"Brayton Cycle Baseload Power Tower CSP System"

Project Start Date: September 1, 2010

Potential for 5, not just 4, approaches to CSP:

1. Troughs
2. Central power towers
3. Linear fresnel
4. Dishes
5. And now modular Brayton towers with dry storage

DOE SunShot Program Review April 23, 2013

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Bruce N. Anderson, CEO
Wilson Solarpower Corporation
617-290-9913
Bruce.Anderson@WilsonSolarpower.com

Project Leadership

Presenting: Bruce N. Anderson, CEO & Chairman

- *Began solar career in 1973 with Masters degree at MIT*
- *1980 Advisory Board Member of NREL (then SERI – Solar Energy Research Institute)*
- *1982 First recipient "Lifetime Achievement Award," American Solar Energy Society*
- *Twice testified to US Congress on energy matters*
- *35-year career CEO*

PI: Bill Treece, Vice President Engineering

- *45-year veteran of microturbine and related technology development & project management*
- *SVP, Capstone Turbine, Strategic Technology (2003-2009); SVP, Engineering (2001-2003)*
- *Director, Sundstrand Turbomach's APU Division*
- *Solar Turbines, Gas Turbine Product Engineering Manager*
- *Holds seven U.S. patents, four patents pending in gas turbines and four in CSP*

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Presentation Outline

- *Concept and Project*
- *Phase 1 results*
- *Phase 2 SOPO*
    - *Zero pressure solar receiver*
    - *Thermal energy storage*
    - *High-temperature heat exchanger*
- *Path forward*

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Project Team Members

Including both Phase 1 and Phase 2

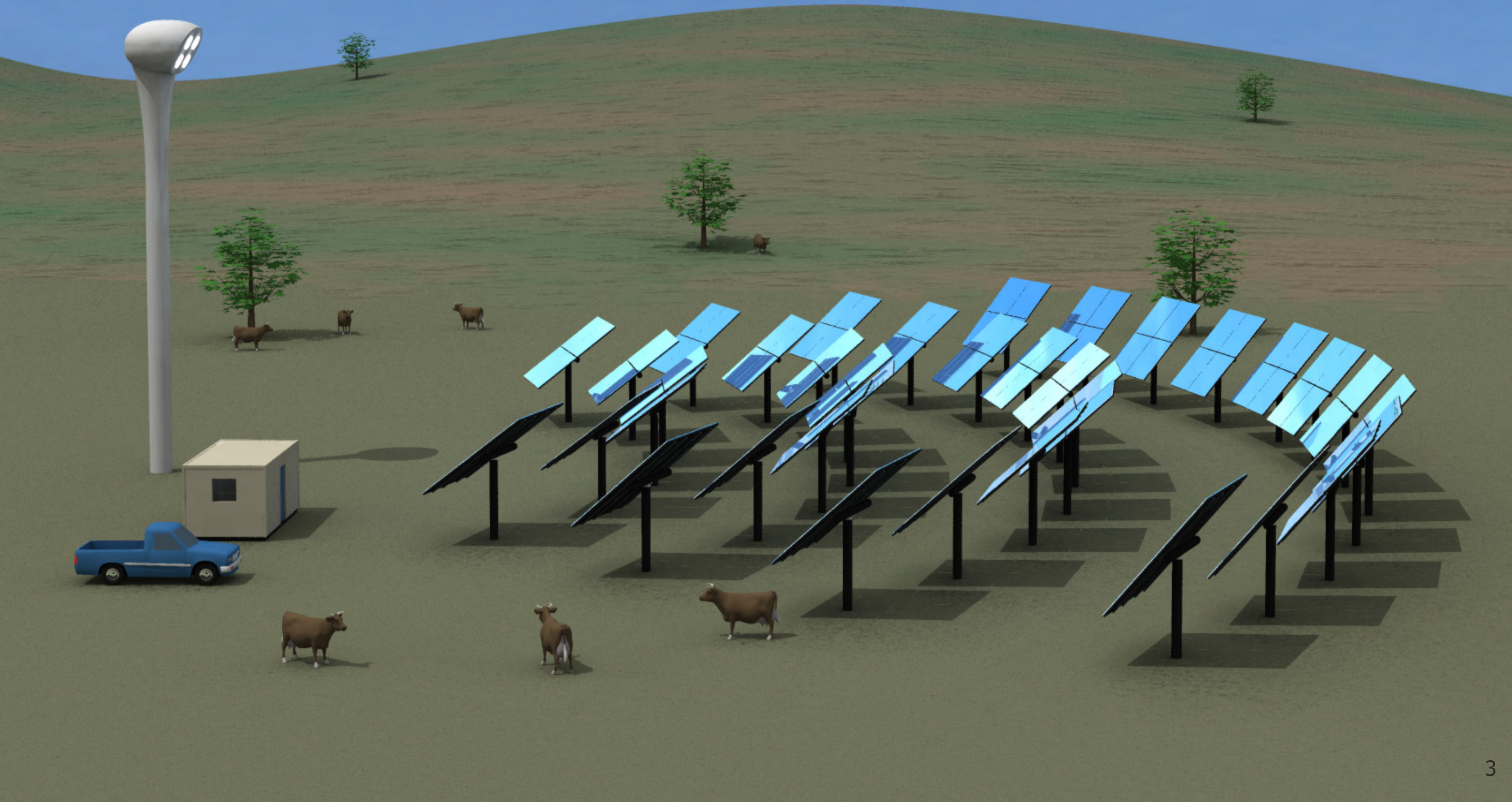
Thank you to our team members

- German Aerospace Center (DLR)
- Saint-Gobain
- Brayton Energy
- WorleyParsons
- Solaflect Energy
- EZKlein
- Oak Ridge National Laboratory
- Sandia National Laboratory
- US Department of Energy funding (of course!)

Brayton Power Towers

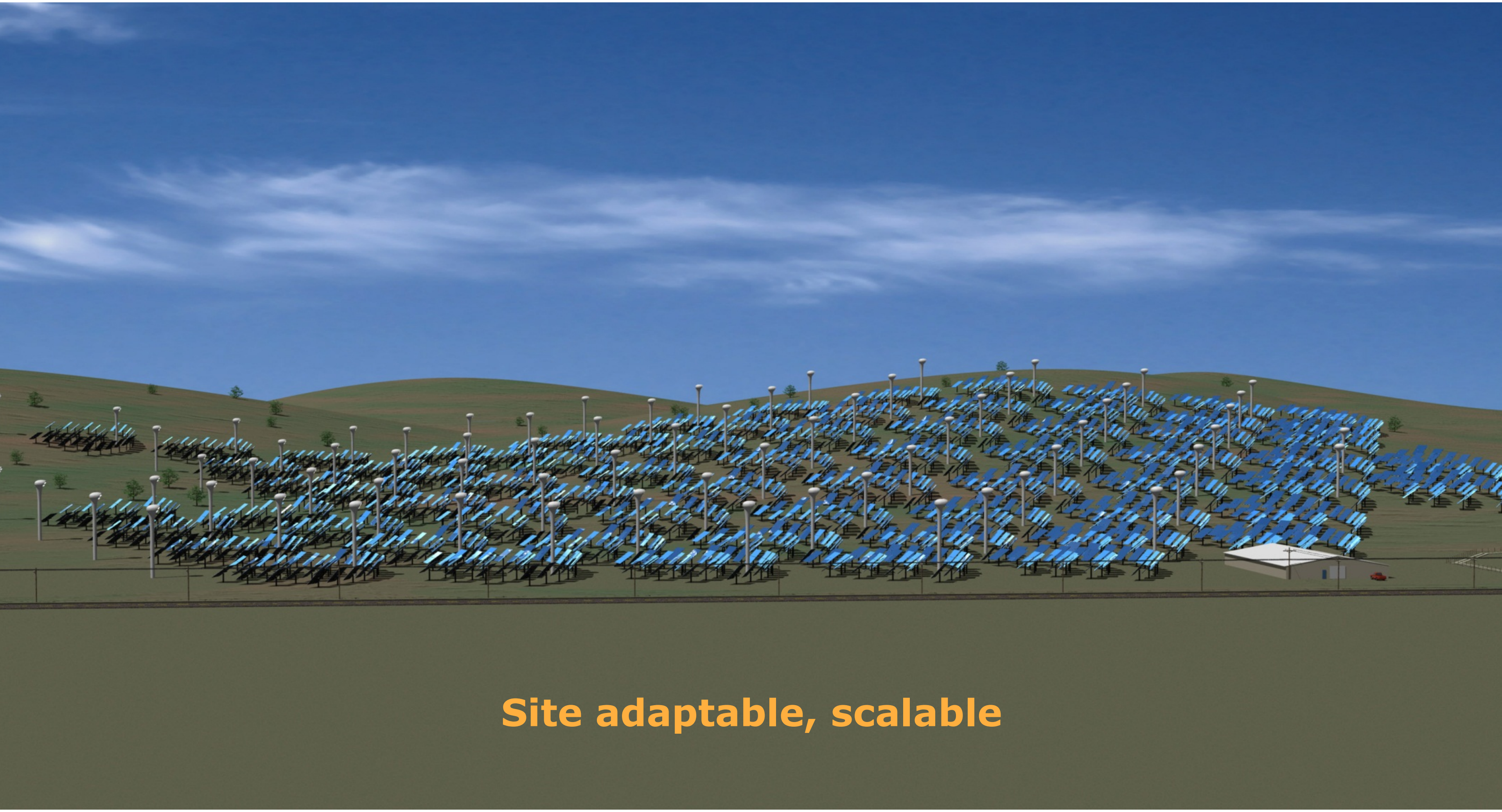
Pre-engineered, standardized modules

- *Targeting <6 cents/kWh, 24/7, 85% solar*
- *Uses compressed, super-heated air (~950^{o}C); no water/steam, oil, salt*



Distributed, Dispatchable 24/7

Few environmental issues



Site adaptable, scalable

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Project Objectives

Baseload CSP competitive with conventional power

- ***PHASE 1 through August 2011***

Identify a utility-scale Brayton-cycle baseload power tower system with a >75% capacity factor, >85% solar fraction, and LCOE of <9 ¢/kWh.

