UC Solar Leads in Solar Thermal Science

Prof. Roland Winston

Director, UC Solar & Distinguished Professor
Schools of Natural Sciences & Engineering

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Summary

- Fundamental limitation for solar concentration
- Solar Thermal Research at UC Solar
  - The Arpa-E project
  - The XCPC project
    - The drum drying project
    - Evaporation Project
    - Mongolia project
  - The CEC combined heat and power project
  - The Solar desalination project.
    - Current DOE Desal project

Thermodynamic limit on concentration

- from $\lambda_{\text{max sun}} \sim 0.5\ \mu$

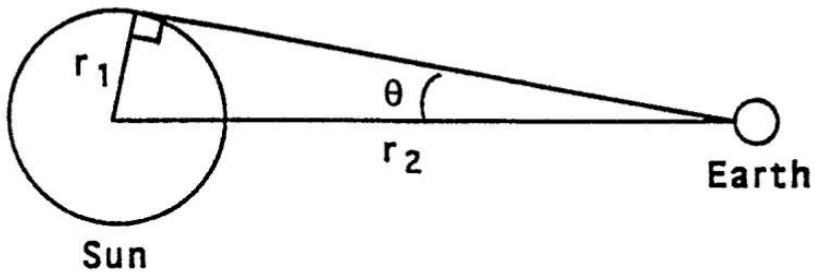
  we measure $T_{\text{sun}} \sim 6000°$ (5670°)

  Without actually going to the Sun!
- Then from σT^4 - solar surface flux~ 58.6 W/mm^2
  - The solar constant ~ 1.35 mW/mm^2
  - The second law of thermodynamics
  - C max ~ 44,000
  - Coincidentally, $C_{max} = 1/\sin^2\theta$
  - This is evidence of a deep connection to optics

Limits to Concentration

$1/\sin^2\theta$ Law of Maximum Concentration

Earth:Sun Example



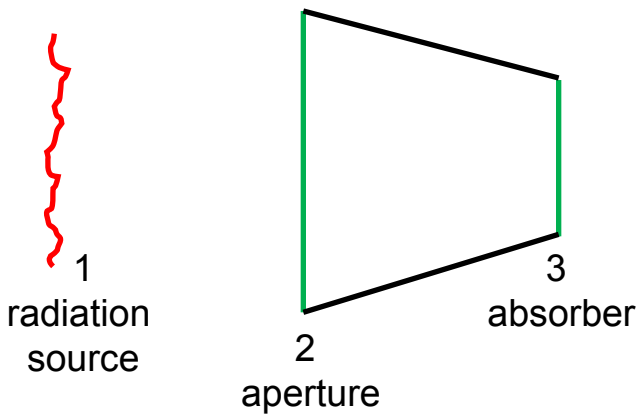
$I_2 = (r_1/r_2)^2 I_1$ **Inverse Square Fall-off of Flux (Gauss's Law)**

$\sin(\theta) = r_1/r_2 \longrightarrow I_1/I_2 = 1/\sin^2\theta$

$CI_2 \leqq I_1$ **(2nd Law of Thermodynamics)**

Maximum Concentration $C = 1/\sin^2\theta = 46{,}000$

The general concentrator problem



Concentration C is defined as A2/A3

What is the “best” design?

Characteristics of an optimal concentrator design

1st law efficiency: energy conservation

$$q_{12} = q_{13} \Rightarrow P_{12} = P_{13}$$

2nd law efficiency:

$$A_1 P_{12} = A_1 P_{13}, but\ A_1 P_{13} = A_3 P_{31}$$

The concentration ratio C:

$$C = \frac{A_2}{A_3}$$

$$A_3 = \frac{A_1 P_{12}}{P_{31}}$$

The maximum concentration ratio C_{max} corresponds to minimum A_3

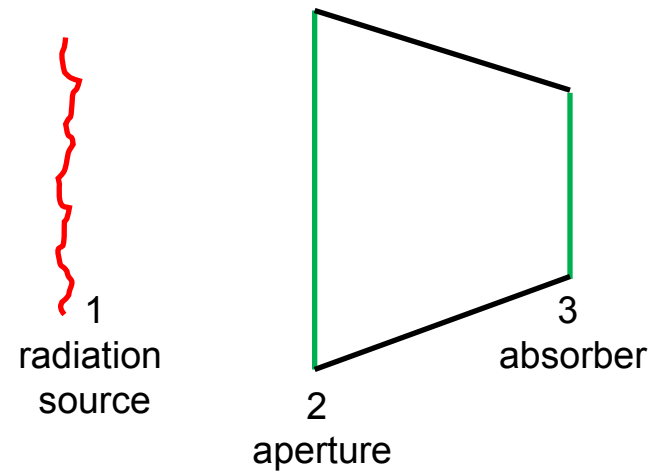
C is maximum IFF $P_{31} = 1$

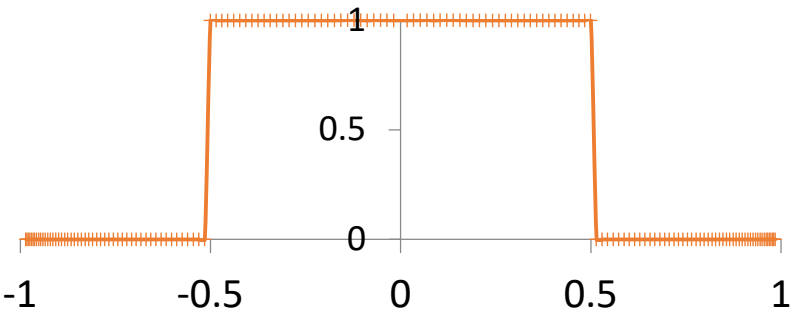
Recall that for maximum thermodynamics efficiency

