Advanced Low-Cost Receivers for Parabolic Troughs

Joel Stettenheim, *President,* (PhD, JD)
stettenheim@norwitech.com

SunShot CSP Program Review
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Strong Team

Norwich Technologies:

Principal Investigator: Joel Stettenheim (PhD)

Troy McBride – CTO (PhD), Oliver Brambles - Senior Development Engineer (PhD)

Creare: overall design and expertise in optical analysis and Zemax software

Patrick Magari (PhD), Brynmor Davis (PhD), Richard Kaszeta (PhD), Nicholas Kittamas (PhD)

ANSYS Consulting Group: expertise in thermal analysis and ANSYS Fluent CFD software

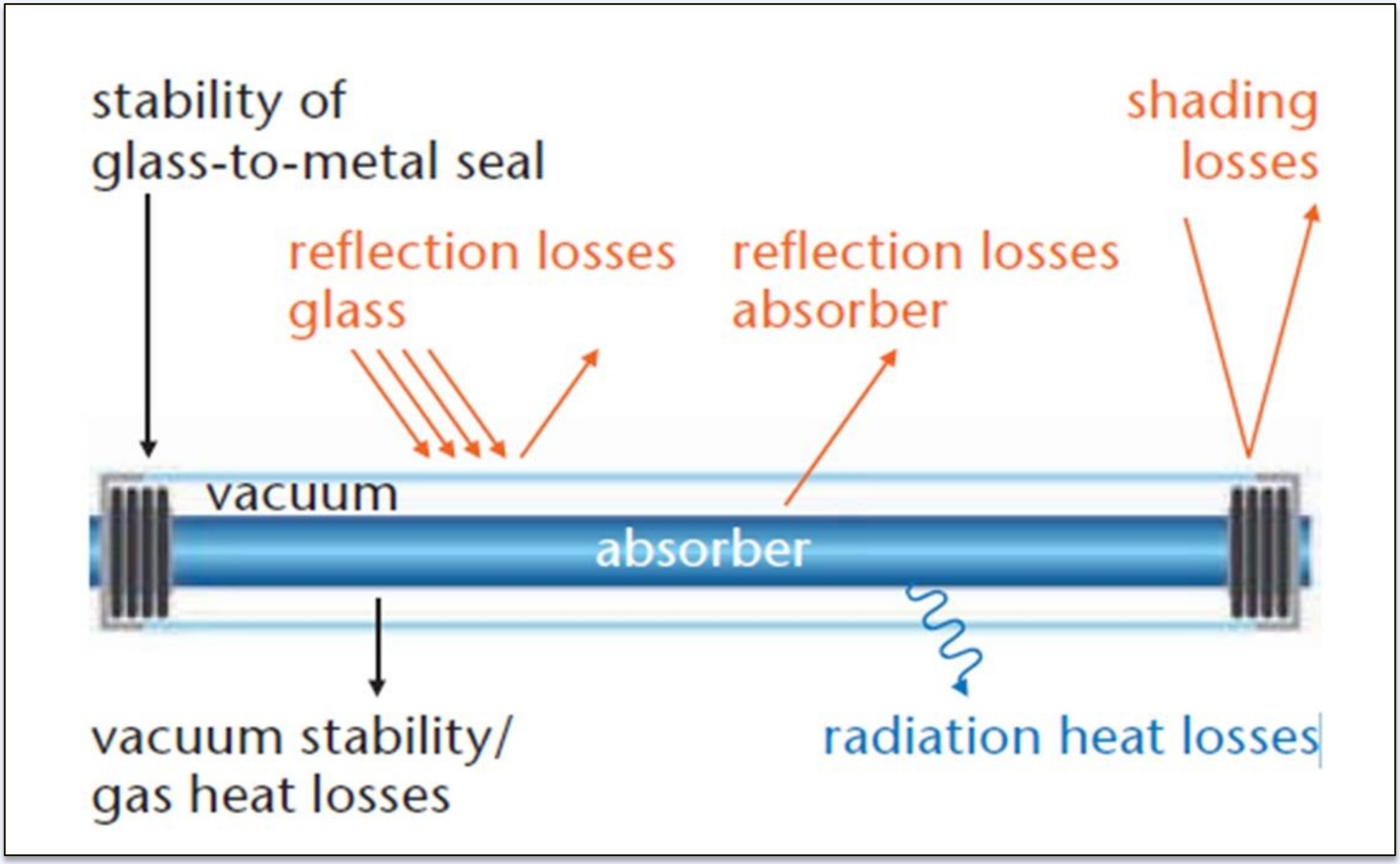
Chi-Yang Cheng (PhD)

Dartmouth Thayer Engineering: Scott Snyder, Emil Cashin, Michelle Burns, Chloe Ruiz-Funes, Jeremy Broulliet, and Utkarsh Agarwal