- ***PHASE 2 through mid 2013***

Develop, build, test, and evaluate an innovative solar receiver and engineer a dry thermal storage system.

- ***PHASE 3 through mid 2015***

Engineer, build, test, and evaluate a single baseload 300-kWe power plant module.

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DOE Phase 1 Summary Results

DOE targets vs Wilson projections

Success criteria	DOE targets	Wilson system
LCOE DOE's gas price of $6.75/MBtu	9 cents/kWh	7.7 cents/kWh
LCOE July 2011 gas price of 4.71/MBtu	NA	6.9 cents/kWh
Capacity factor	75% (6500hr)	75-100%
Solar fraction	85% (5585hr)	>5585hr
Receiver costs	$170/kWe	$80/kWe
Thermal storage costs	$75/kWh	$55/kWh
Heliostat cost	$120/m^2	$90/m^2

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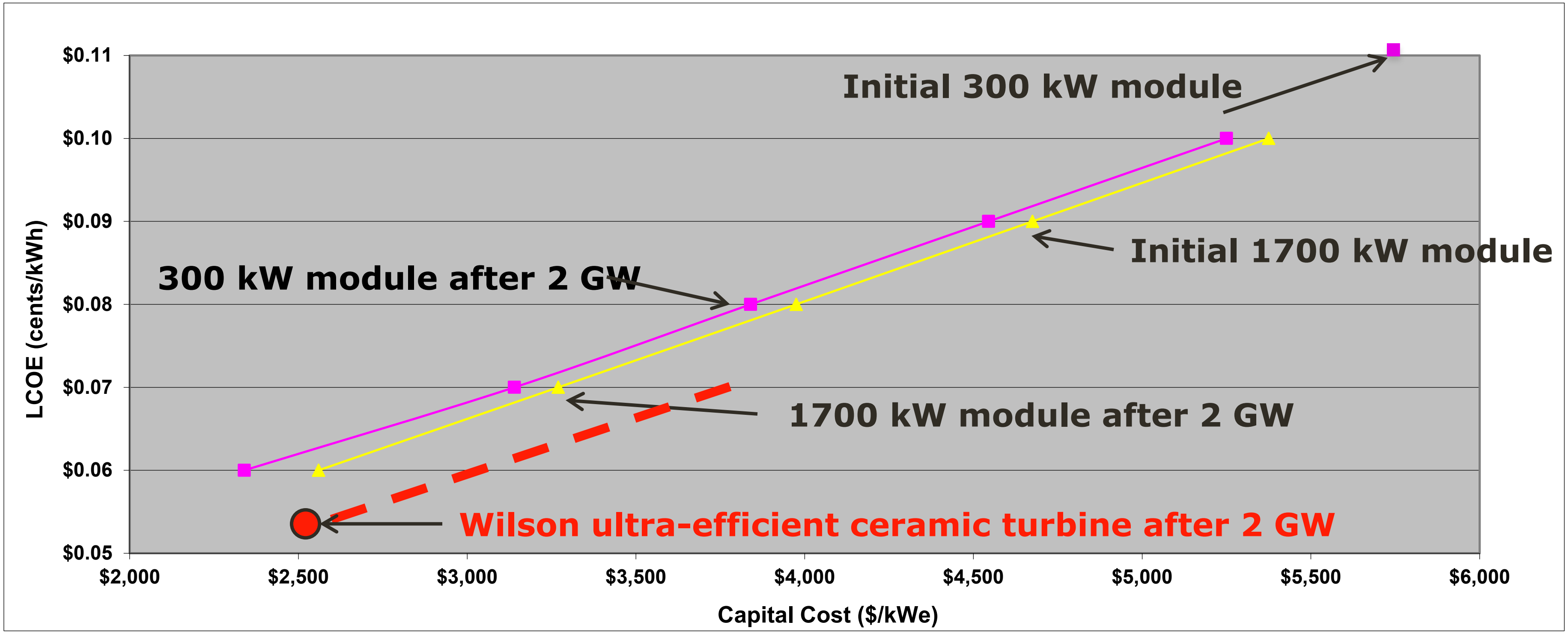
LCOEs vs CAPEX for $4.75 gas

SAM - 100 MW plant at Daggett, CA, USA (2700 kWh/m2/yr)

38.7% Efficiency, 75% Capacity Factor (65% Solar, 10% Fuel)
42% Efficiency, 75% Capacity Factor (67% Solar, 8% Fuel)
ESTIMATED: 54-60% Efficiency, 75% Capacity Factor (65% Solar, 10% Fuel)



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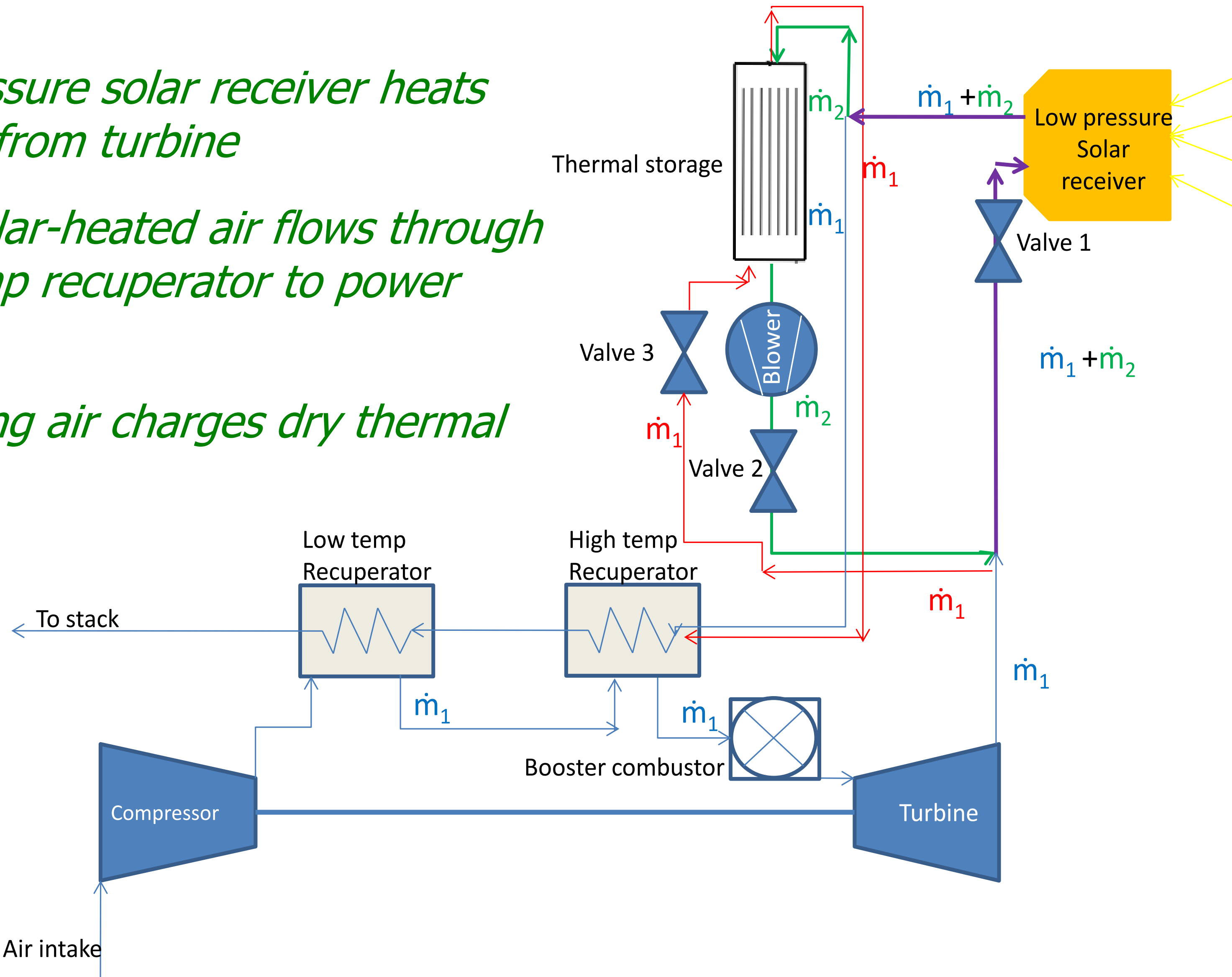
Proprietary Low Pressure System

- *Low pressure solar receiver heats exhaust from turbine*
- *Some solar-heated air flows through high-temp recuperator to power turbine*
- *Remaining air charges dry thermal storage*



