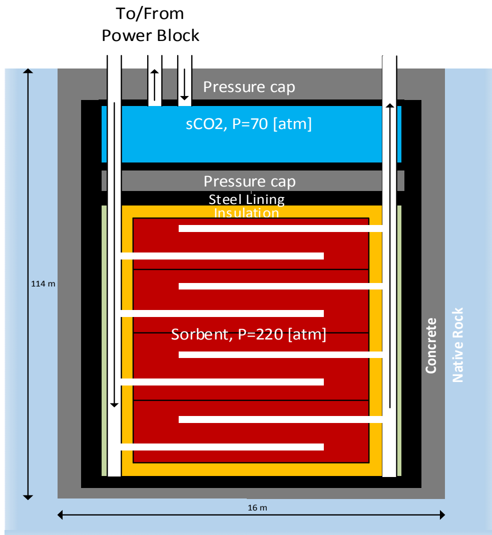
- 10 hrs of storage, 2000 MWh_{th}
- T=585-675 degC, P= 70-300 atm
- All major TCES components are contained in a underground. The surrounding bedrock is used as a cost-effective means of pressure containment.
- Possibly constructed using mine-shaft drilling technology: 16 m diameter, 114 m deep.
- Sorbent is loaded into parallel packed beds, with a fluid path length of 5 m and a pellet size of at least 200-650 µm.
- Existing underground storage: natural gas storage hasbeen demonstrated at similar volumes capable of >500 atm.[1,2]



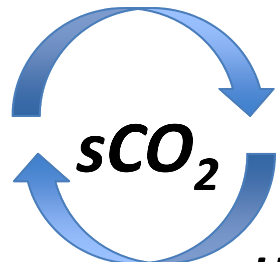
[1] Lavine, A. S., Lovegrove, K. M., Jordan, J., Anleu, G. B., Chen, C., Aryafar, H., and Sepulveda, A., 2016, "Thermochemical Energy Storage with Ammonia: Aiming for the Sunshot Cost Target," *SOLARPACES 2015*
[2] Glamheden, "Excavation of a cavern for high-pressure storage of natural gas", Tunneling& Underground Space Tech., 2006.

MgO-based TCES offers potentially the fewest components of any TCES for CSP

High pressure!

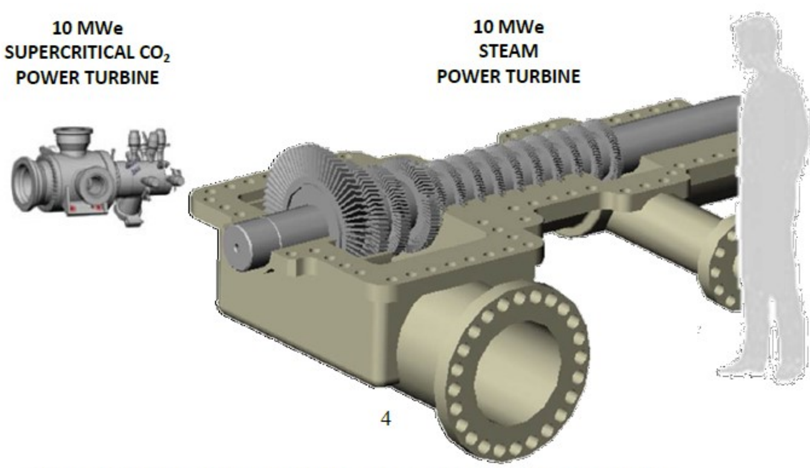


sorbate

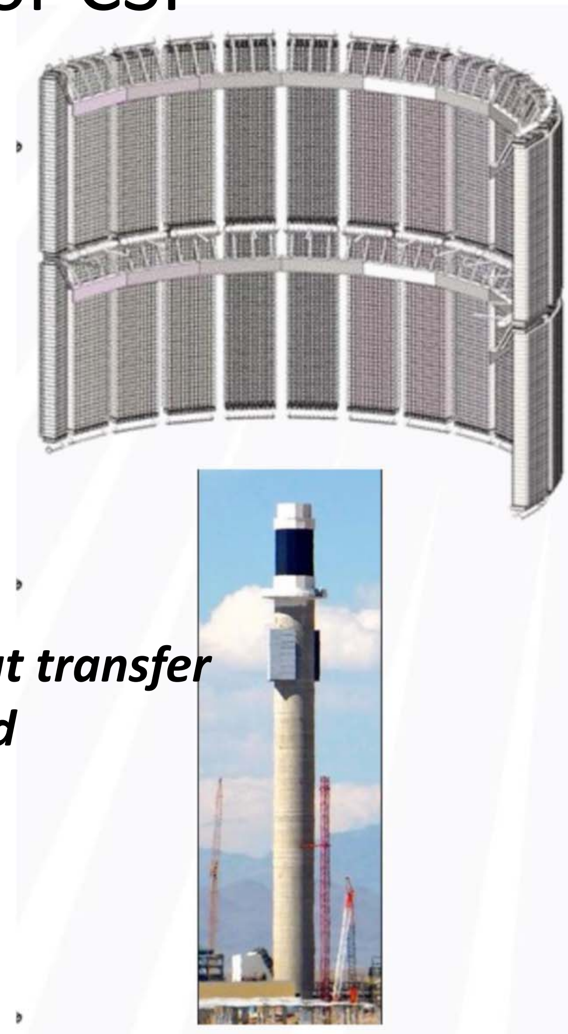


Working fluid

Heat transfer fluid



Echogen's 10 MWe sCO_2 power turbine compared to a 10 MWe steam turbine.