Parabolic Trough CSP

150 MW Kramer Junction, SEGS Plants 3-7

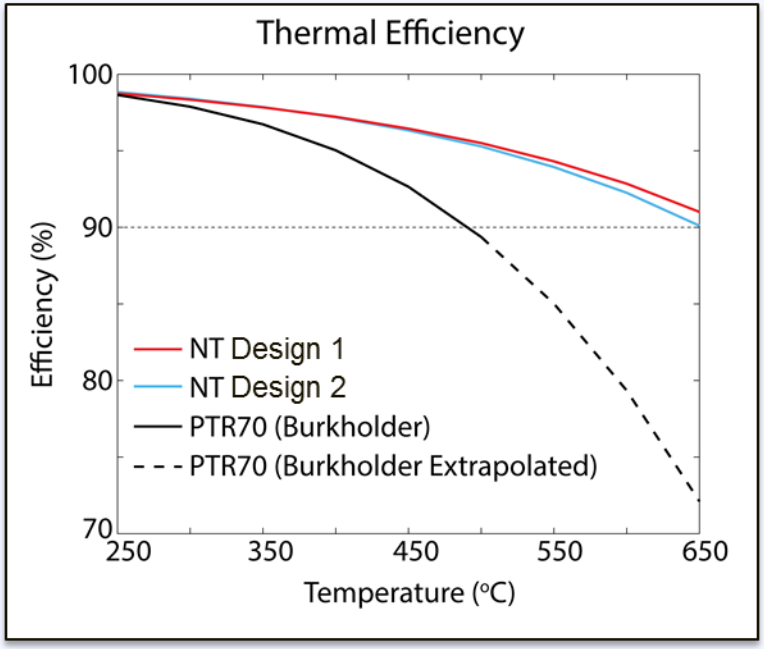
SOA Receiver Challenges



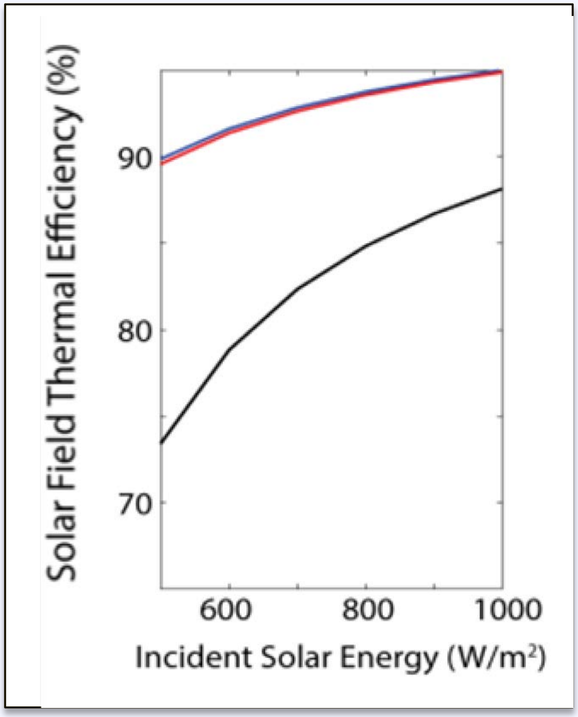
http://www.schott.com/newzealand/english/download/schott_solar_csp_memorandum_en_medium_resolution.pdf

Key Results and Outcomes

At 650 C



250 to 650 C



- **Thermal efficiency** for 2 candidate designs >90% with exit temperature > 650C
- **Optical efficiency** for 2 candidate designs near or exceed SOA
- **Eliminate Vacuum** resulting in simpler structure to build and maintain
- **Acquisition Cost:** Estimated materials and manufacturing 20% lower than SOA

Work Summary

Budget Period 1

✓Task 1.1: Materials study

✓Task 1.2: Optical analysis

✓Task 1.3: Thermal loss analysis

✓Task 1.4: Materials selection

✓Task 1.5: Testing procedures and protocols

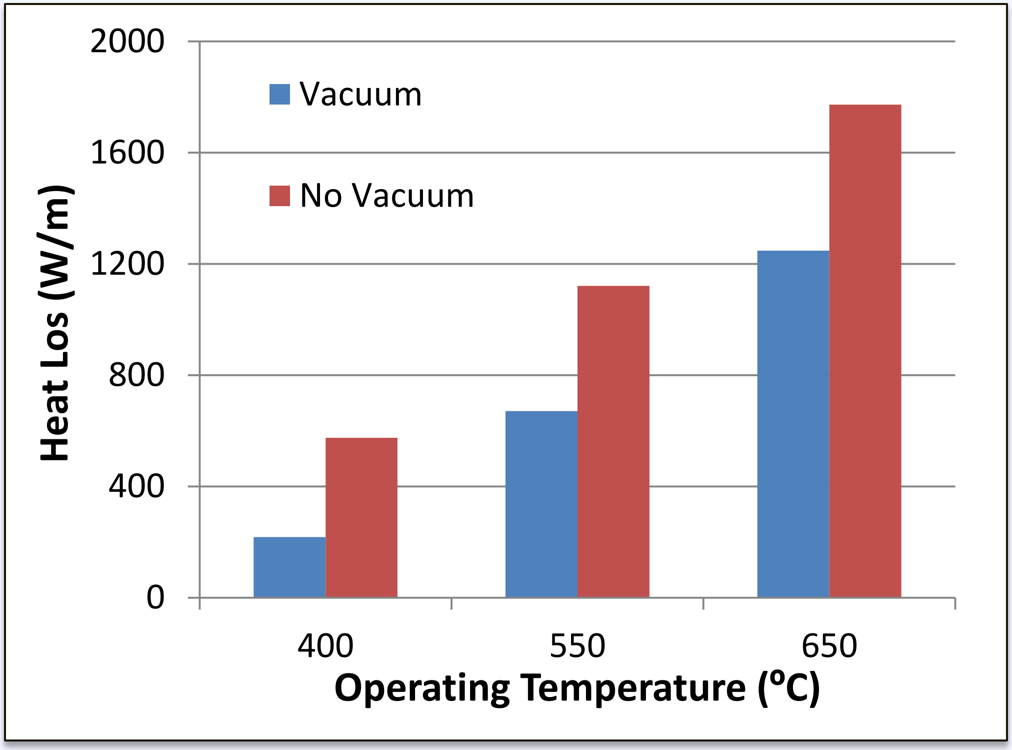
✓Task 1.6: Cost and performance estimates

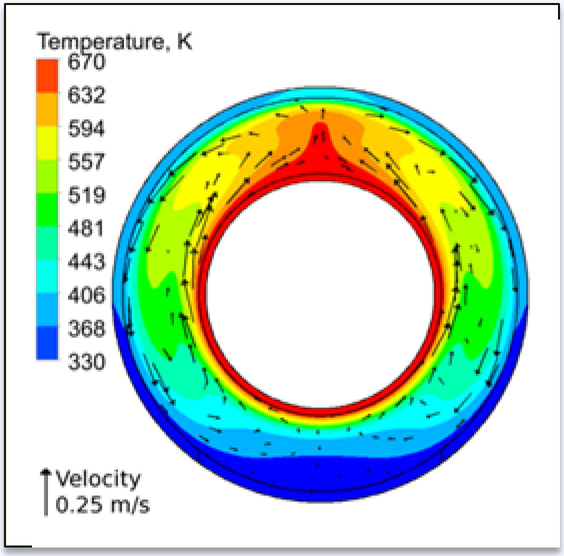
✓Task 1.7: Finalized prototype design and procurement

Thermal Introduction

- **Modeling work – Dr. Chi-Yang Cheng** of **ANSYS, Dr. Oliver Brambles** of **Norwich Technologies**, and Thayer School of Engineering students
- **Thermal performance** of candidate receiver configurations determined through analysis of radiative-loss, convective-loss, and conductive-loss models in **ANSYS FLUENT**, a comprehensive finite-volume computational fluid dynamics (CFD) program.
- Radiative heat transfer losses were solved using **discrete-ordinates (DO) radiation model**
- **Radiation, conduction and convective heat transfer models are coupled** in the FLUENT solver through the energy equation and the core Navier-Stokes equations.