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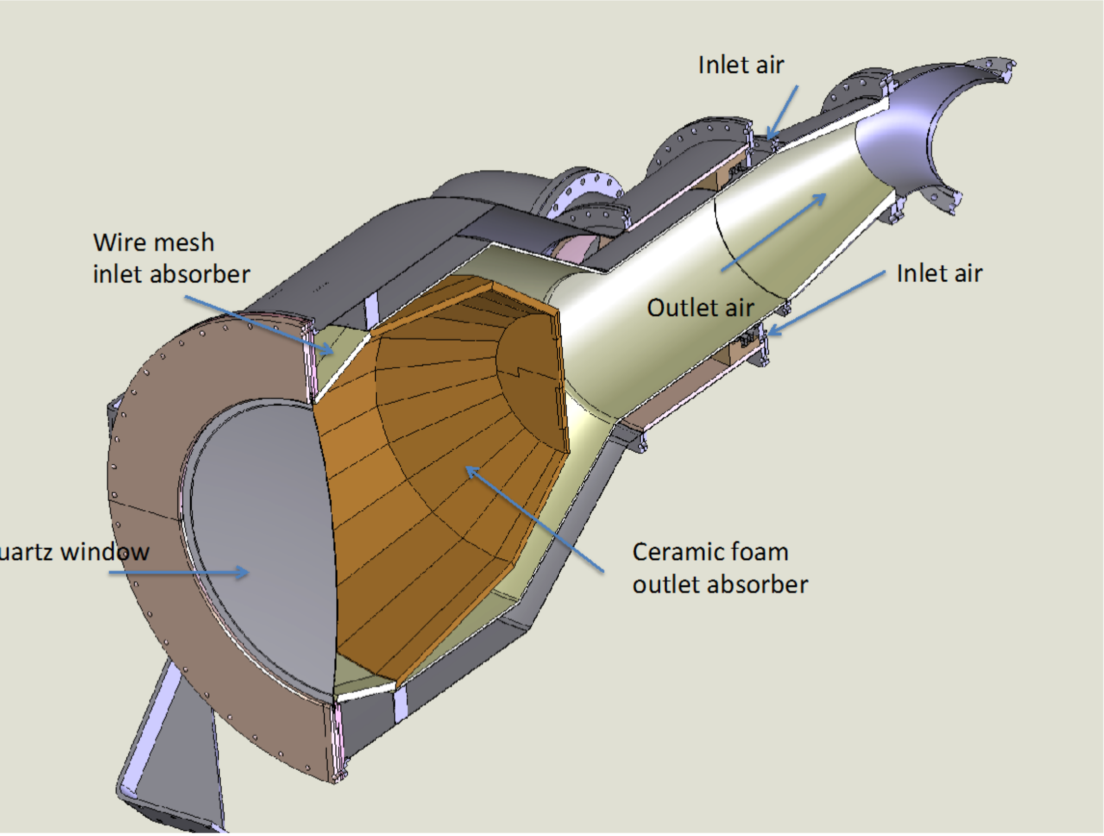
Wilson Solar Receiver™

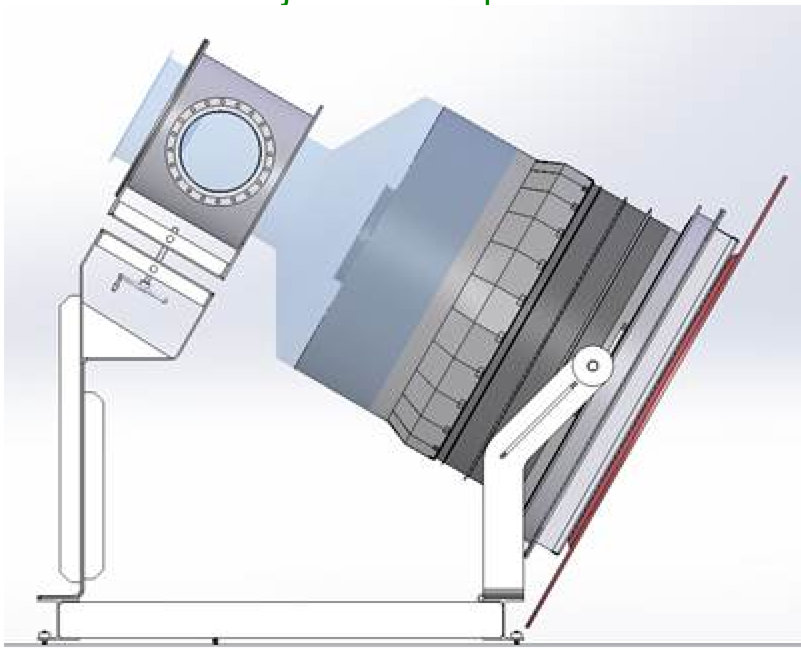
DLR development partner; ~950C; 7X greater power



The air flow from the turbine and/or the thermal storage system flows around the perimeter of the receiver, enters the cavity formed by the absorber near the front of the receiver near the quartz window, passes through the ceramic absorber, and exits through the rear.

Note that the quartz window has been modified in the final design from a single piece to multiple panes

The angle of the receiver can be adjusted in response to latitude.



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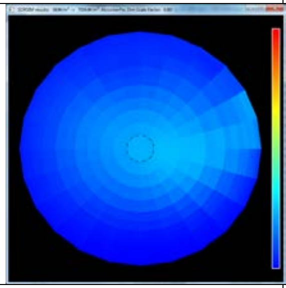
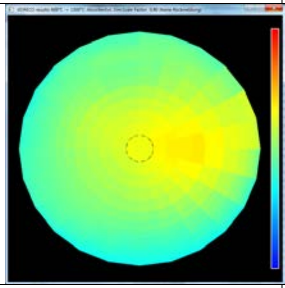
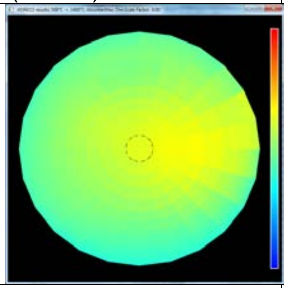
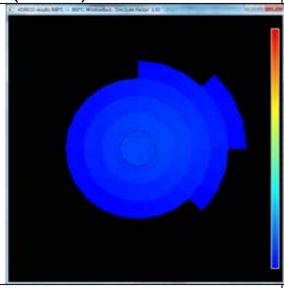
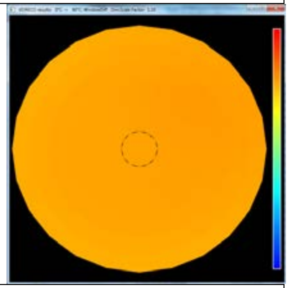
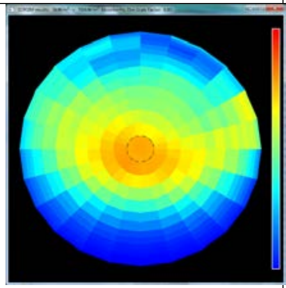
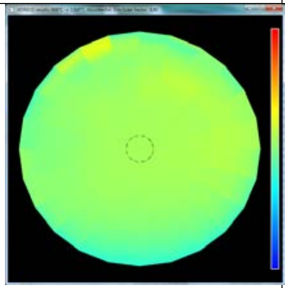
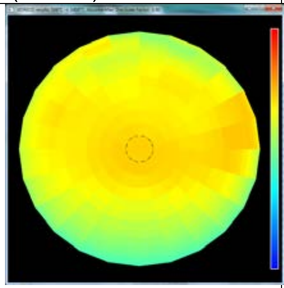
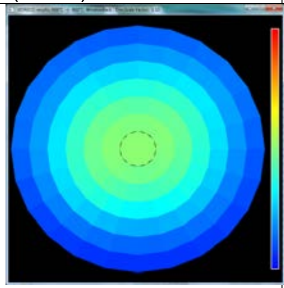
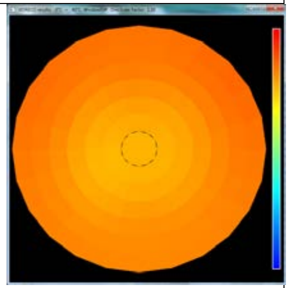
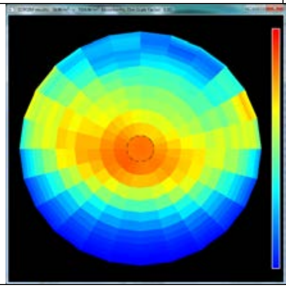
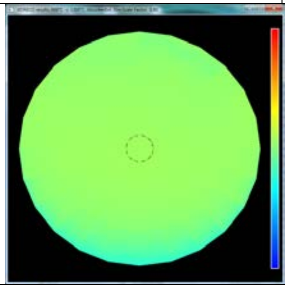
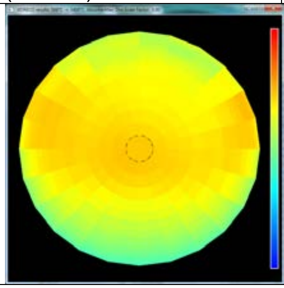
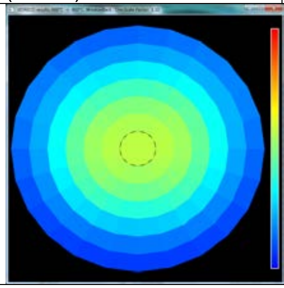
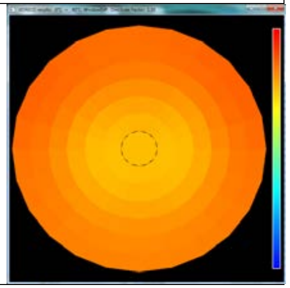
Key Receiver Temperature Profiles