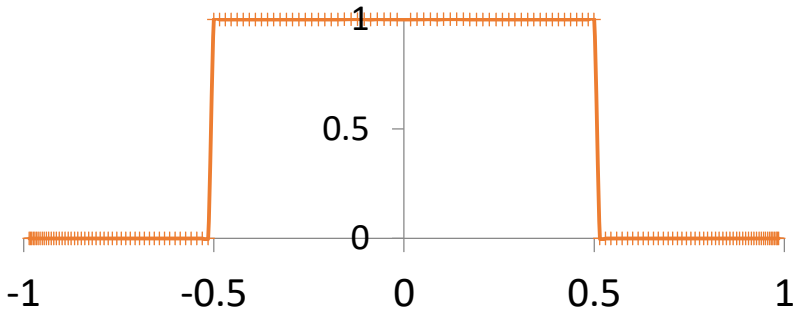
$$A_1 P_{12} = A_1 P_{13} = A_3$$

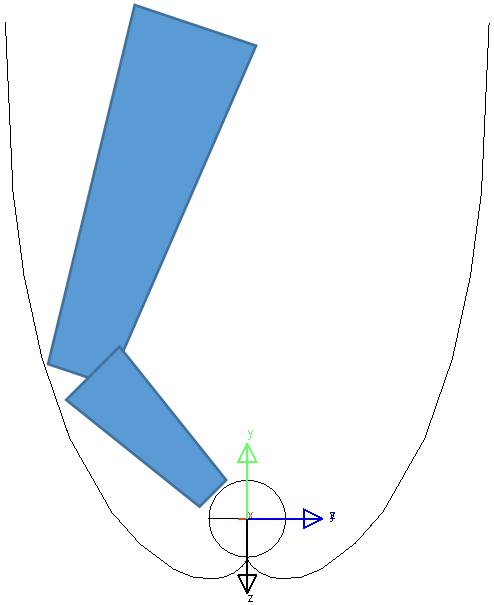
Then $A_2 P_{21} = A_3$

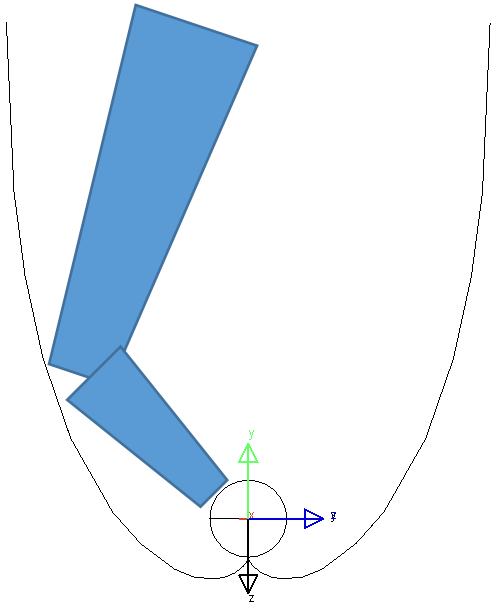
$$C_{max} = 1/P_{21}$$

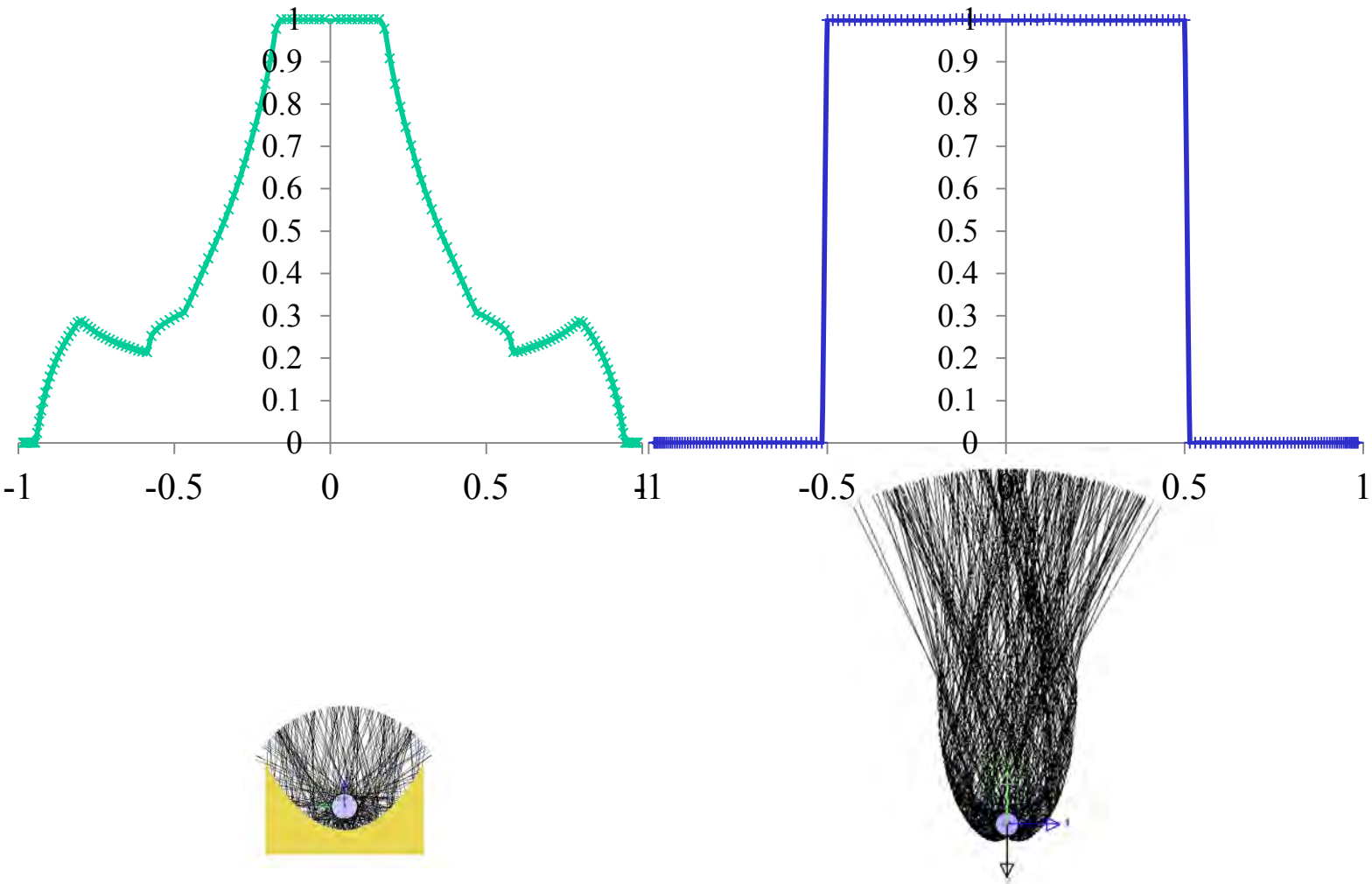



1
0.5
0
-1
-0.5
0
0.5
1


1
0.5
0
-1
-0.5
0
0.5
1






1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-1
-0.5
0
0.5
1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.5
0.5
1

•A more useful geometry for a parabolic trough thermal concentrator is a tubular receiver.

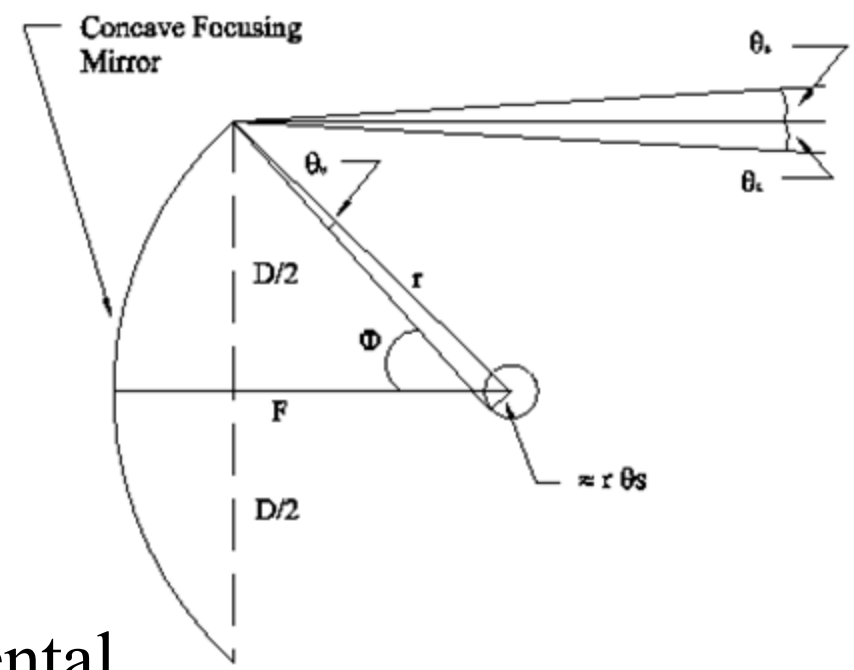
- Concentration relation

  $\sin\phi / \pi \sin\theta$

- Maximum value

  $1/(\pi \sin\theta)$ at 90^0 rim angle.

- Falls short of the fundamental limit by a factor π !



$$C = D/ 2 \pi r \sin \theta_s = \sin \phi / \pi \sin \theta_s$$
$$\leq 1/\pi \sin \theta_s \leq \underline{(1/ \pi)\, C_{max}}$$

CHANGING WHAT'S POSSIBLE

Record Breaking Exergy from Sunlight

U.S. DEPARTMENT OF ENERGY

UNIVERSITY OF CALIFORNIA UCMERCED

gti

Berkeley UNIVERSITY OF CALIFORNIA

1. TEAM

University of California, Merced

- Roland Winston, PhD
  - Co-Principle Investigator
  - Professor, Solar Optics

- Lun Jiang, PhD
  - Post-Doc, Hybrid Receiver Project Leader

- Bennett Widyolar
  - Grad Student, Concentrating Experimental System

- Jonathan Ferry
  - Grad Student, Solar Cell Testing

UCMERCED

> Jiba Dahal
  - Grad Student, Vacuum System

> Melissa Ricketts
  - Grad Student, Optics Design & Simulation

1. TEAM

University of California, Berkeley

- Eli Yablonovitch, PhD
  - Professor, Solid State Physics

- Gregg Scranton
  - Grad Student, Solar Cell Fabrication

1. TEAM

Gas Technology Institute

- Aleksandr Kozlov, PhD
  - Principle Investigator
  - Thermal Storage, Heat Transfer