ECHOGEN power systems

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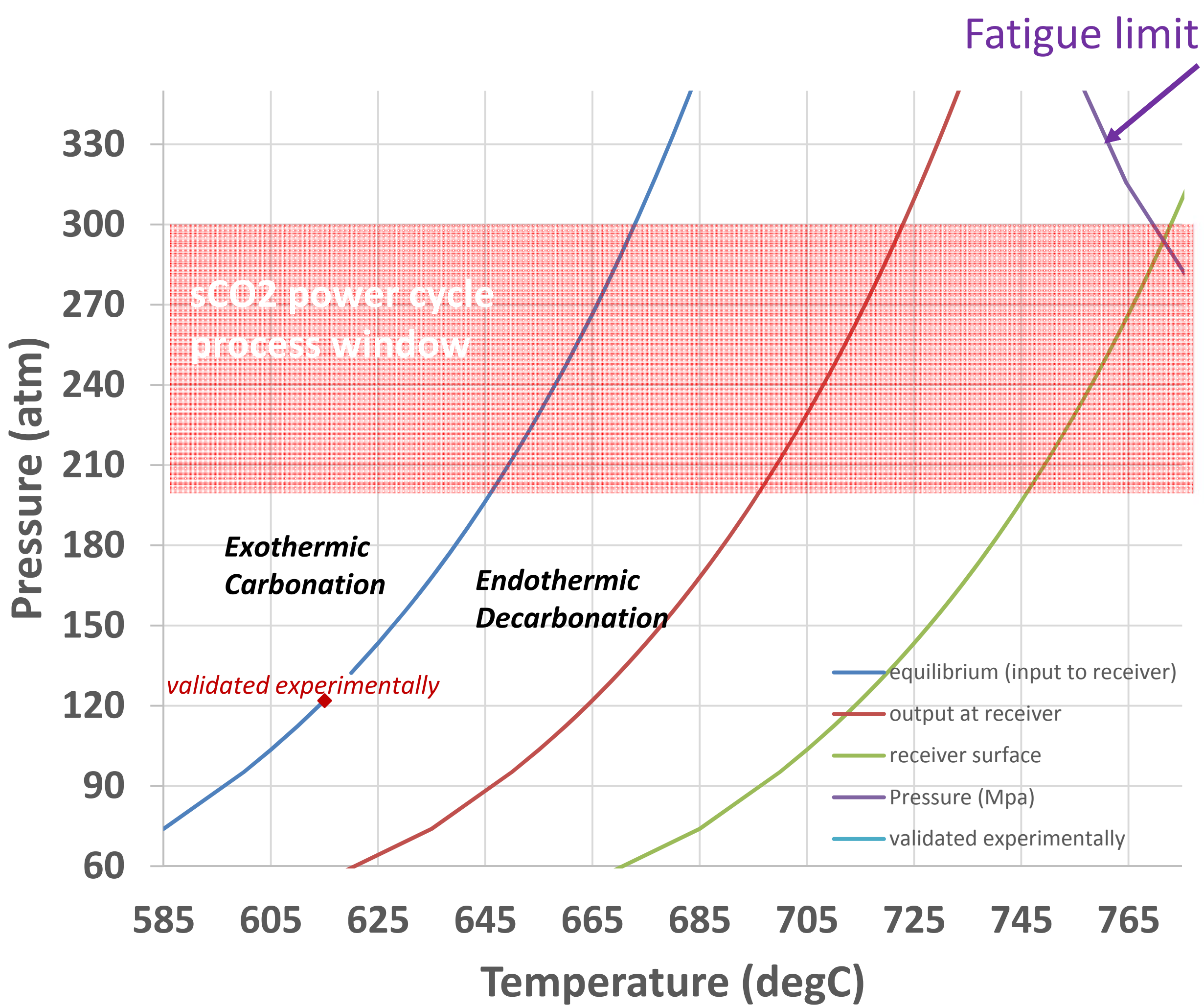
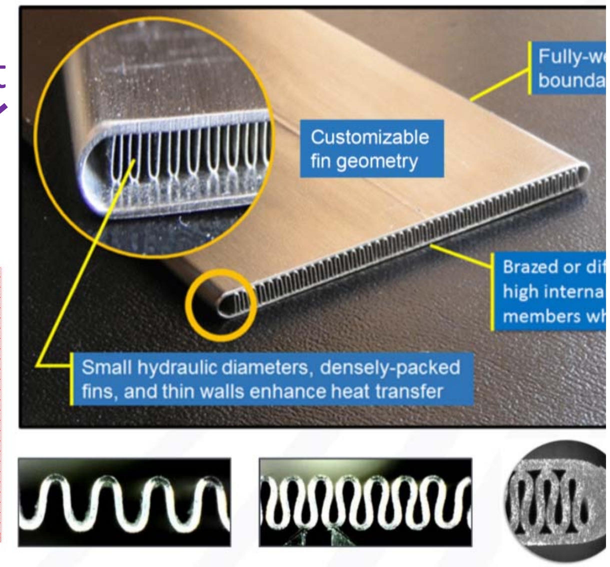
Reaction Thermodynamics