PROT4	absorber solar flux distribution [kW/m²]	absorber exit temperature [°C]	max. absorber temperature [°C]	max. window temperature [°C]	window temperature difference [°C]
color scale (max. value)	0 … 700 kW/m²	600 …1300°C	500 …1400°C (1094°C)	600 …800°C (617°C)	0 …80°C
21.03. 7:00 1.43 kg/s 384 kW 67.9% DNI 450 W/m²					
color scale (max. value)	0 … 700 kW/m²	600 …1300°C	500 …1400°C (1168°C)	600 …800°C (703°C)	0 …80°C
21.03. 10:00 5.20 kg/s 1913 kW 87.2% DNI 860 W/m²					
PROT4	absorber solar flux distribution [kW/m²]	absorber exit temperature [°C]	max. absorber temperature [°C]	max. window temperature [°C]	window temperature difference [°C]
color scale (max. value)	0 … 800 kW/m²	600 …1300°C	500 …1400°C (1178°C)	600 …800°C (716°C)	0 …80°C
21.03. 12:00 (DP) 5.85 kg/s 2151 kW 87.9% DNI 900 W/m²					

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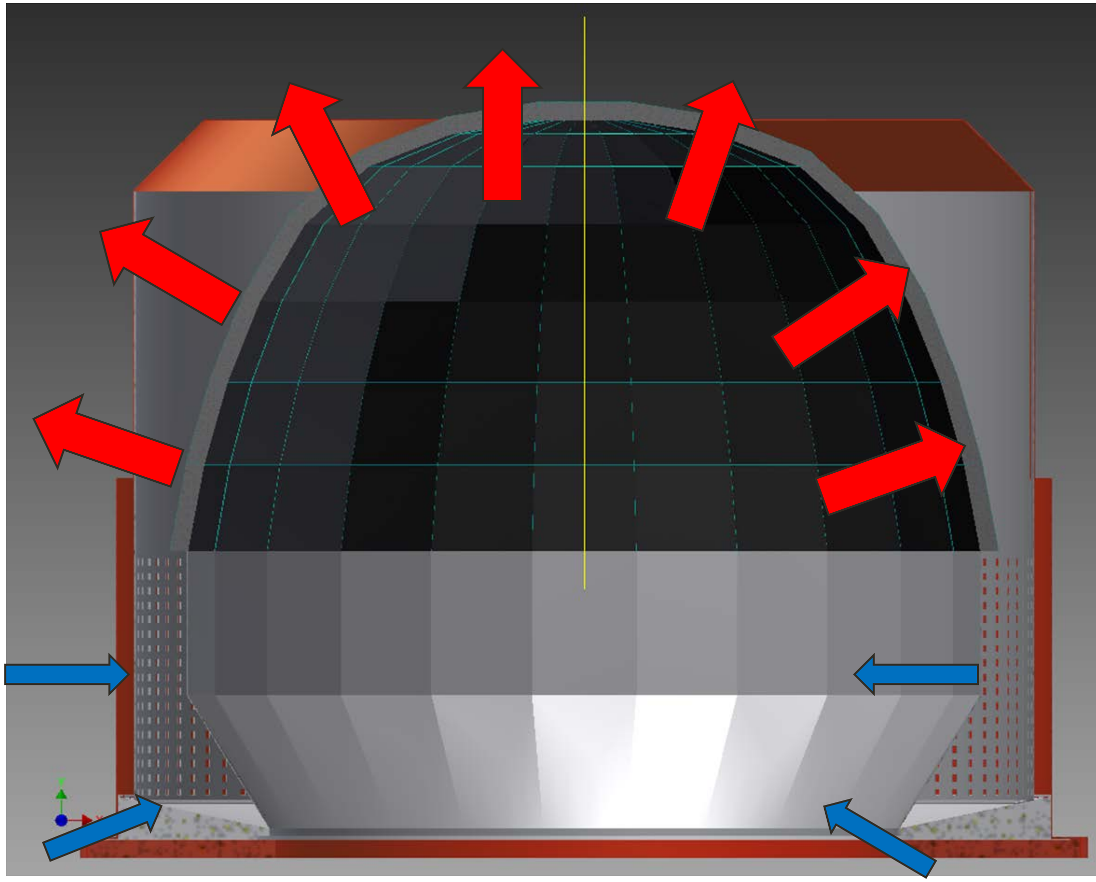
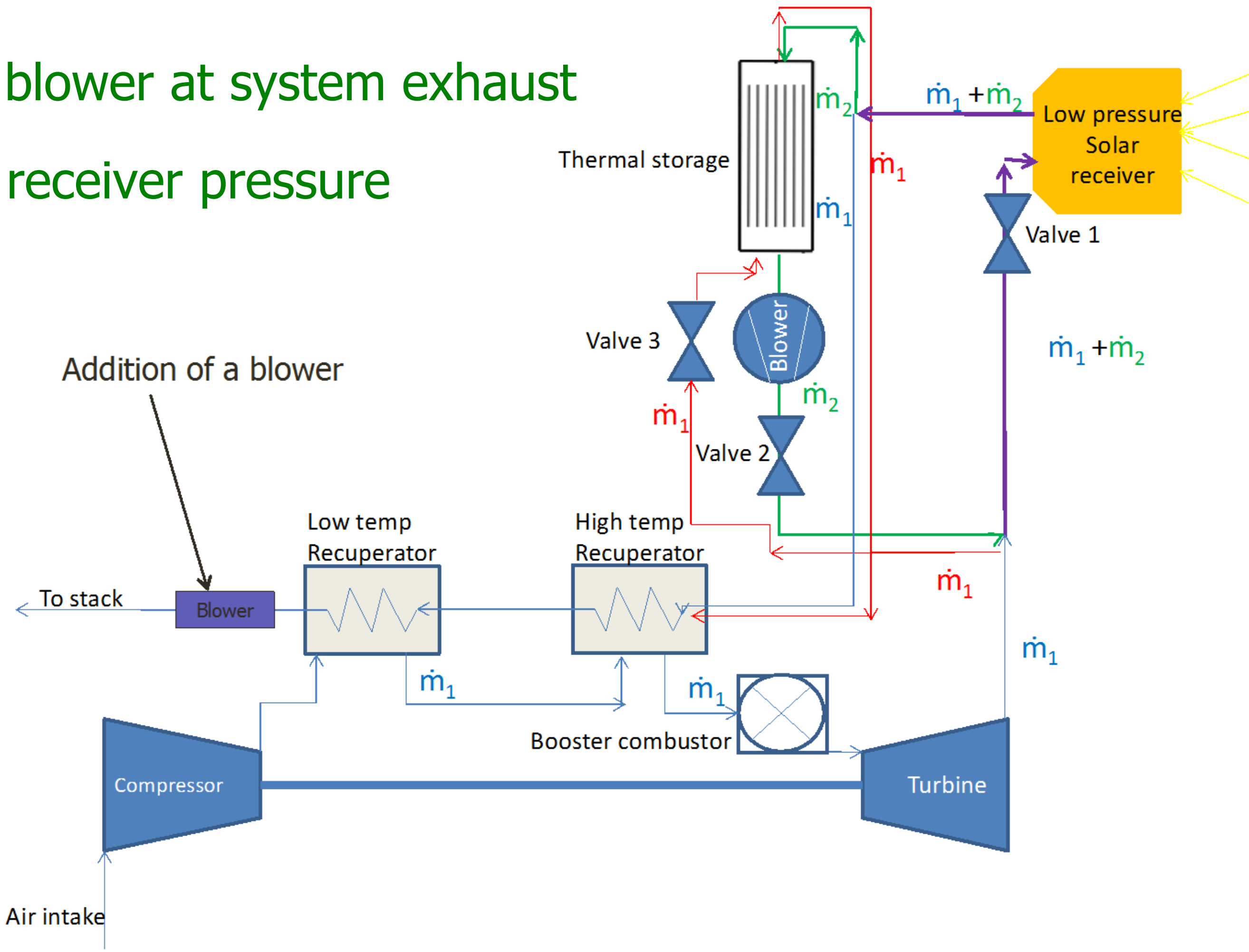
Receiver Design Challenges

- 950°C ⇒ HT metal alloys, ceramics
- Differential thermal expansion of metal and ceramic
- Significant upscaling from existing designs