- David Cygan
  - Project Management

- Hamid Abbasi
  - Project Management

- Joseph Pondo
  - Thermal System Testing

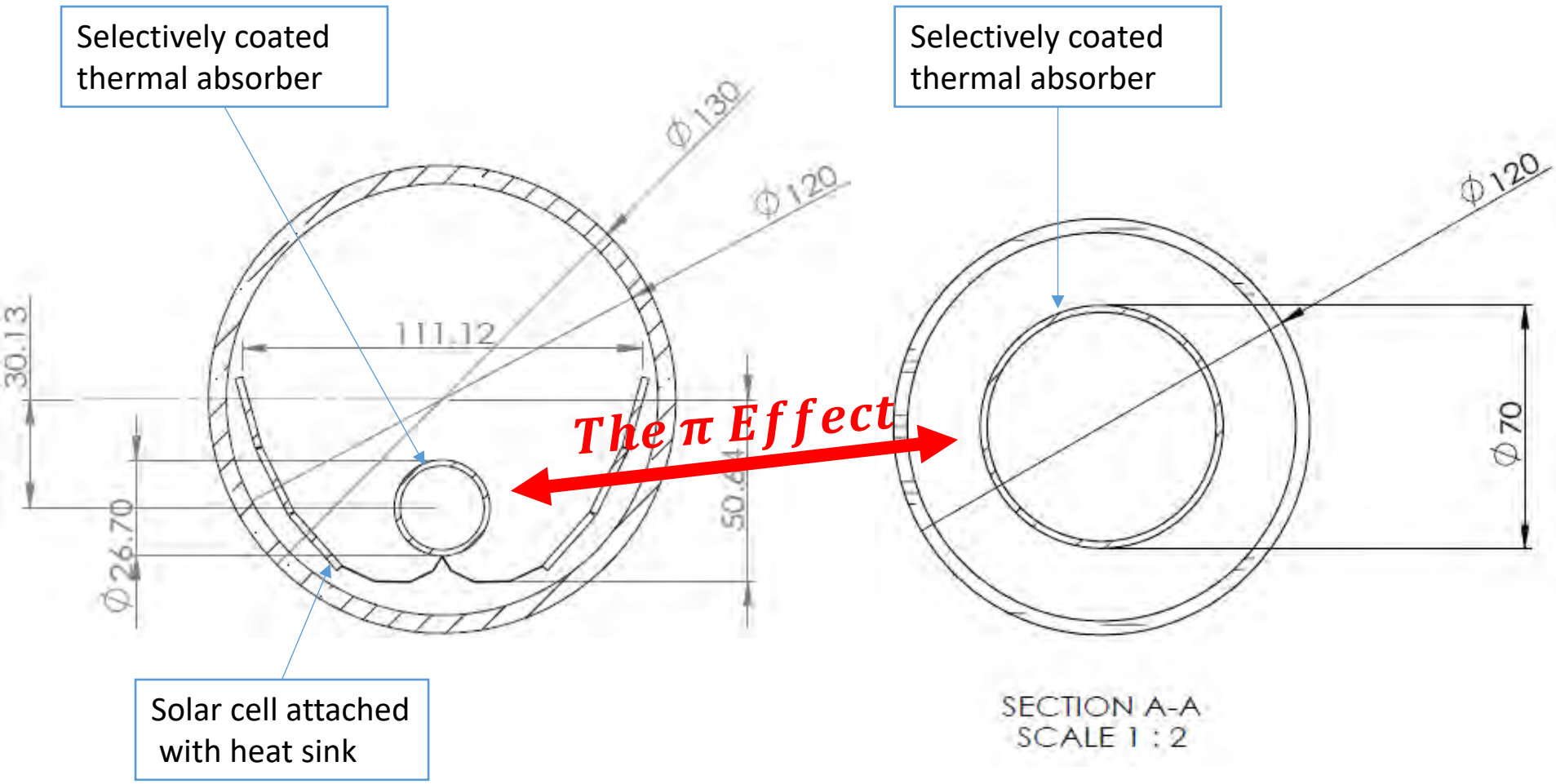
> Sandeep Alavandi
  - Thermal System Analysis

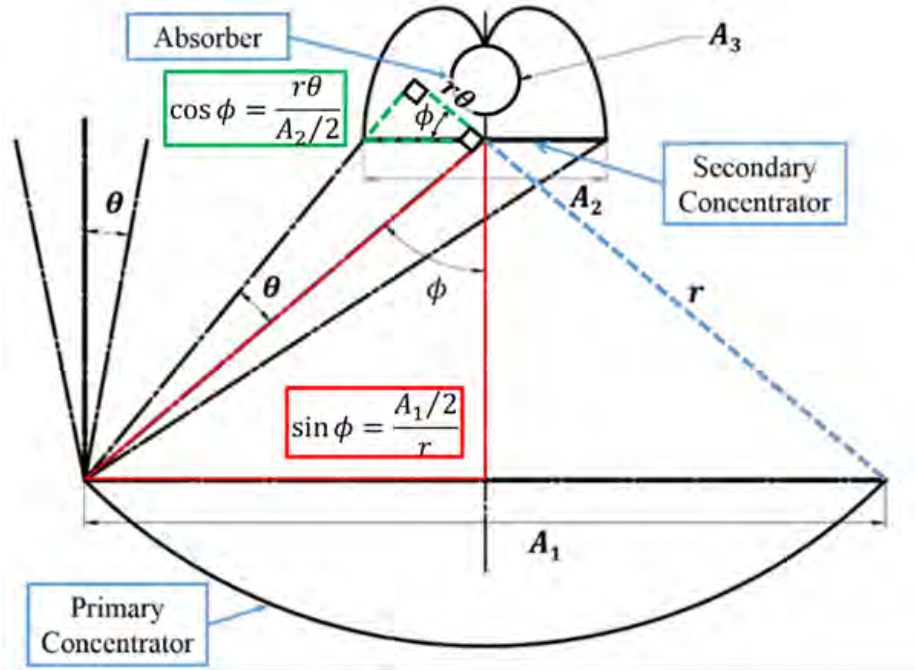
> Joseph Rabovitser, PhD
  - System Modelling