$MgO + CO_2 \leftrightarrow MgCO_3 + \mathit{106\ kJ}$





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Integrated sCO_2 Process Flow Diagram

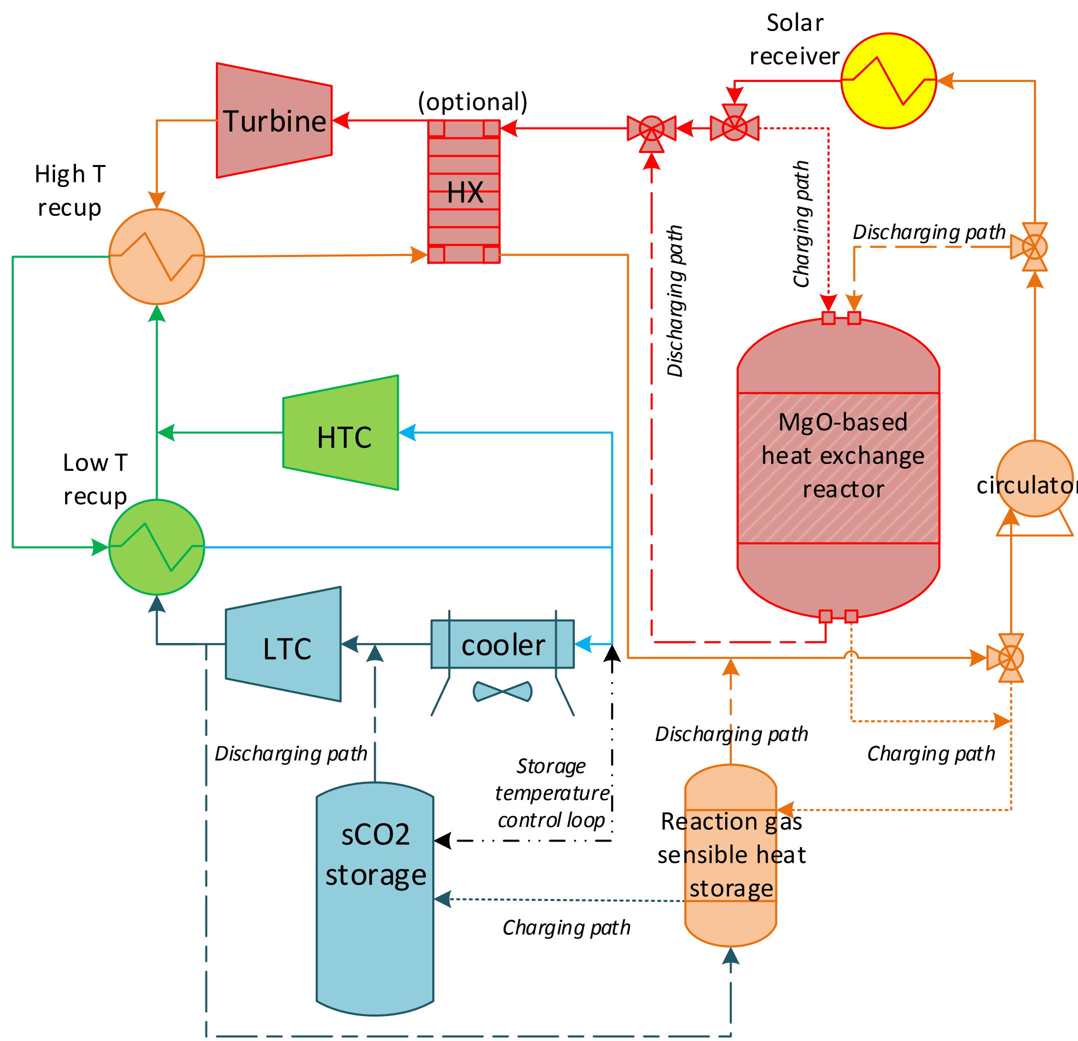
Features:

- "reheat" cycle is utilized to accept thermal energy under a smaller temperature range: 50°C as opposed to 200°C
- Ability to maintain near-constant power production during transient on-sun conditions with a single reactor