SOA Model Validation





- **CFD simulations** of convection effects within air-filled receiver designs were **validated by comparing to published correlations and NREL data**.
- **Heat loss increases** when vacuum fails due to convection within annulus
- Receiver model with lost vacuum **matched NREL data to within 4%**
  - degradation of coating due to loss of vacuum further increases loses

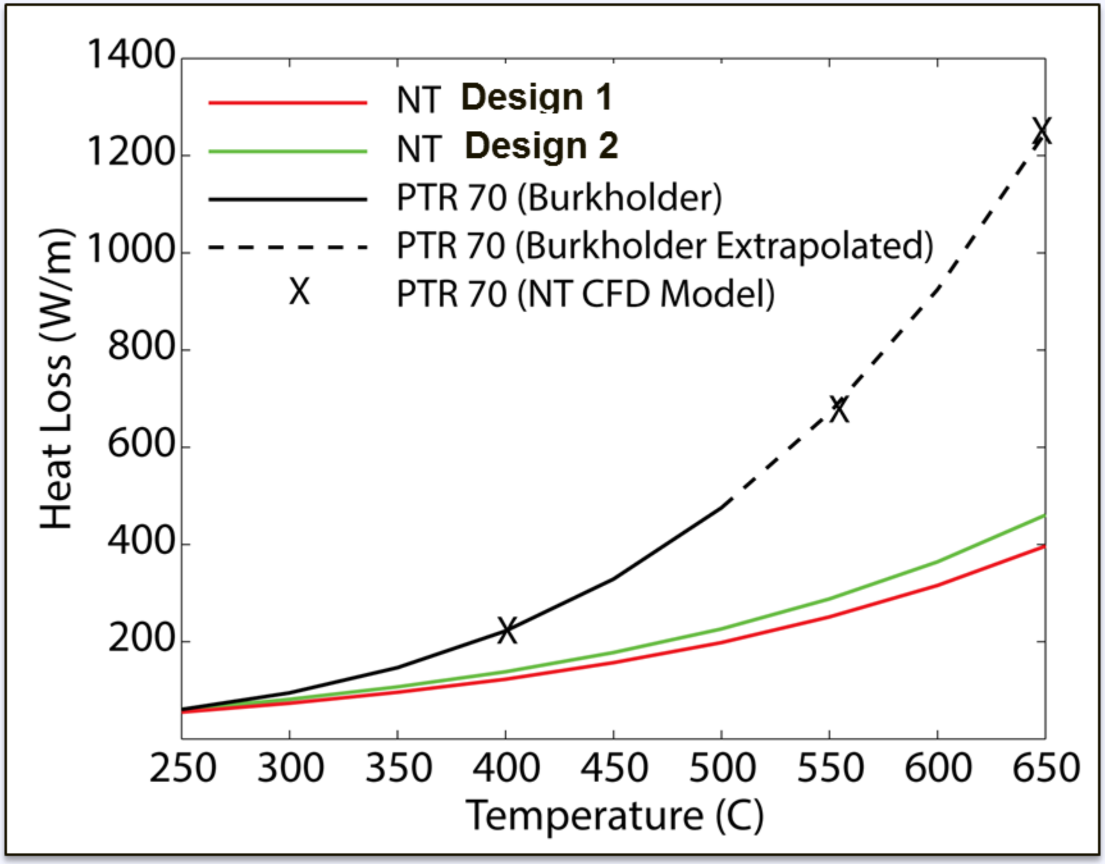
NT Receiver Heat Loss

Baseline CFD model
heat loss due to radiation (conduction/ convection are assumed negligible).

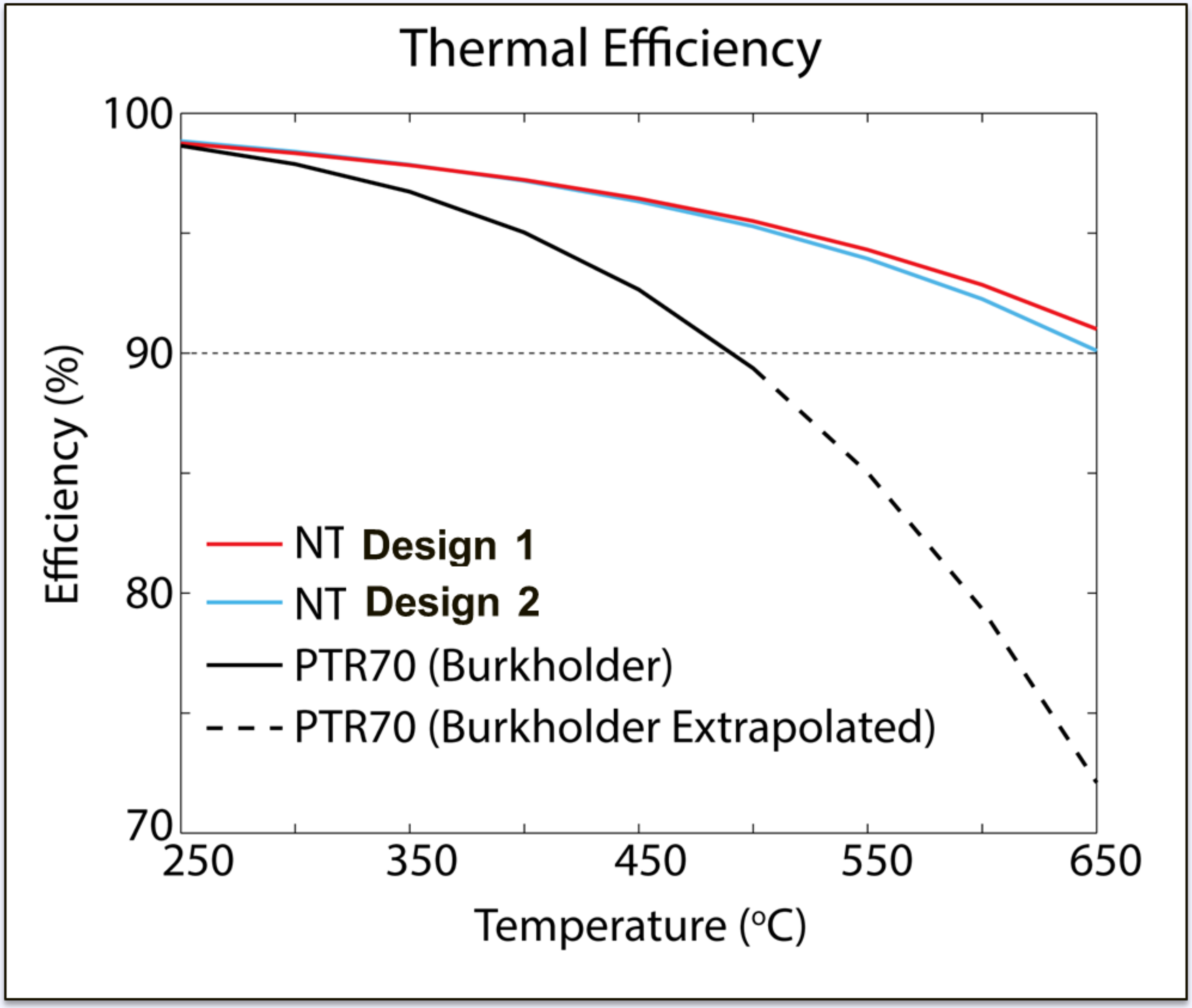
Model validated
NREL test results for the Schott PTR70 (*Burkholder and Kutscher,* 2009).