Proprietary Zero Pressure System

- Add small blower at system exhaust
- Near-zero receiver pressure



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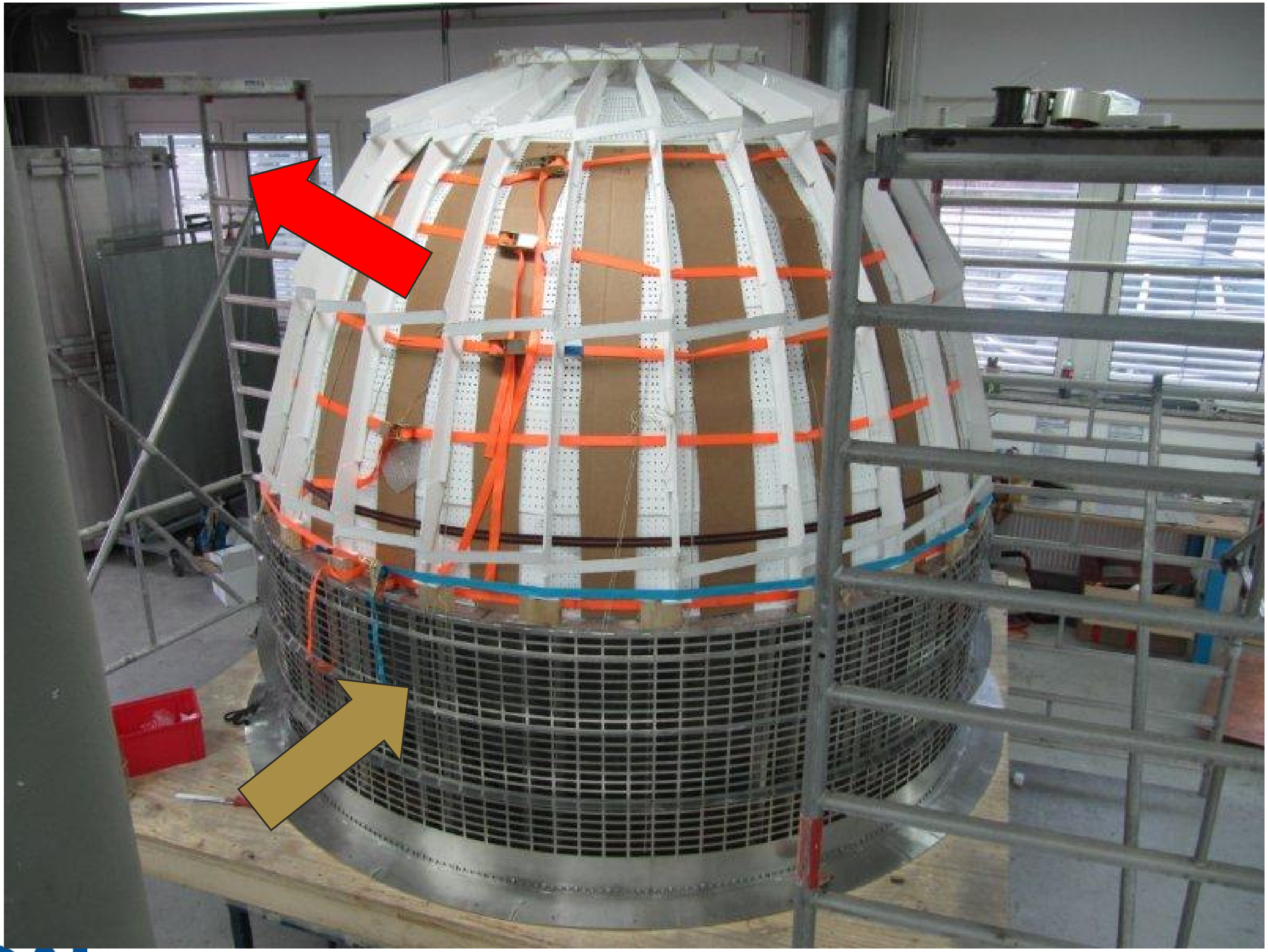
Whole Absorber Assembly



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Zero Pressure Solar Receiver

Performance summary

- Efficiencies up to 88%
- Low pressure drop
- Mass flow regulation significantly improves temperature distribution
- Absorber temperatures acceptable
- Window temperatures acceptable
- Flux distribution varies with sun position

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Zero Pressure Solar Receiver

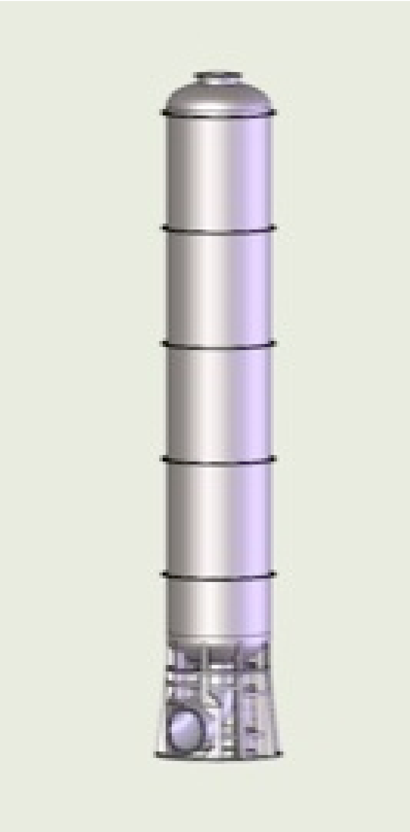
Next Steps

- Cold test
- Hot test on Sandia power tower
- Begin life test as part of full 300-kWe pilot power plant module

Wilson Thermal Storage™

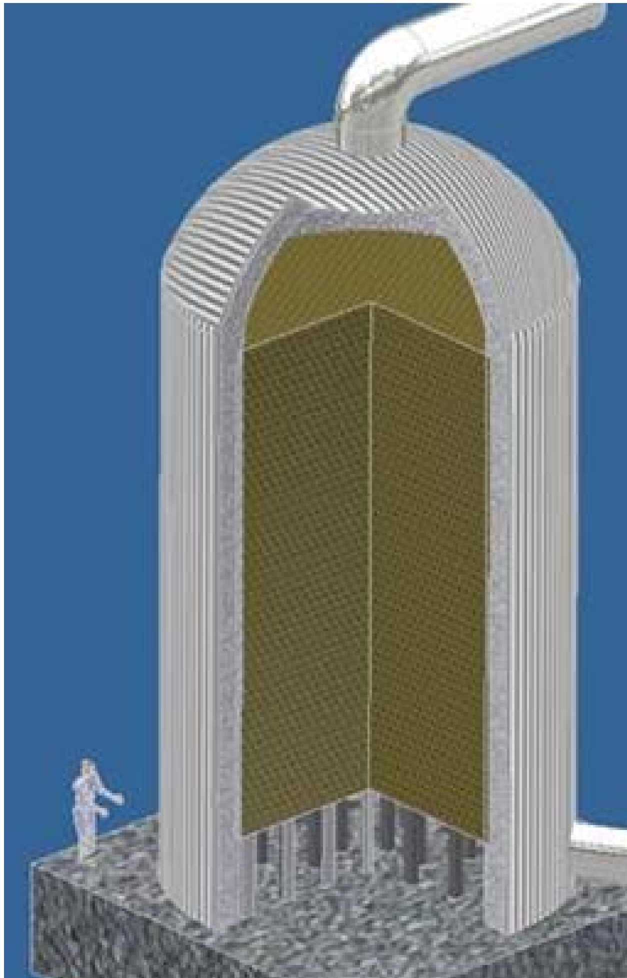
Saint-Gobain development partner; 100+ year-old technology

300 kWe model



- *Cost:*
  - *DOE, Wilson target: <$80/kWh*
  - *<20% of batteries*
- *650ºC – 970ºC*
- *Dry, e.g., ceramics*
- *Excellent thermal gradients and utilization factors*

1700 kWe model



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Principal Thermal Storage Issue Areas

- Pressure drop/parasitic losses
- Interior insulation
- Storage media support grate