New major components:

1) heat exchange reactor
2) sCO_2 storage vessel
3) sensible heat storage system for the reactive CO_2.
4) circulator

Additional minor components include cyclone separators or filters (not pictured) to eliminate the transport of sorbent fines



Round-trip Exergy Efficiency

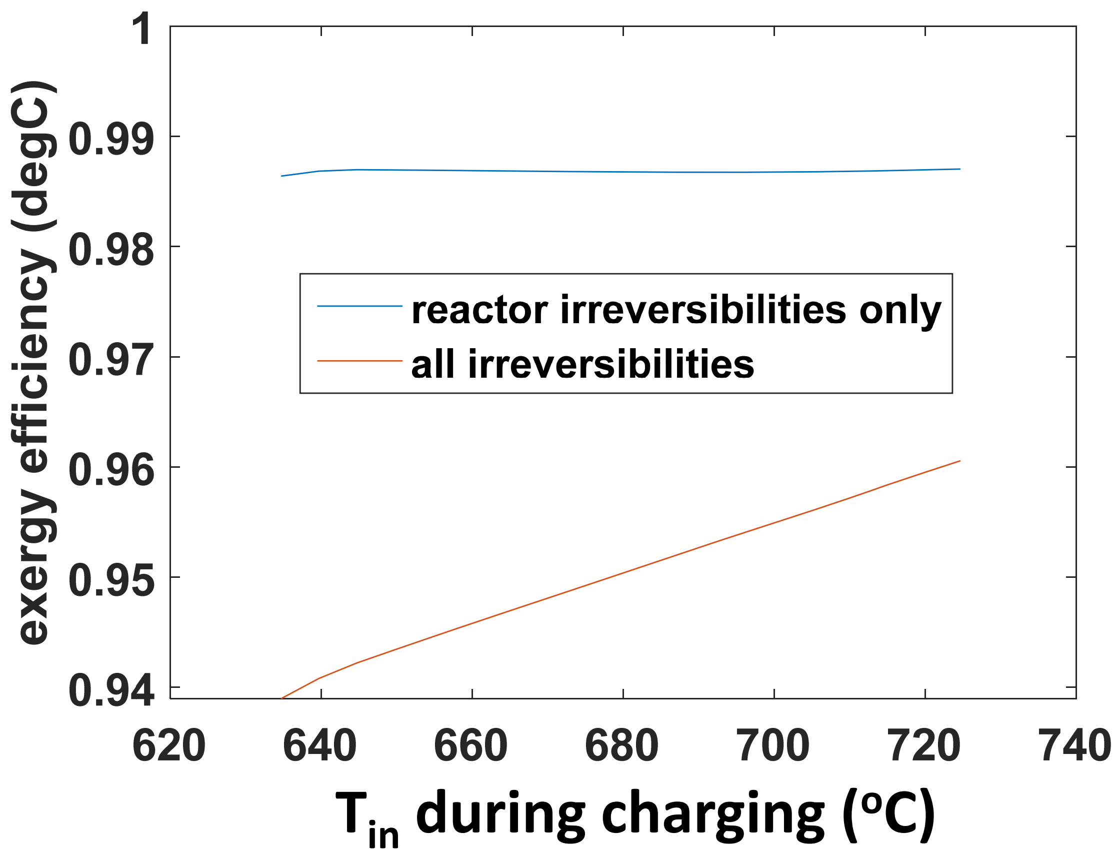
- Discharge (carbonation) pressure is held constant 300 atm (675ºC).
- Charging (decarbonation) pressure swept from 73 atm to 300 atm
- Chemical heat pump operation is possible but there is an efficiency penalty