Close correspondence
CFD values match experimental and extrapolated NREL results to within 1% for 400 ºC and 550 ºC, and within 3% for 650 ºC.

Norwich Technologies Designs
Both designs have better performance > 250 ºC and significantly better at high T



Thermal Efficiency



Both designs have thermal efficiency >90% at 650C.

Thermal efficiency of NT designs > PTR 70 for temps > 250C

Optical Introduction (Task 1.2)

- The **optical performance** of the collector/receiver system is **analyzed using Zemax 12 Release 2** - a powerful optical design tool based on physical ray-tracing and numerical system optimization.
- Zemax optical analysis was developed by optics expert and experienced Zemax software user **Brynmor Davis, Ph.D., of Creare, Inc** and **NT employees**.
- Analysis began with **modeling and validation of SOA** receiver, followed by extensive analyses of new receiver designs.
- **Many thousands of cases were explored** using macros and work by Thayer School of Engineering students and Oliver Brambles.
- **Sensitivity analyses gave insight into optical behavior of different receiver geometries** and allowed development of co-optimized receiver design based on optical and thermal performance.

Optical Performance of SOA Receiver

$$\eta_{opt} = \tau\,\alpha$$

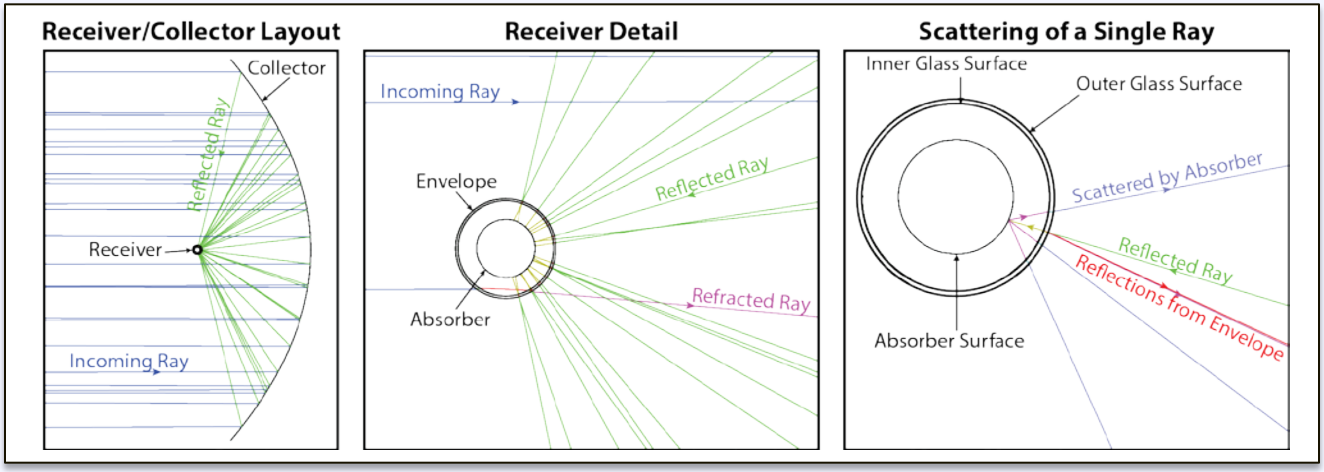
η_{opt} = optical efficiency of a receiver:
τ = transmittance of glass envelope,
α = the short-wave solar absorptivity of receiver coating

	Percentage (%)
Transmittance of glass envelope:	96
Absorptivity of receiver coating:	95
SOA receiver optical efficiency:	**91**

- Value must be modified to account for losses due to collector optical errors, bellow shading etc.
  - Estimated loss of 2% due to these errors
- **Total receiver optical efficiency reduced to 89%**