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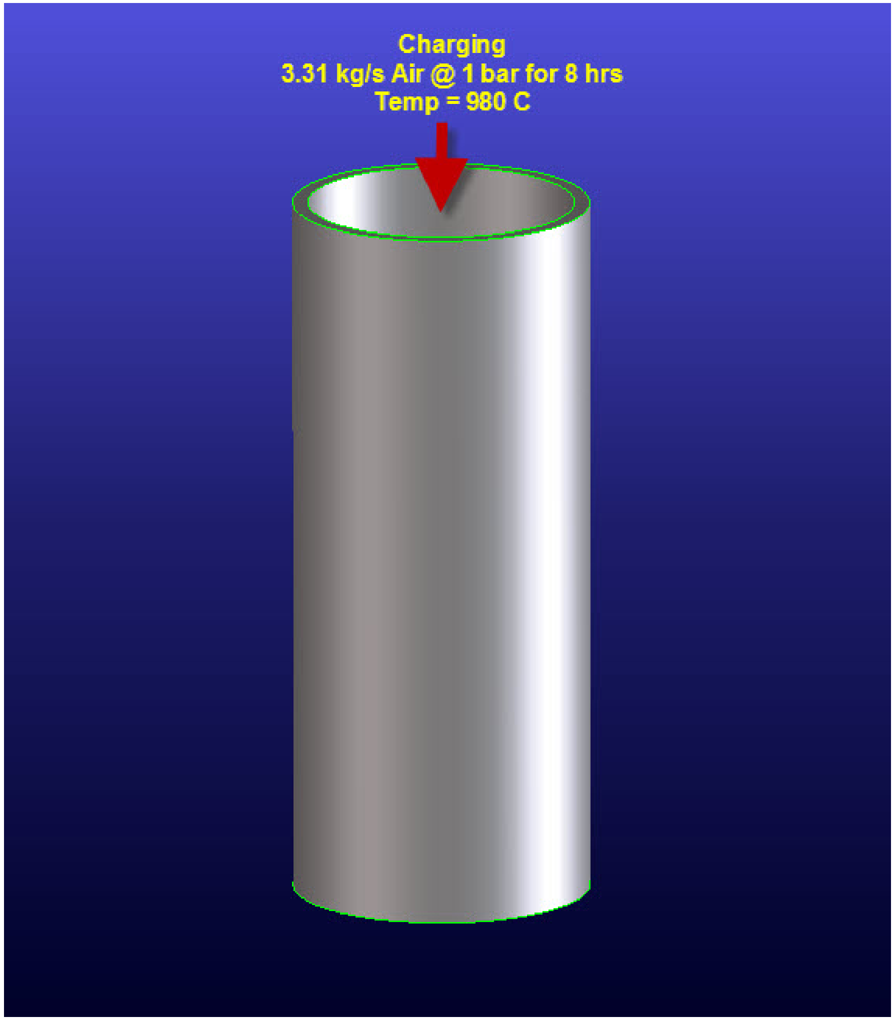
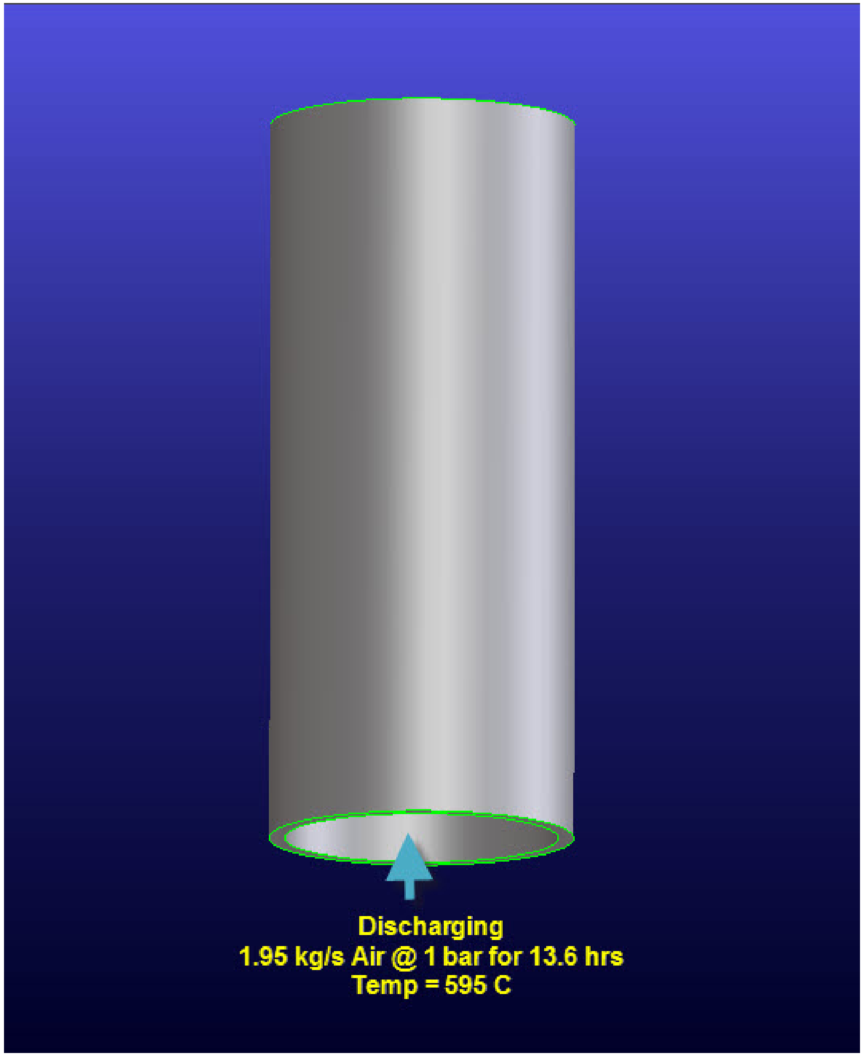
Charge and Discharge Operation





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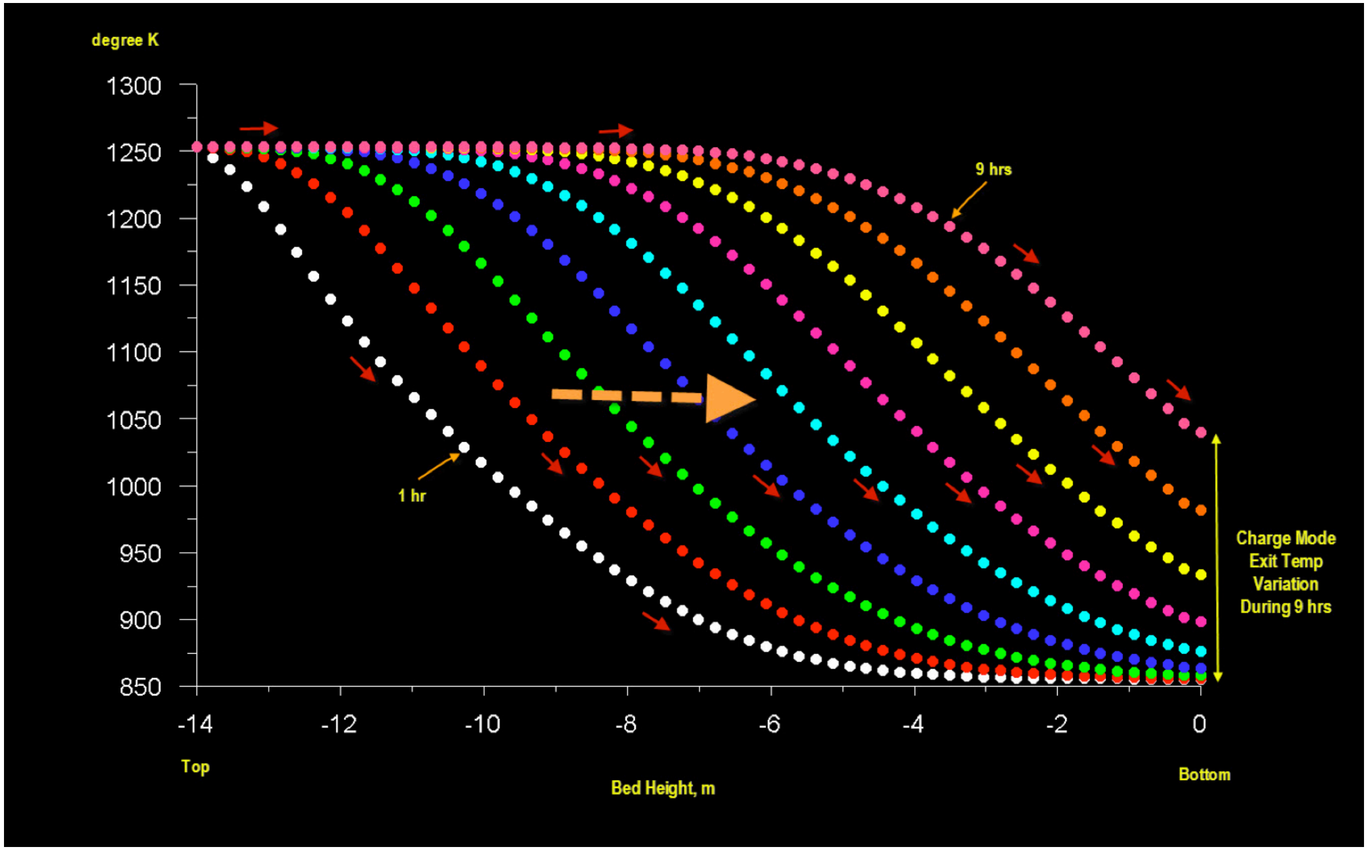
Charge Mode

Typical Thermal Profile Evolution during 9.0 hrs of sun



The receiver-heated air flows from left (tank top) to right (tank bottom). Variable speed flow enables near-constant inlet temperatures. In this analysis, the outlet temperature is allowed to rise to as high as 750C.