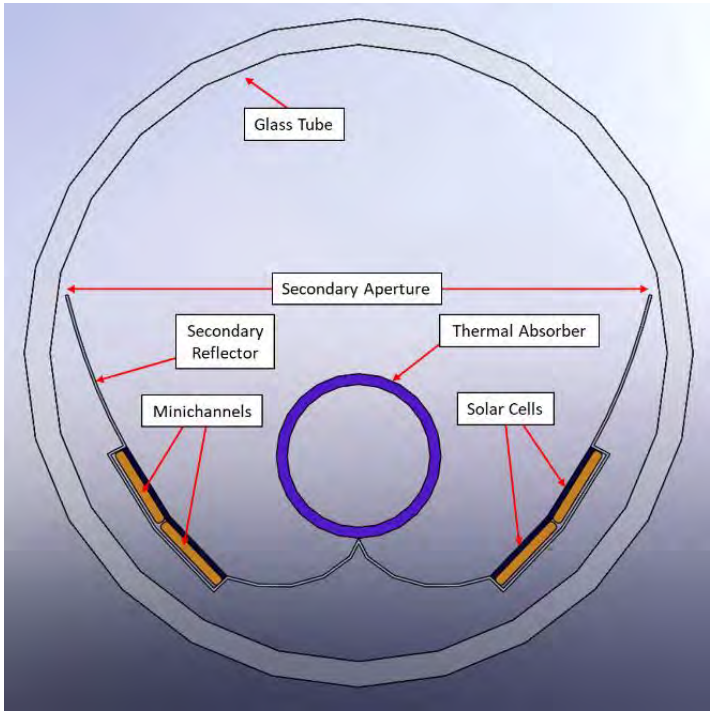
> Alek Tang
  - T2M, Licensing

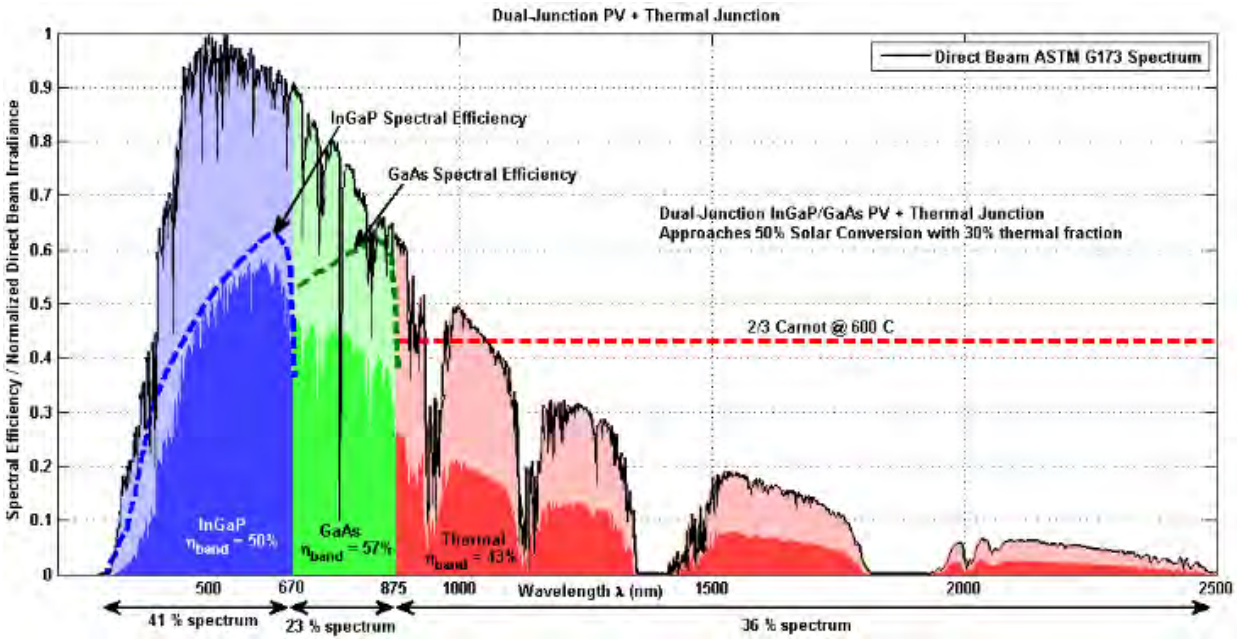
Comparison of Nonimaging and conventional at 1:1 scale