Reactor irreversibilities

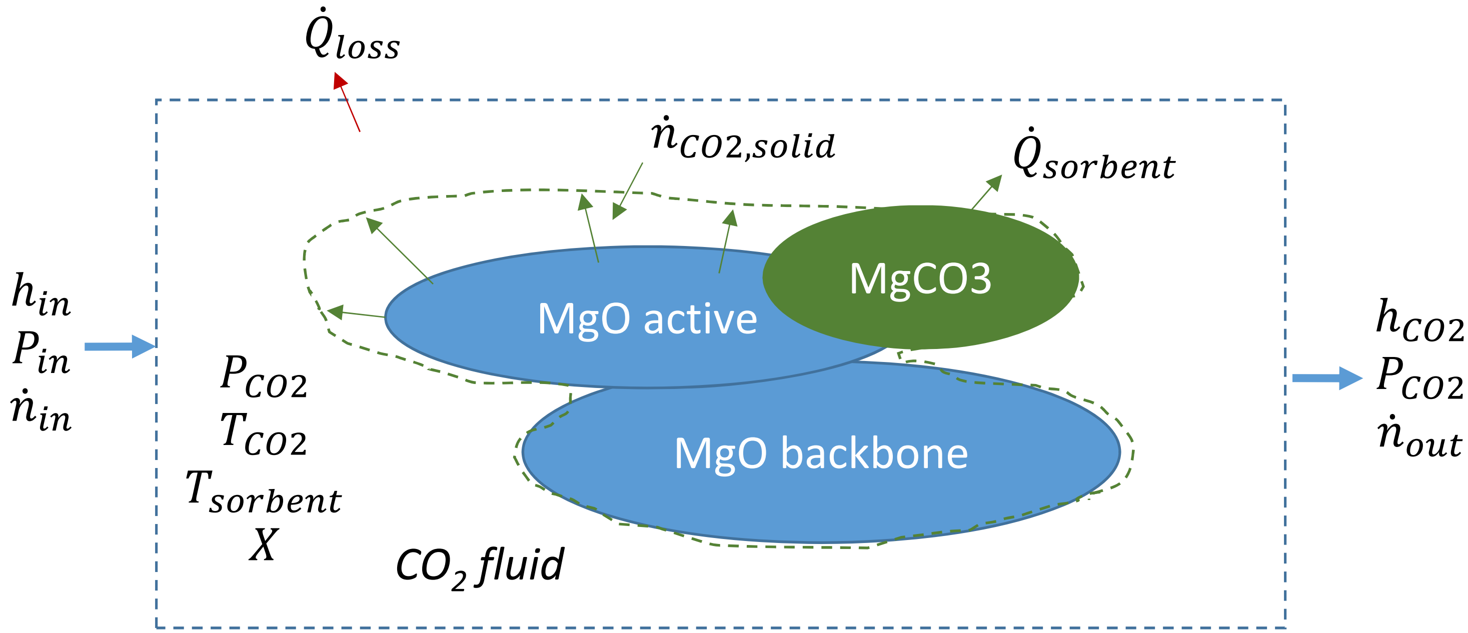
dT_bed_approach	2ºC
dT_decarbonation	50ºC
dT_carbonation	50ºC
Efficiency_thermal_insulation	0.99

Balance of plant irreversibilities

2nd_law_efficiency_power_cycle	0.7
dT_loss_sensible_heat_storage_reaction_gas	50ºC
2nd_law_efficiency_compressor	0.93



Transient 0D Model Development



CO_2 Inputs, Reactor initial conditions

System of ODEs
- Mass balances
- Momentum balance
- Energy balances
- Reaction kinetics

Matlab solver

Results

$$\frac{dX}{dt} = \frac{A_f}{R_c T_{sorbent}} \exp\left(\frac{-E_A}{R_c T_{sorbent}}\right)\left(P_{CO_2} - P_{eq}\left(T_{sorbent}\right)\right) * product\_layer\left(X\right)$$

Transient 0D Simulation

<u>Simulation inputs</u>

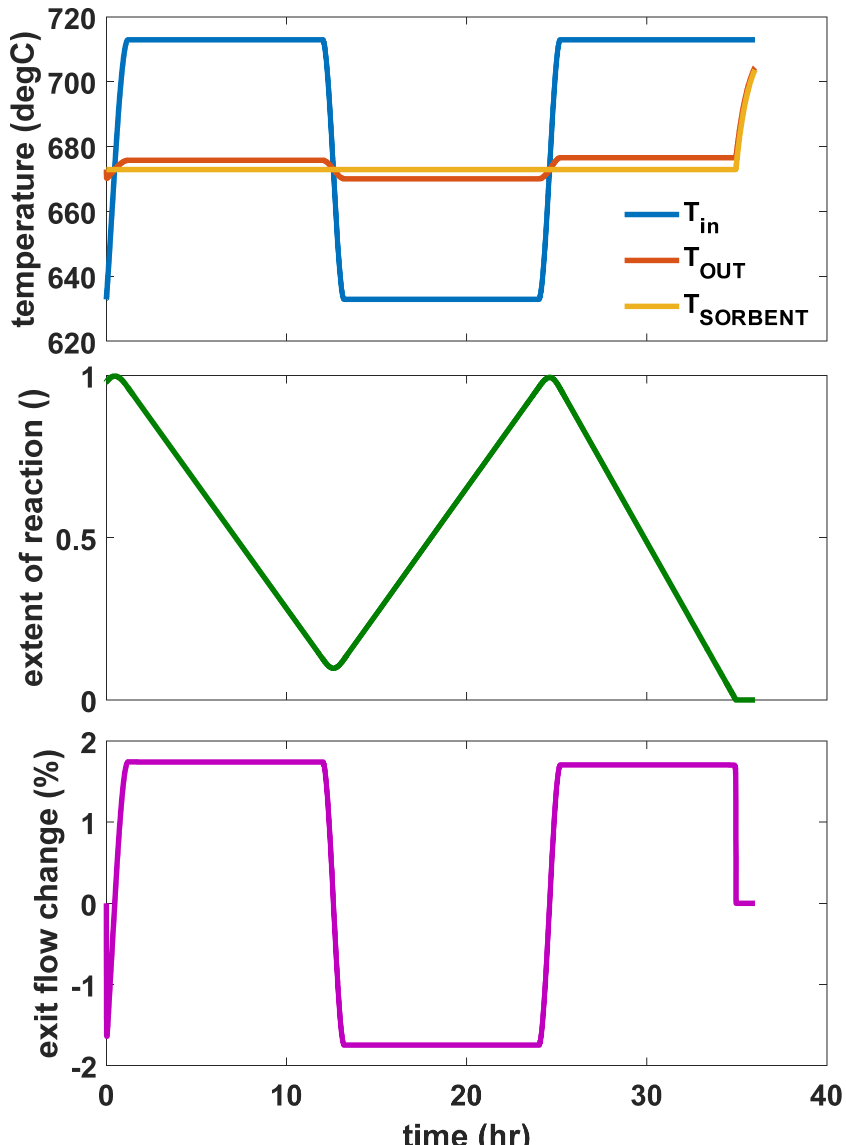
- P=300 atm (no losses)
- Mass flowrate=constant (normalized)
- T_{in} is time varying on 12-hr half-cycle
- System intentionally driven to an "over charged" state