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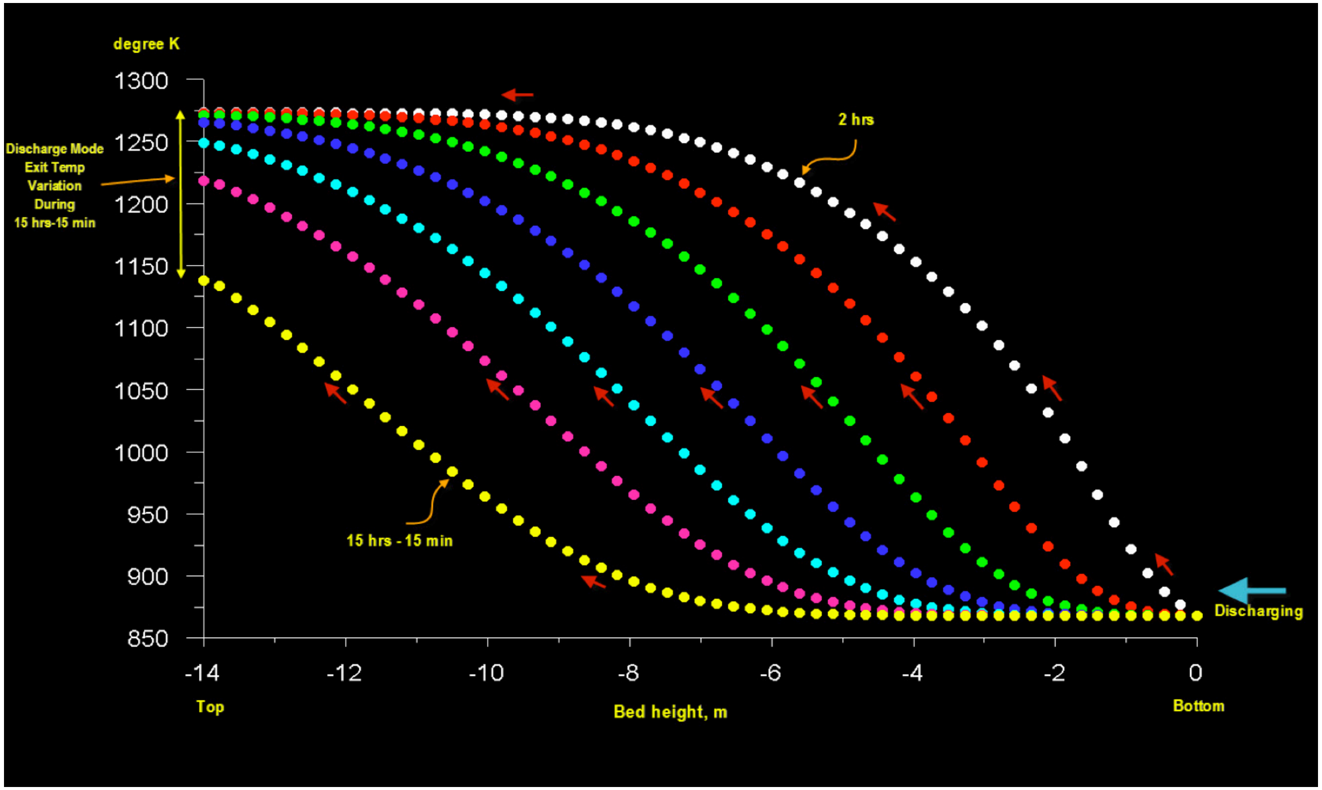
Discharge Mode

Typical Thermal Profile Evolution during 15 hrs of discharge



The exhaust air from the turbine enters at the right (tank bottom) and exits at the left. The exit temperature drops over time, and with it the power output of the turbine. The turbine of choice has high part-load efficiencies. In addition, depending on customer demand, fuel can be added in the combustor to maintain full power.

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Thermal Energy Storage System

Next steps

- Optimize between 10ft and 12ft systems for lowest LCOE
- Finalize the engineering of the system that yields the lowest LCOE.
- Prepare drawings, price, select suppliers, issue POs
- Build and test as part of a full 300-kWe pilot power plant module

High Temperature Heat Exchanger

Testing program

- Testing by Dr. Bruce Pint, ORNL
- Test Haynes 214 alloy
- Test 2 mil, 4 mil, 5 mil, 6 mil and 10 mil thicknesses
- Test up to 8000 hours: 9 hours hot, 1 hour cold, 800 cycles
- Test specimens at 950C, 1000C, and 1050C

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High Temperature Heat Exchanger

Principal test results

- No samples of any thickness successfully cycled at 1050C
- Most foil thicknesses survive nicely at 950C
- 5 mil and especially 6 mil thickness are best performing thicknesses at 1000C

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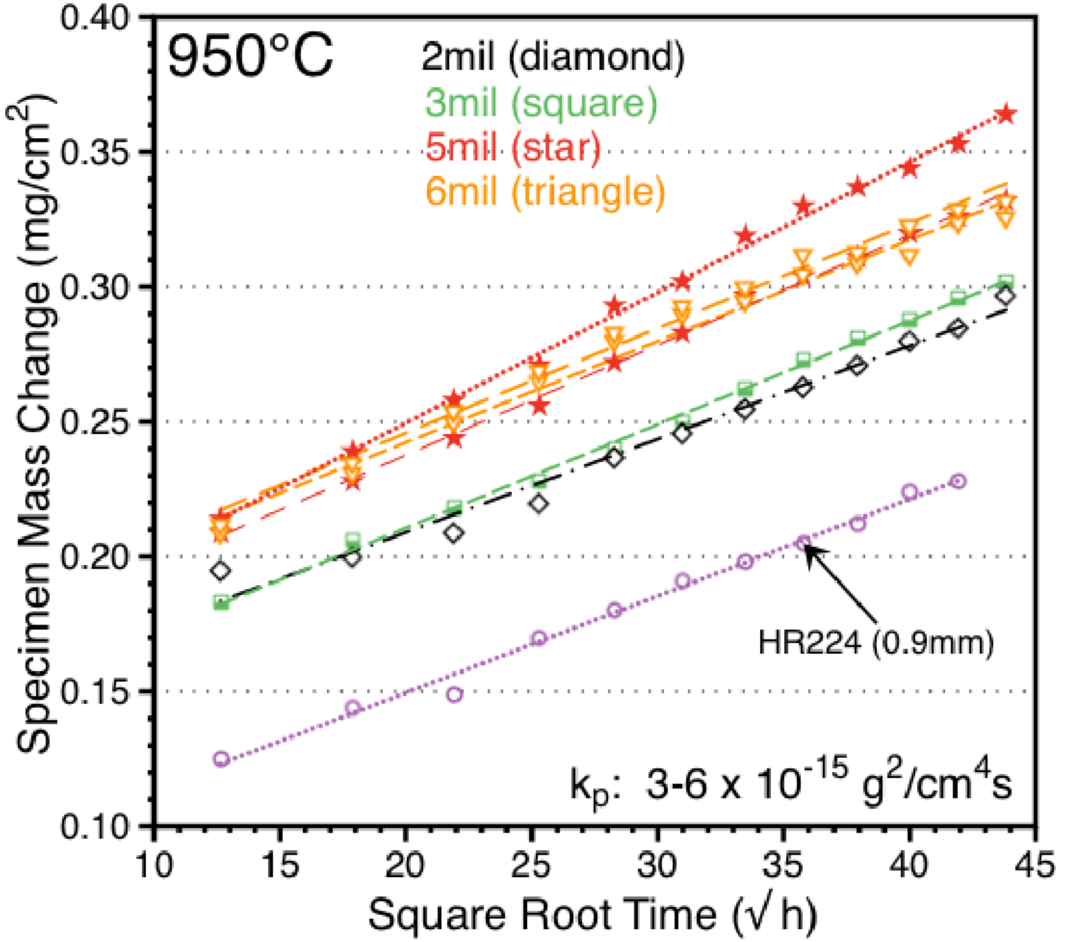
High Temperature Heat Exchanger

Test results at 950°C



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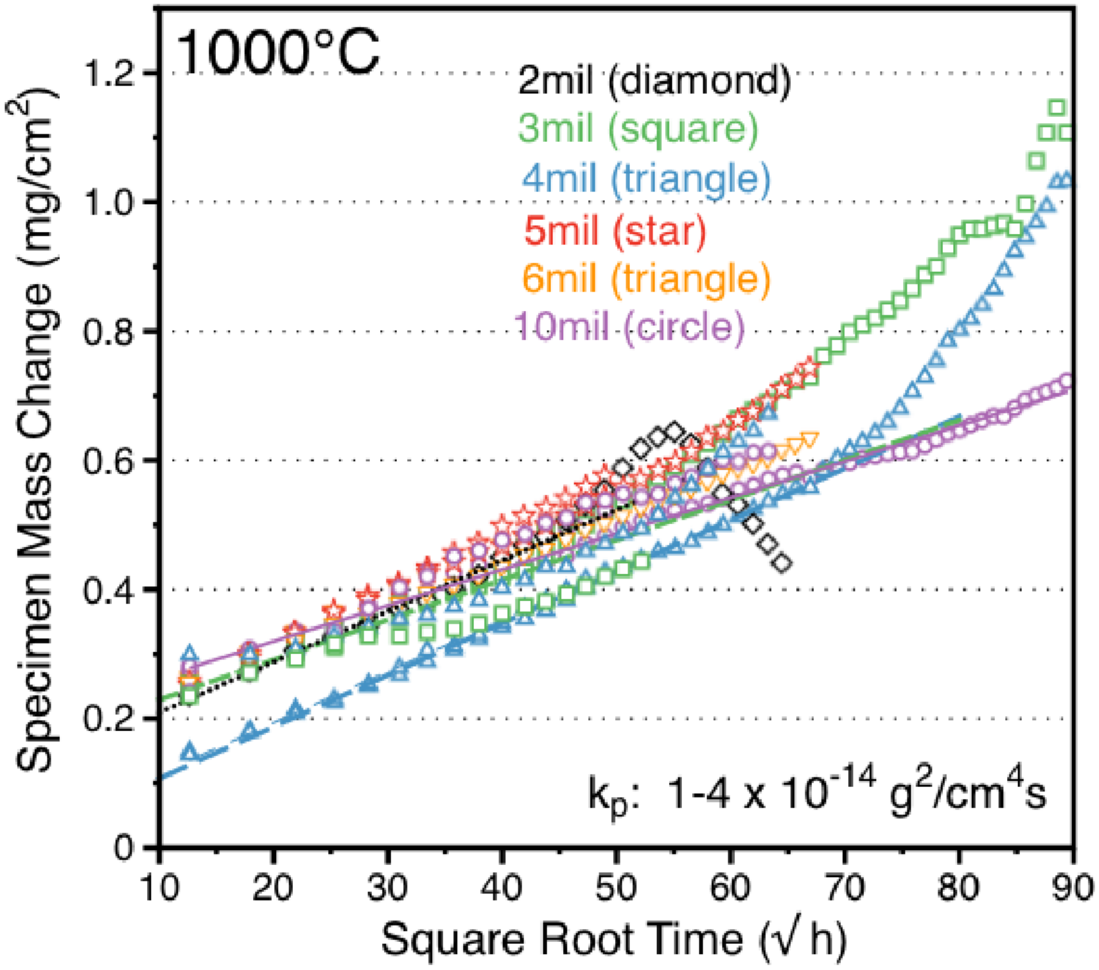
High Temperature Heat Exchanger