- 3X smaller tube area means lower radiative loss at same T

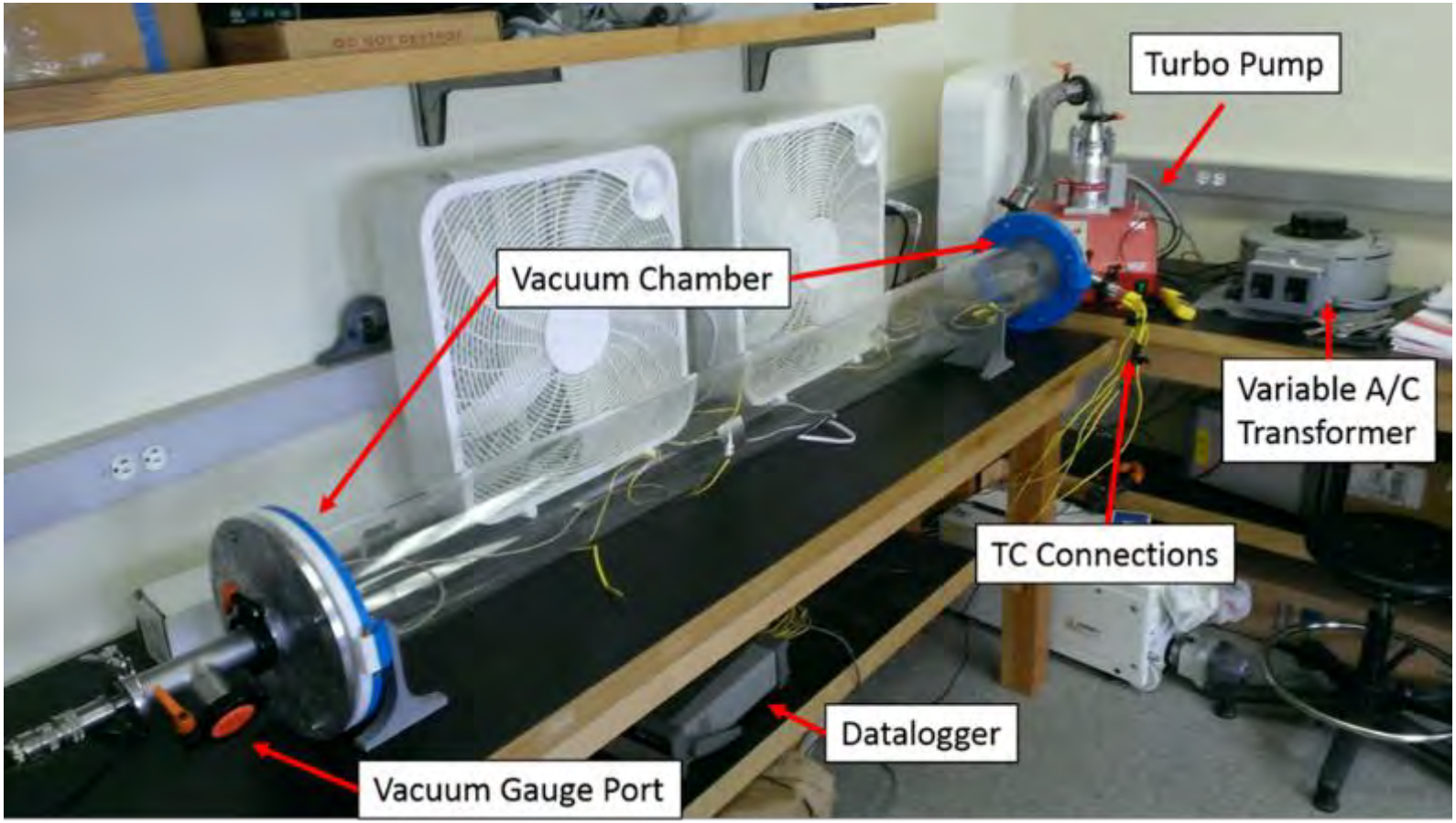


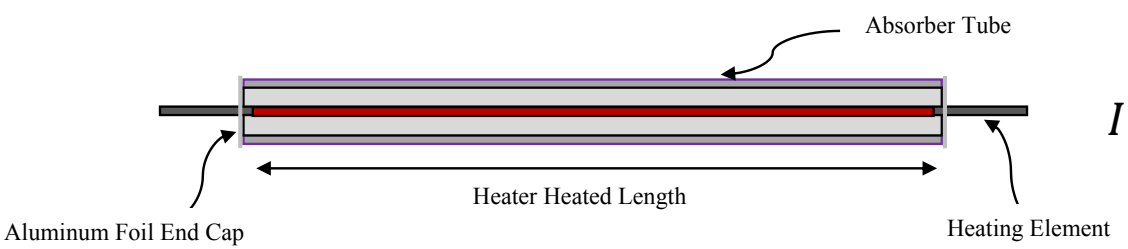

Absorber
$\cos\phi = \frac{r\theta}{A_2/2}$
A_3
$r\theta$
ϕ
Secondary Concentrator
A_2
θ
θ
ϕ
r
$\sin\phi = \frac{A_1/2}{r}$
A_1
Primary Concentrator


Glass Tube
Secondary Aperture
Secondary Reflector
Thermal Absorber
Minichannels
Solar Cells