SOA Model Validation

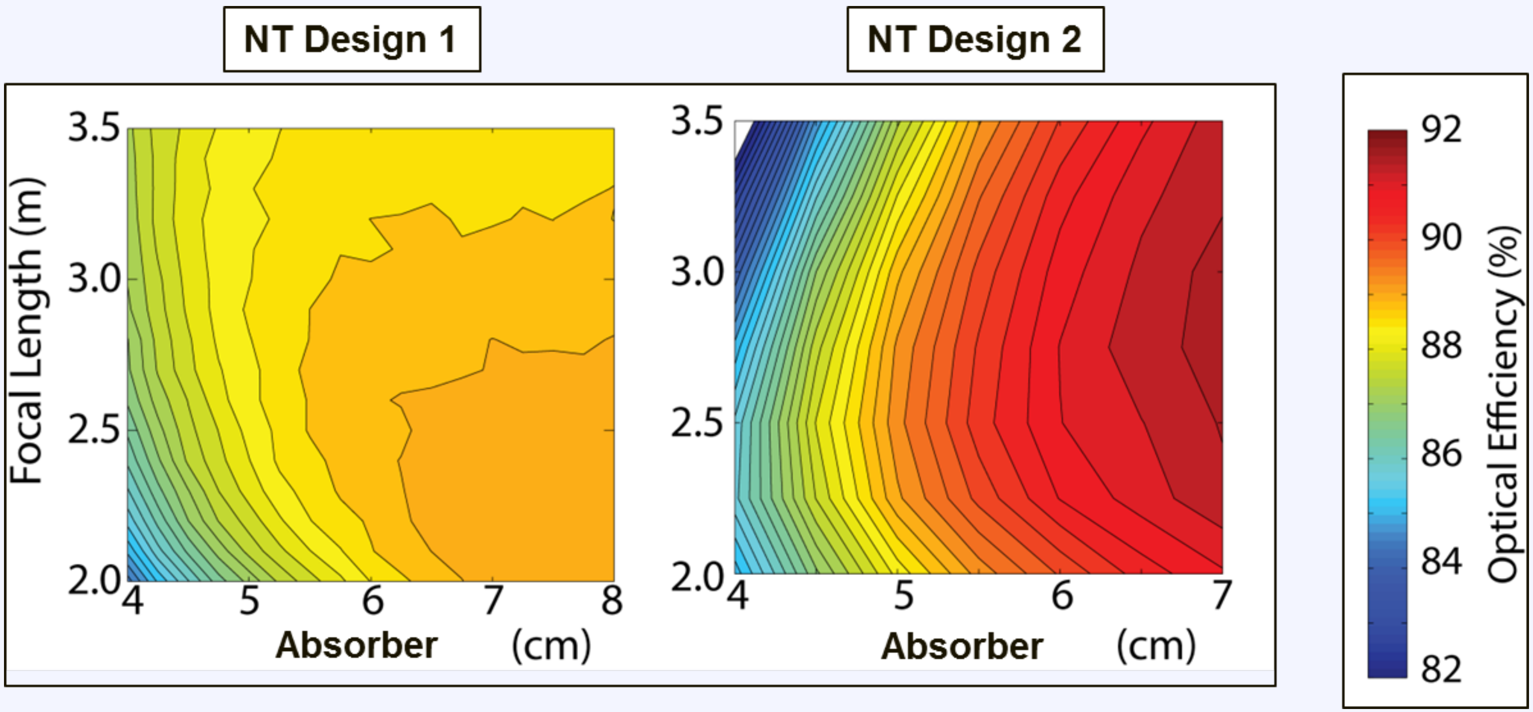
Source - sun modeled as **spatially homogeneous distribution** and **uniform angular distribution** within a **4.7mRad-radius disk.**



- Glass surfaces
  - **98% transmittance** of incident light (independent of incidence angle)
  - **specularly reflect** remaining 2%.
- Absorber tube
  - absorbs 95% of incident light
  - remaining 5% is scattered according to a Lambertian model.
- Collector is modeled as being 100% reflective and free of dirt.

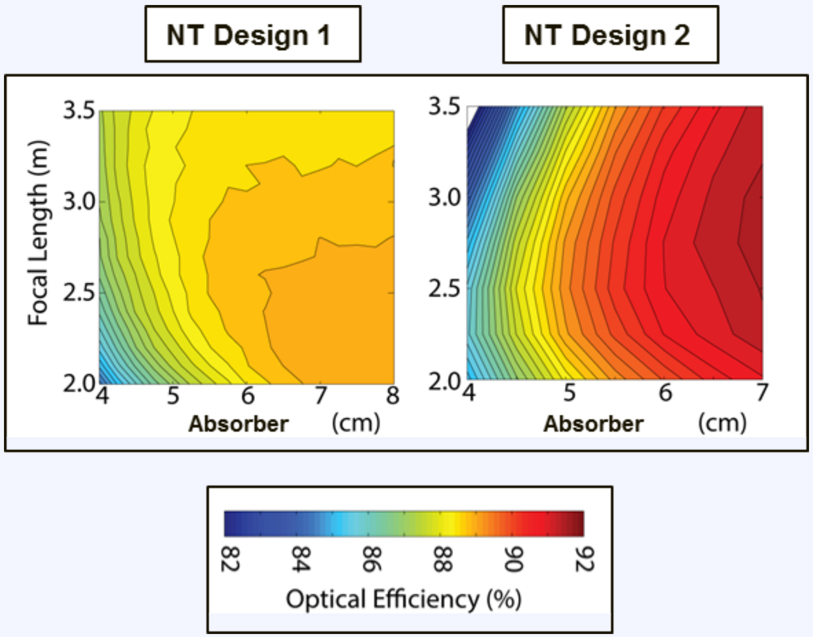
Detector Location	Power (W)	Power (% of Power on Collector)
Source	1.00	-
Collector	0.926	100
Outside Glass Envelope	0.926	100
Inside Glass Envelope	0.888	95.9
Absorbing Central Tube	0.844	91.1

Parameter Study - $\eta_{optical}$

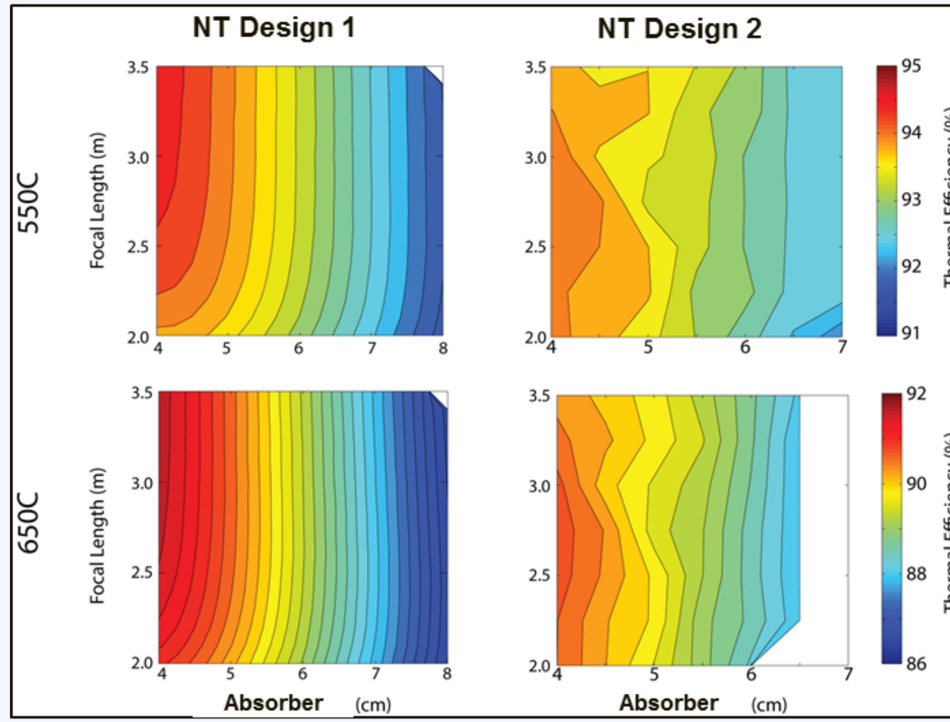


- Design 2 has higher maximum optical efficiency
- Design 1 has higher efficiency at smallest absorber size