Test results at 1000ºC



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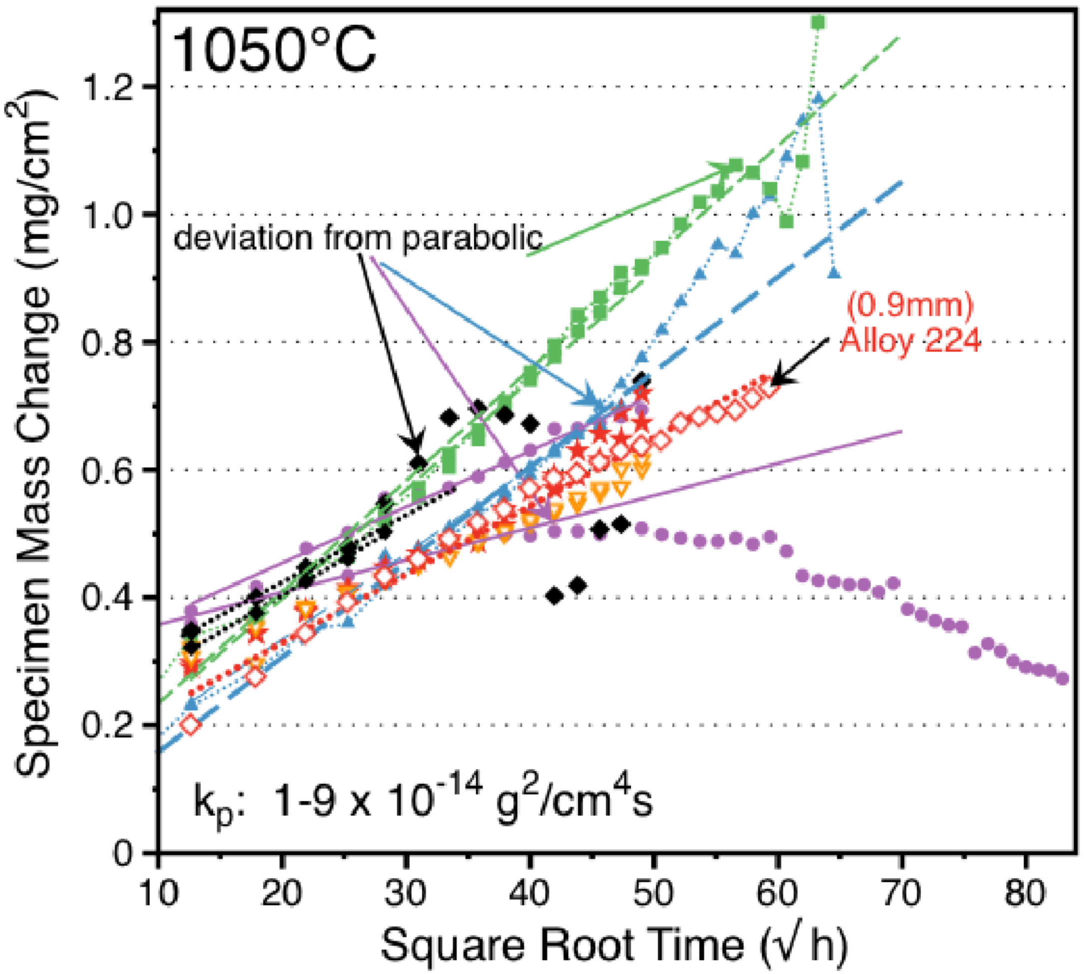
High Temperature Heat Exchanger

Test results at 1050°C



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High Temperature Heat Exchanger

Major takeaway of the testing results

Based on initial lifetime modeling using actual test results:

6 mil HR214 foil "optimistically can make 100,000h operating at 975° C."

- Bruce Pint, ORNL

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High Temperature Heat Exchanger

Next Steps

- Measure the remaining Al content in the specimens for the life prediction. This requires metallography and microprobe.
- Secure a supplier and fabricate/test prototype heat exchanger
- Begin life test as part of full 300-kWe pilot power plant module

Path Forward for Brayton CSP

- **Essential next step:** engineer, deploy and test full 300-kWe pilot power plant module with storage
- **Parallel continued developments for higher efficiency, lower cost Brayton CSP:**
  - Smaller, lighter weight storage at ~950ºC and hotter
  - Wilson's ultra-efficient ceramic microturbine (~50% efficiency)
  - Low cost, narrow focus heliostats
  - Particle receivers
  - Super-critical CO2
  - Low emissivity coatings for absorber
  - Low reflectivity coatings for window

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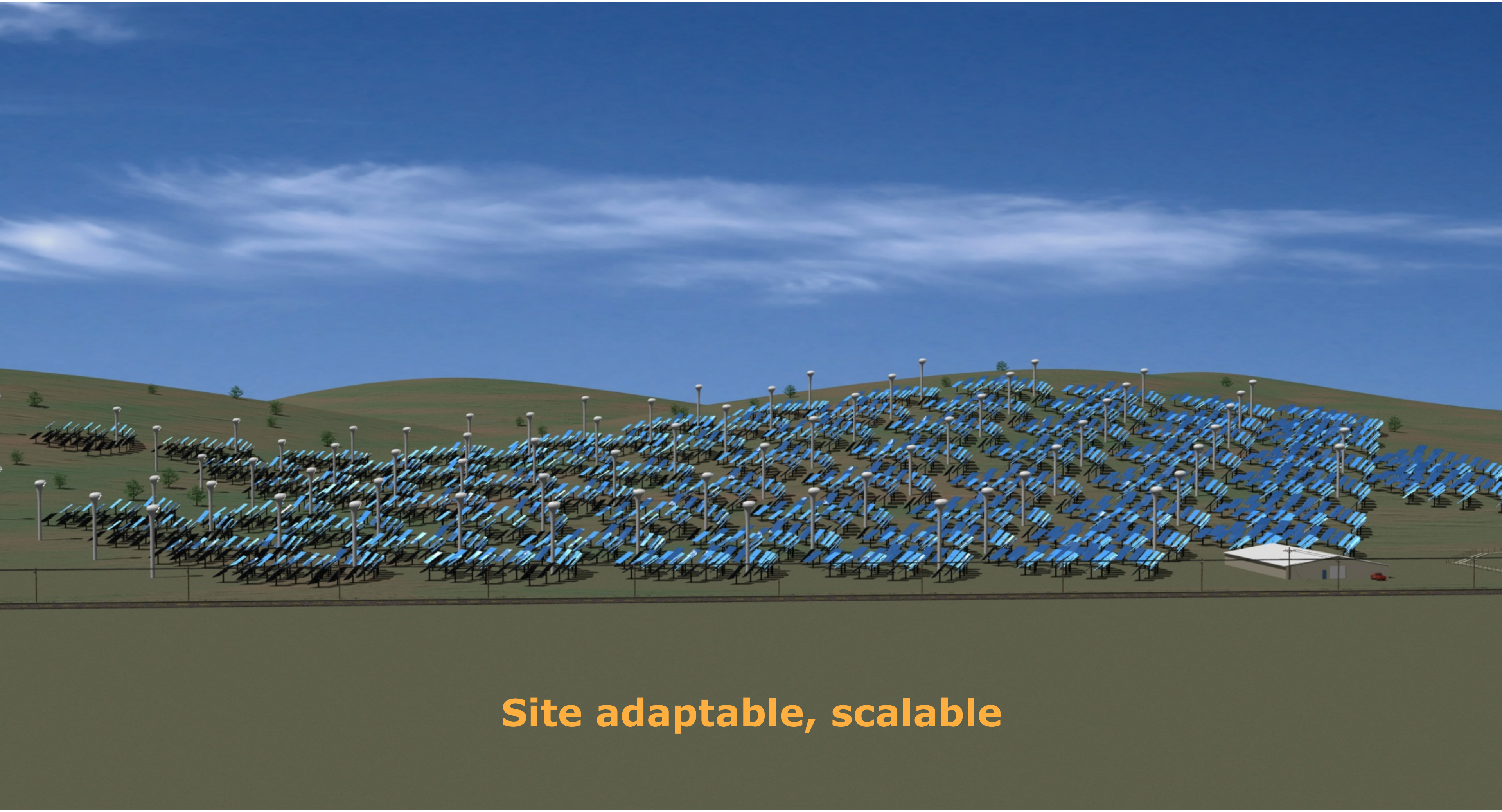
Distributed, Dispatchable 24/7

Few environmental issues



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Future Brayton CSP Plants with storage

Unusual grid services, e.g., flexibility