<u>Model results</u>

- $T_{sorbent}$ remains at a stable value until system is overcharged, after which both $T_{sorbent}$ and T_{CO2} approach T_{in}
- Basic operation of prototype model is validated

<u>Future work</u>

- Extend to 1D
- Use measured sorbent properties



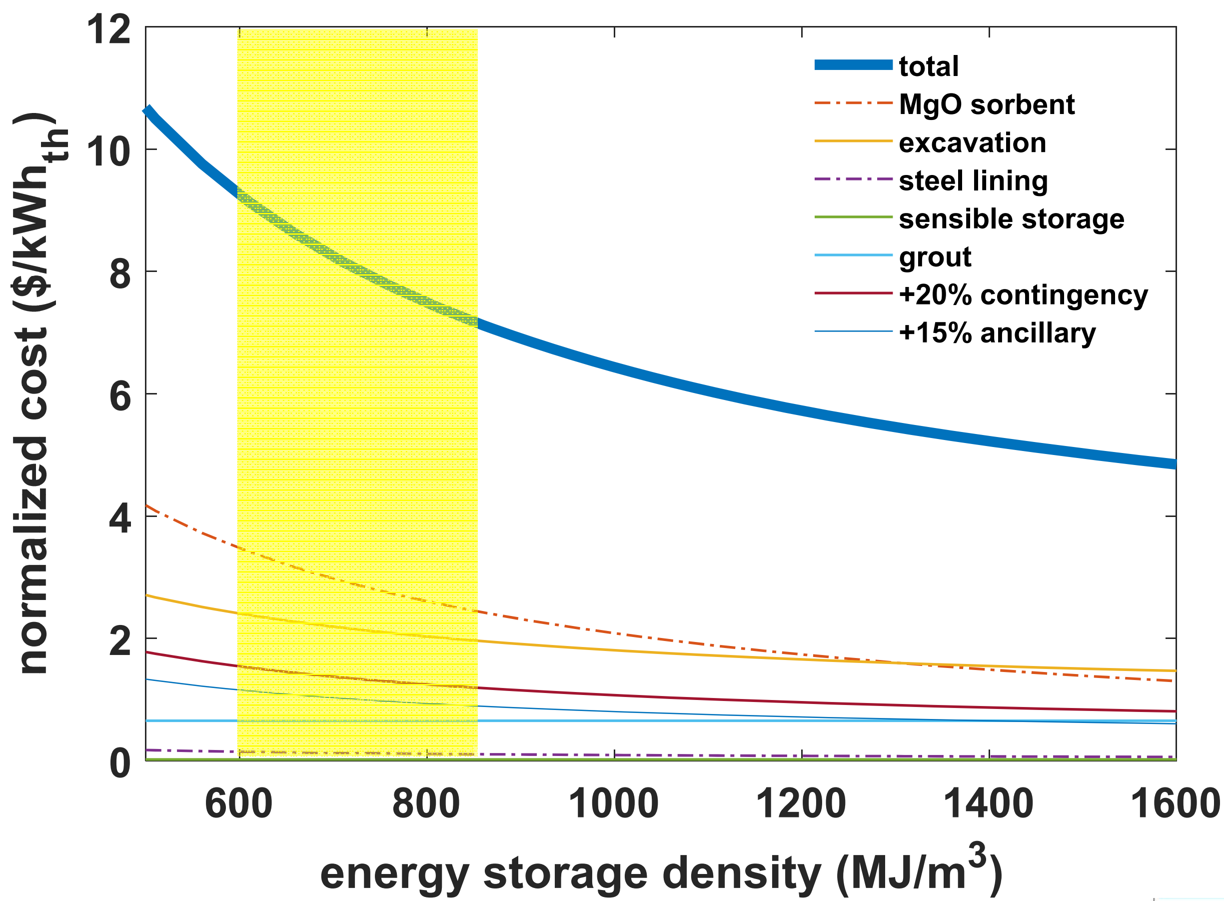
Technoeconomic Analysis

Major cost drivers:

1) energy density of the MgO-based sorbent (\$500/$ton_{sorbent}$ assumed)

2) Underground excavation (\$400/m^3 assumed)

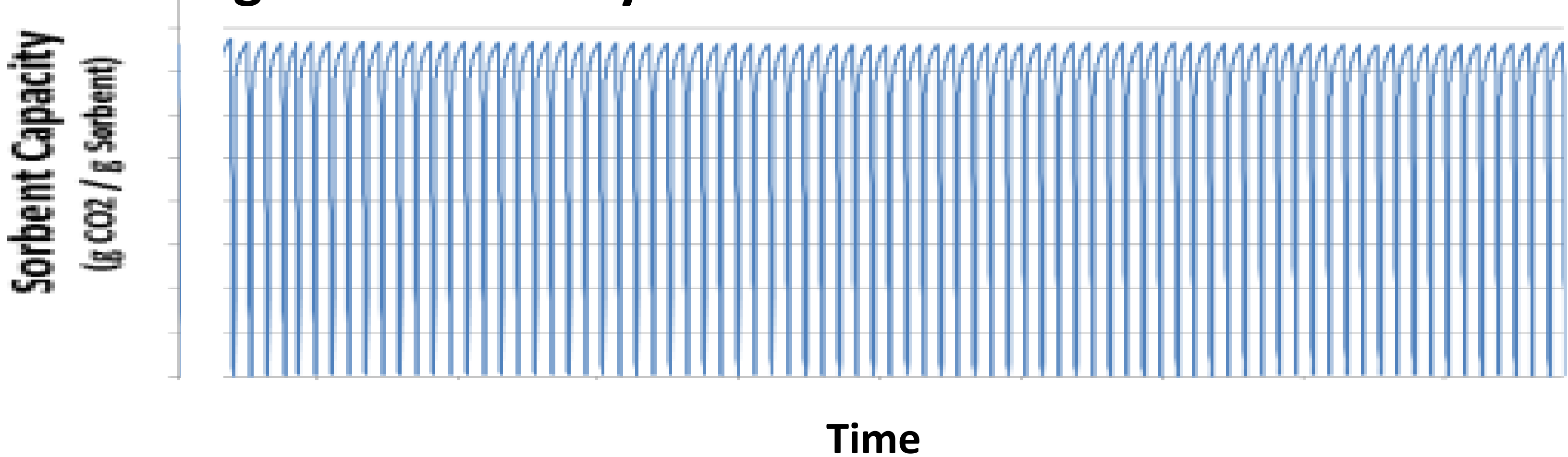
Total estimated cost basis: 7-9 \$/kWh_{th}



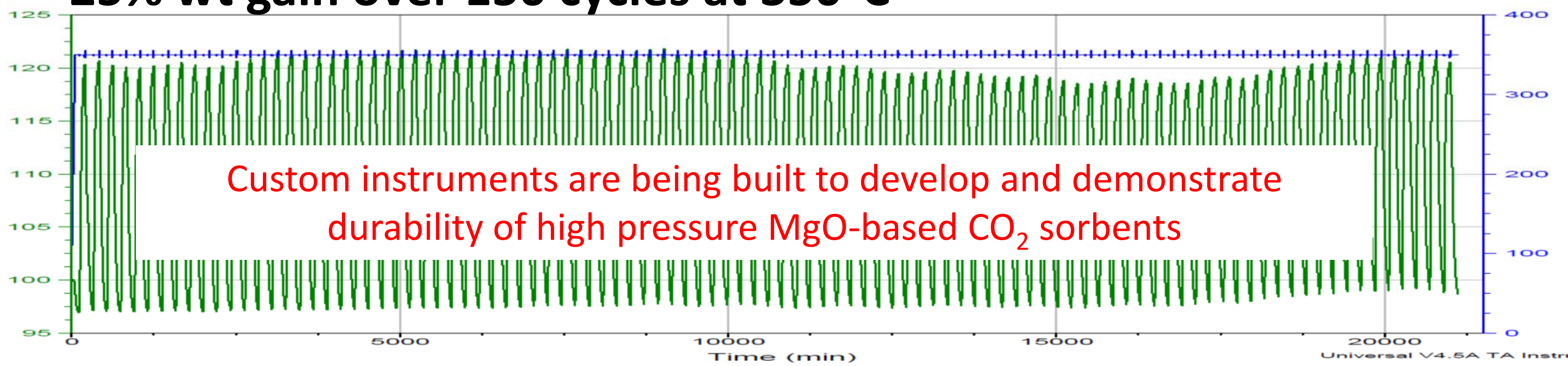
OUTHERN ESEARCH

Sorbent Durability Tests in TGA

CaO-based stabilized CO_2 synthetic sorbent
38% wt gain over 100 cycles at 750°C



MgO-based promoted CO_2 synthetic sorbent
25% wt gain over 150 cycles at 350°C



Summary

- SR has engineered high performance CaO- and MgO-based CO_2 sorbents and thermal energy systems. Similar methods and approaches will be applied to development of the high pressure MgO-based TCES system.
- Identified a viable path to meet or exceed **SunShot performance targets**
  - Exergy efficiency = 96 %
  - Capital cost ≤ $10/kWh$_{th}$ for a commercial plant
  - Power cycle efficiency ≥ 50%