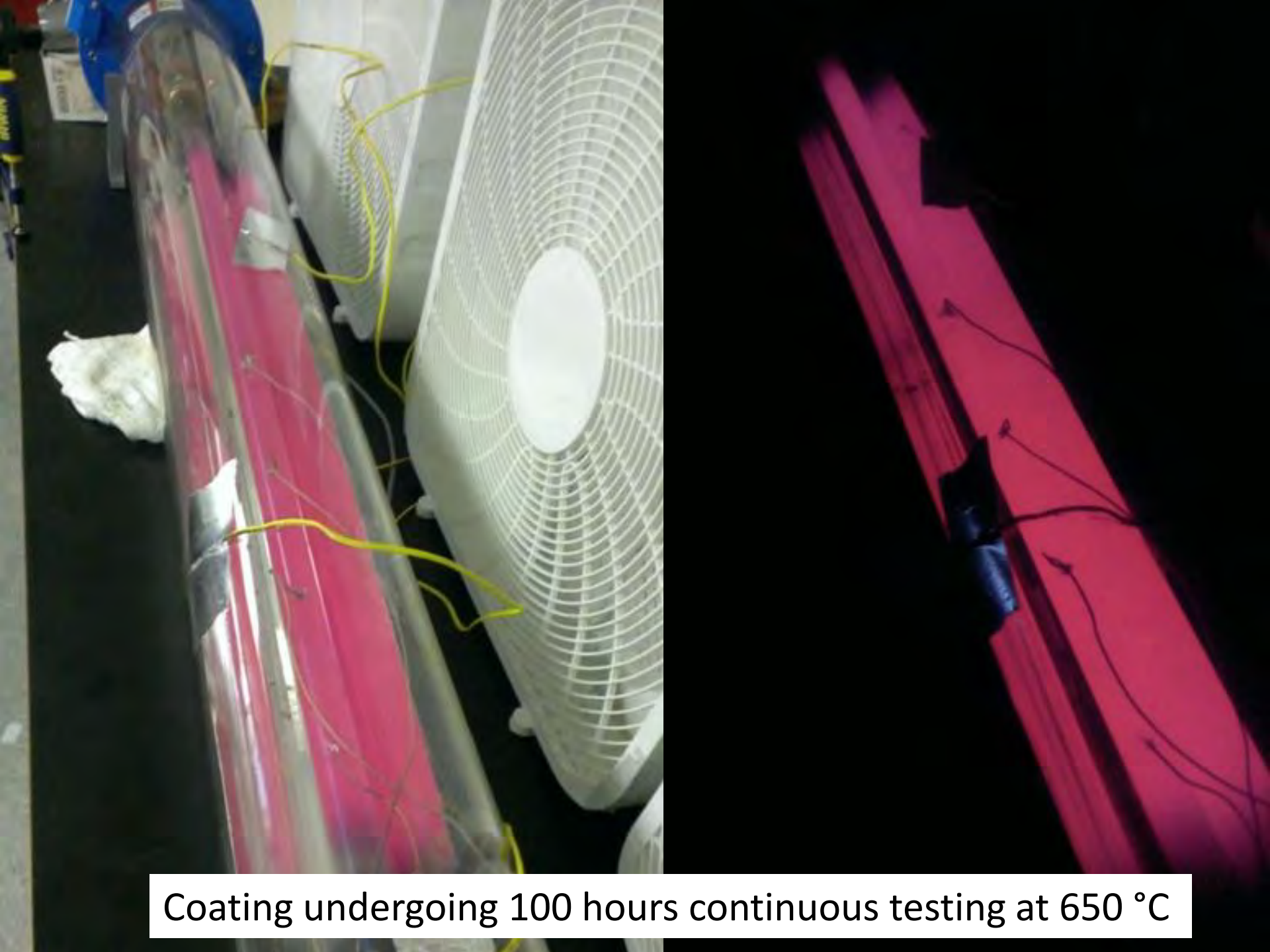

Dual-Junction PV + Thermal Junction
Direct Beam ASTM G173 Spectrum
InGaP Spectral Efficiency
GaAs Spectral Efficiency
Dual-Junction InGaP/GaAs PV + Thermal Junction
Approaches 50% Solar Conversion with 30% thermal fraction
2/3 Carnot @ 600 C
Spectral Efficiency / Normalized Direct Beam Irradiance
InGaP
η_{band} = 50%
GaAs
η_{band} = 57%
Thermal
η_{band} = 43%
Wavelength λ (nm)
500
670
875
1000
1500
2000
2500
41 % spectrum
23 % spectrum
36 % spectrum