Co-optimized Efficiencies

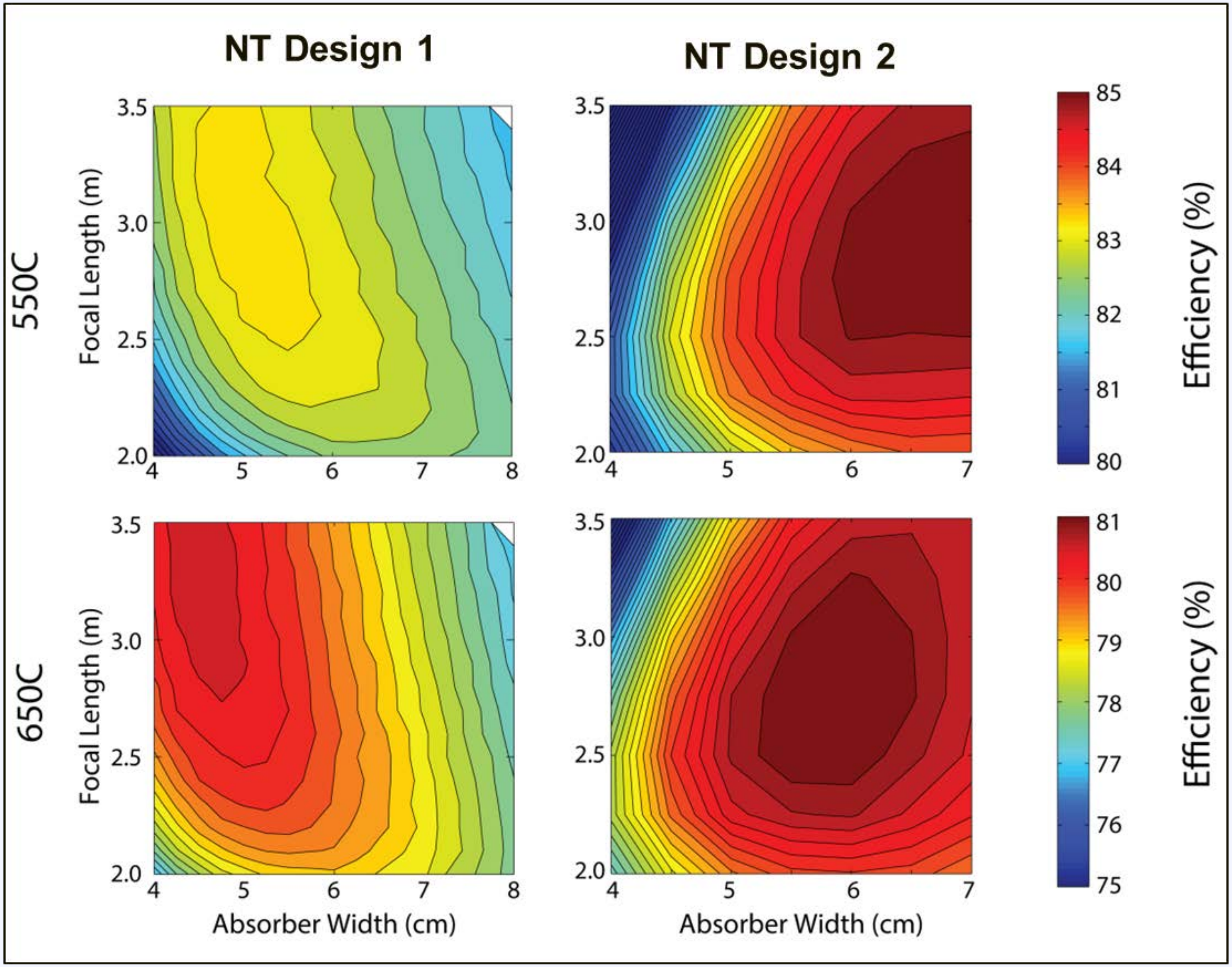


Optical Efficiency

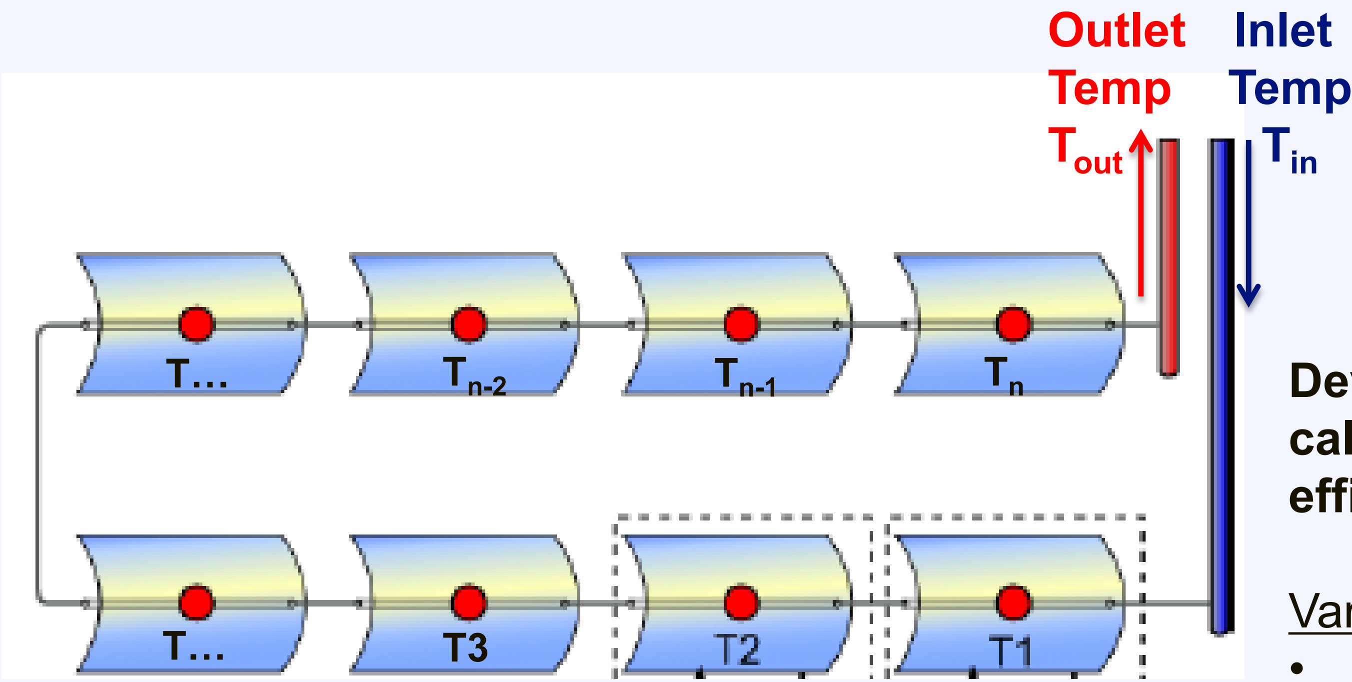


Thermal Efficiency