Technical Challenges

- Sorbent performance and total life-cycle costs
- Low cost, high pressure, underground reactor construction
- Integration and controls of the receiver + thermal storage + power cycle

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Acknowledgements

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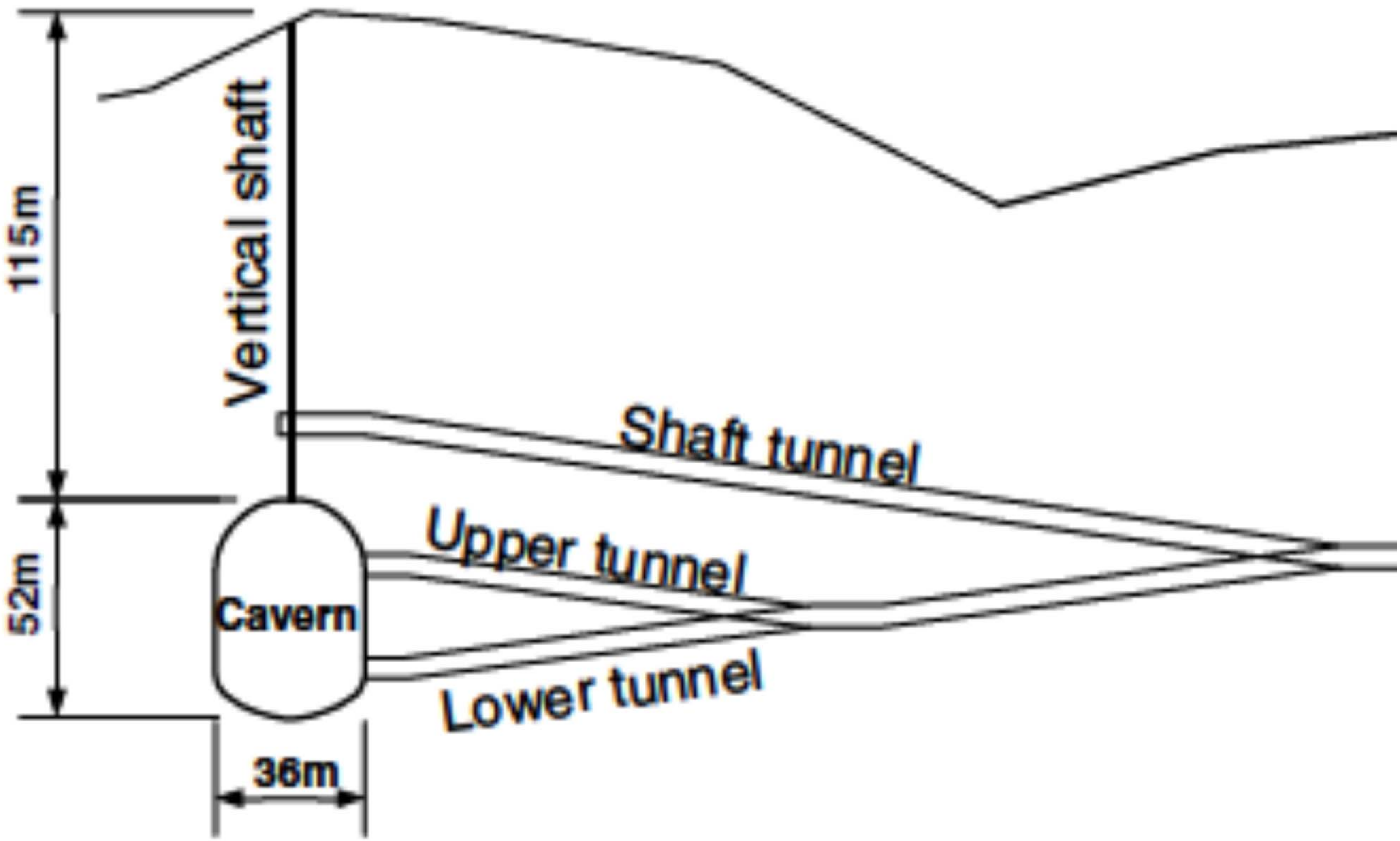
SunShot U.S. Department of Energy



Glamheden, "Excavation of a cavern for high-pressure storage of natural gas", Tunneling& Underground Space Tech., 2006.