Total Efficiency



Solar Field Efficiencies



Developed model to calculate solar field efficiency.

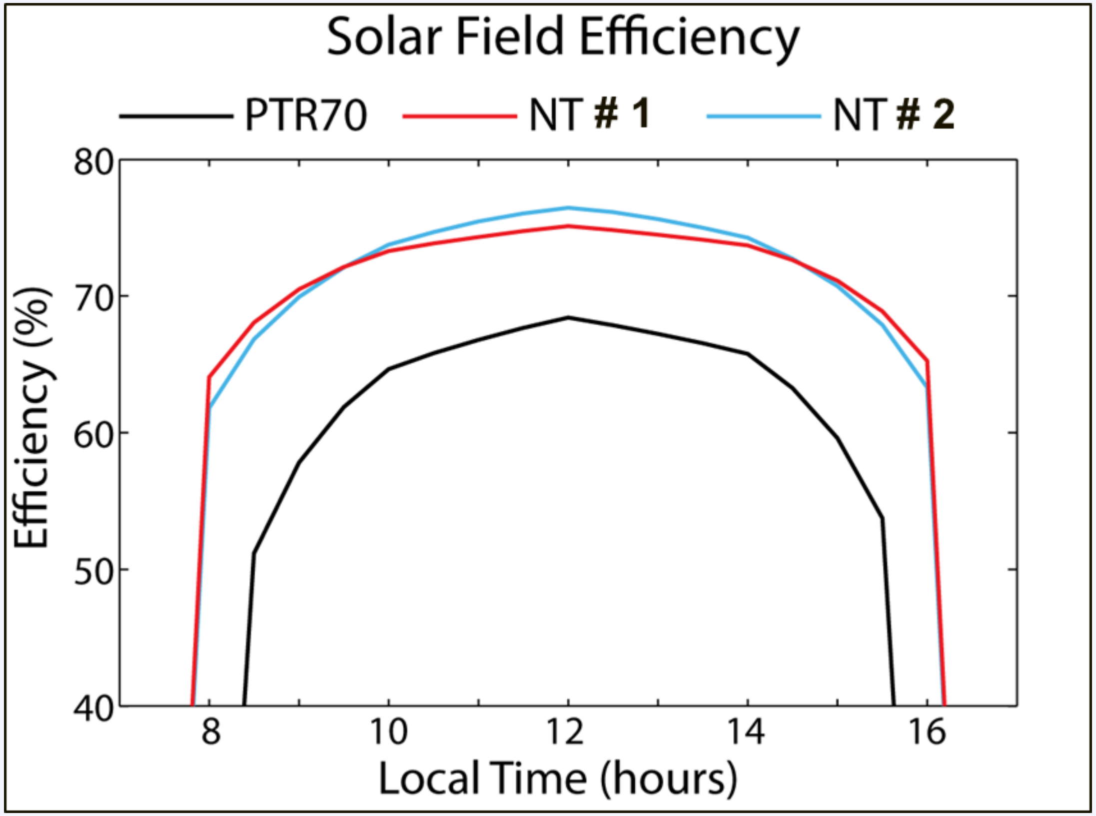
Variables include:

- Inlet and Outlet Temperatures
- Solar Insolation
- Collector/Receiver Tilt

- Proper efficiency analysis considers efficiency at range of temperatures

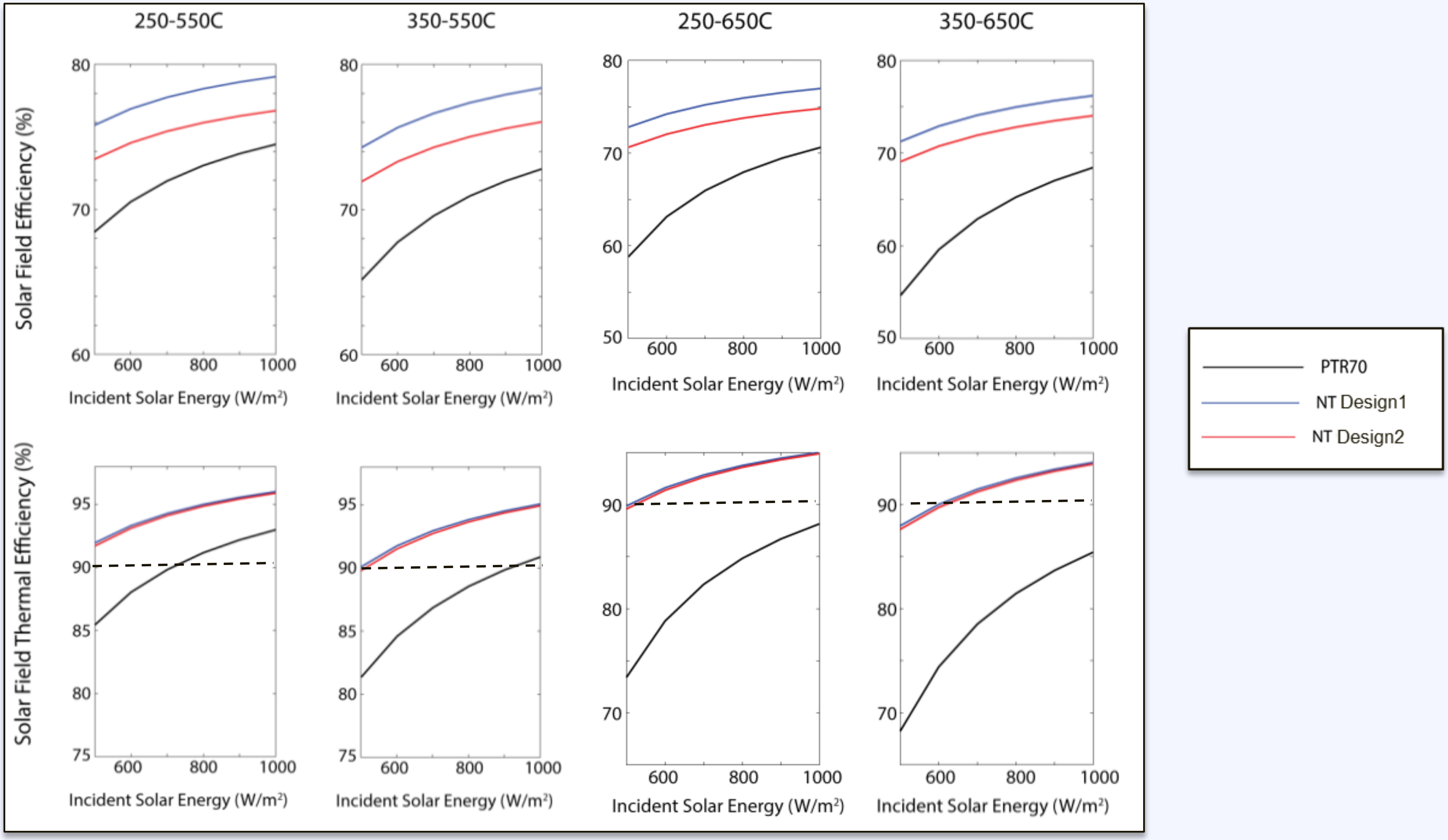
http://www.nrel.gov/docs/gen/fy12/51459.pdf

Day Efficiency



- Efficiency also varies with insolation (i.e., time day/year, location)
- NT receivers more efficient over all insolation values
  - due to higher (fixed) thermal losses of traditional receivers at each temperature

Solar Field Efficiencies

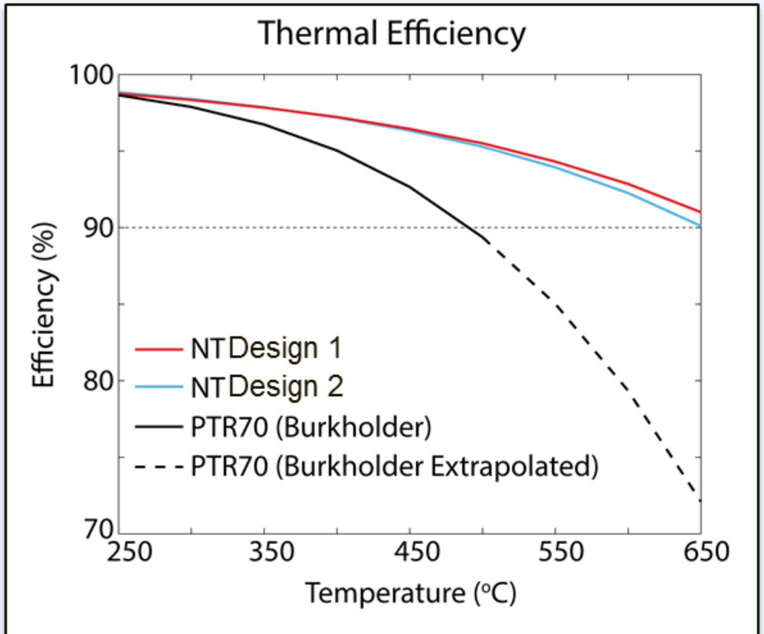


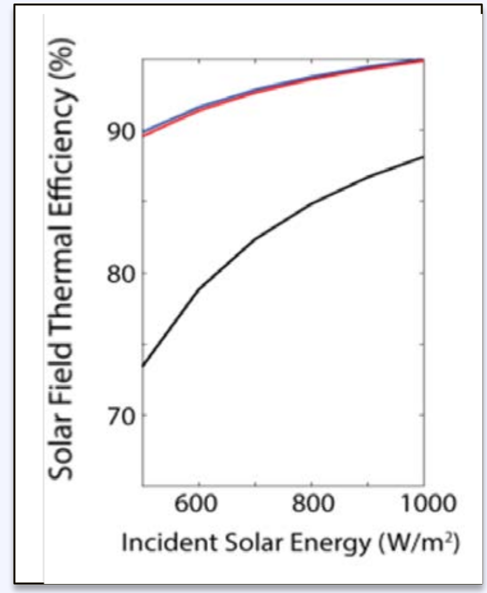
- Solar field thermal and total efficiencies – temperature & insolation variation
- SunTrap in all cases outperforms PTR70

Next Steps

Tasks/Milestones Category	Tasks / Milestones	Project Timeline (months) 1–3	4–6	7–9	10–12
Prototype analysis and design	1.1. Materials matrix				
	1.2. Optical analysis				
	1.3. Thermal loss analysis				
	1.4. Materials selection				
	1.5. Testing procedure and protocol				
	1.6. Cost and performance analysis				
	1.7. Finalize prototype design and procurement				
Prototype build	2.1. Build prototype & test apparatus				
Prototype testing	3.1. Test Prototype				
	3.2. Project Management & Reporting				
Company & marketing development	2.2. Company and Marketing Development				

Summary





- **Thermal efficiency** for 2 candidate designs >90% with exit temperature > 650C
- **Eliminate Vacuum** resulting in simpler structure to build and maintain
- **Acquisition Cost:** Estimated materials and manufacturing 20% lower than SOA
- **Next Steps:** - building and testing prototype, field demonstration phase

stettenheim@norwitech.com – (802) 384 - 1333