Emissivity Testing of Selective Coatings At Temperature

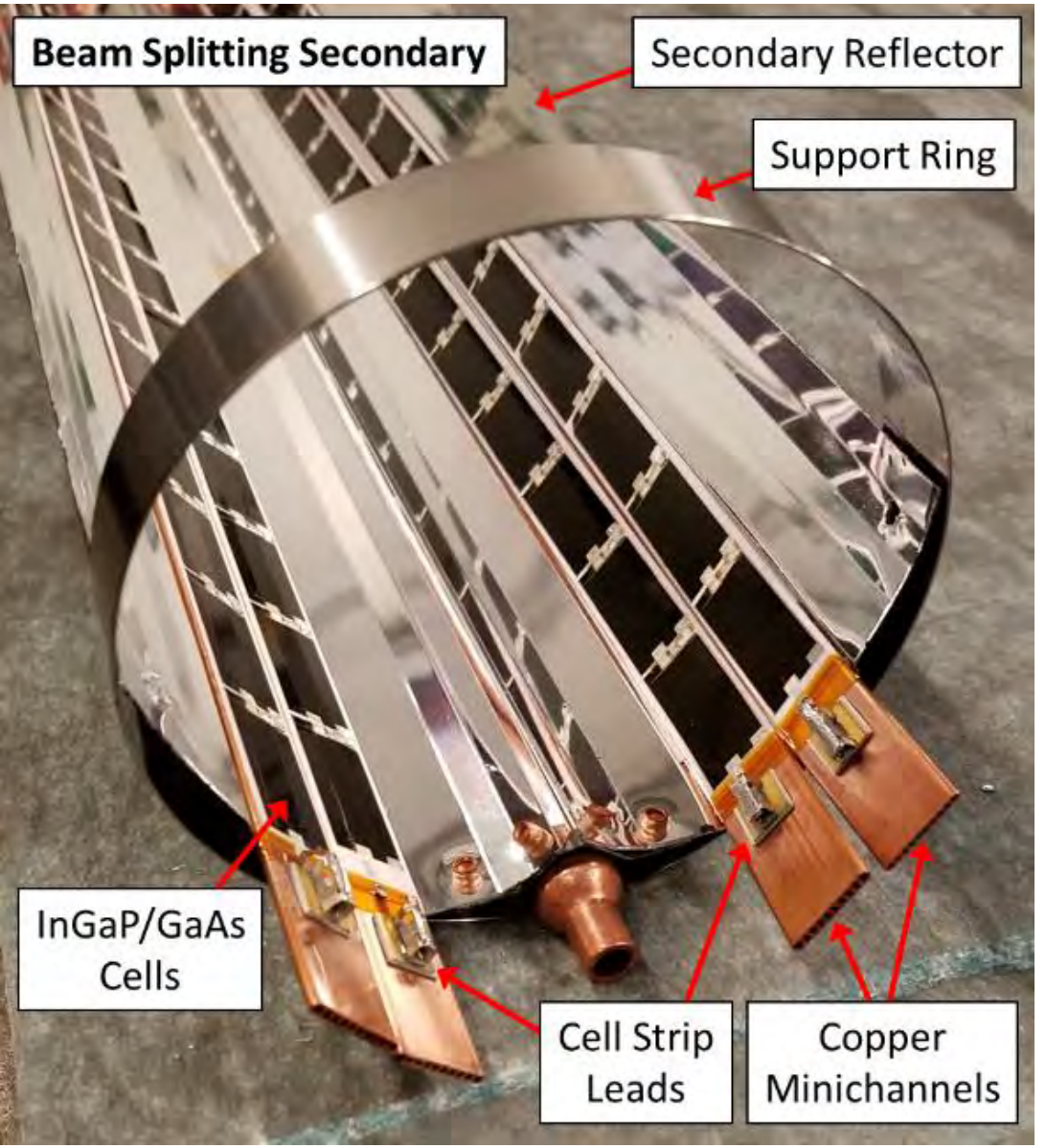


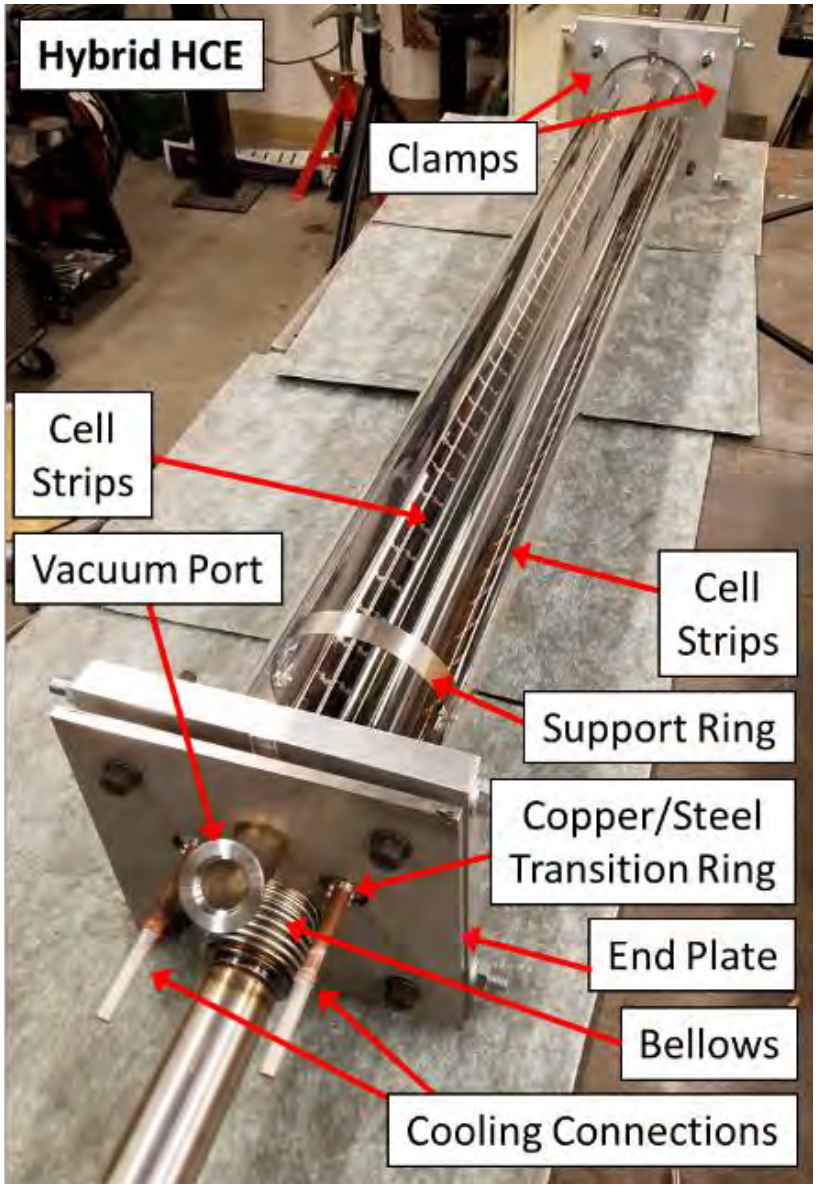


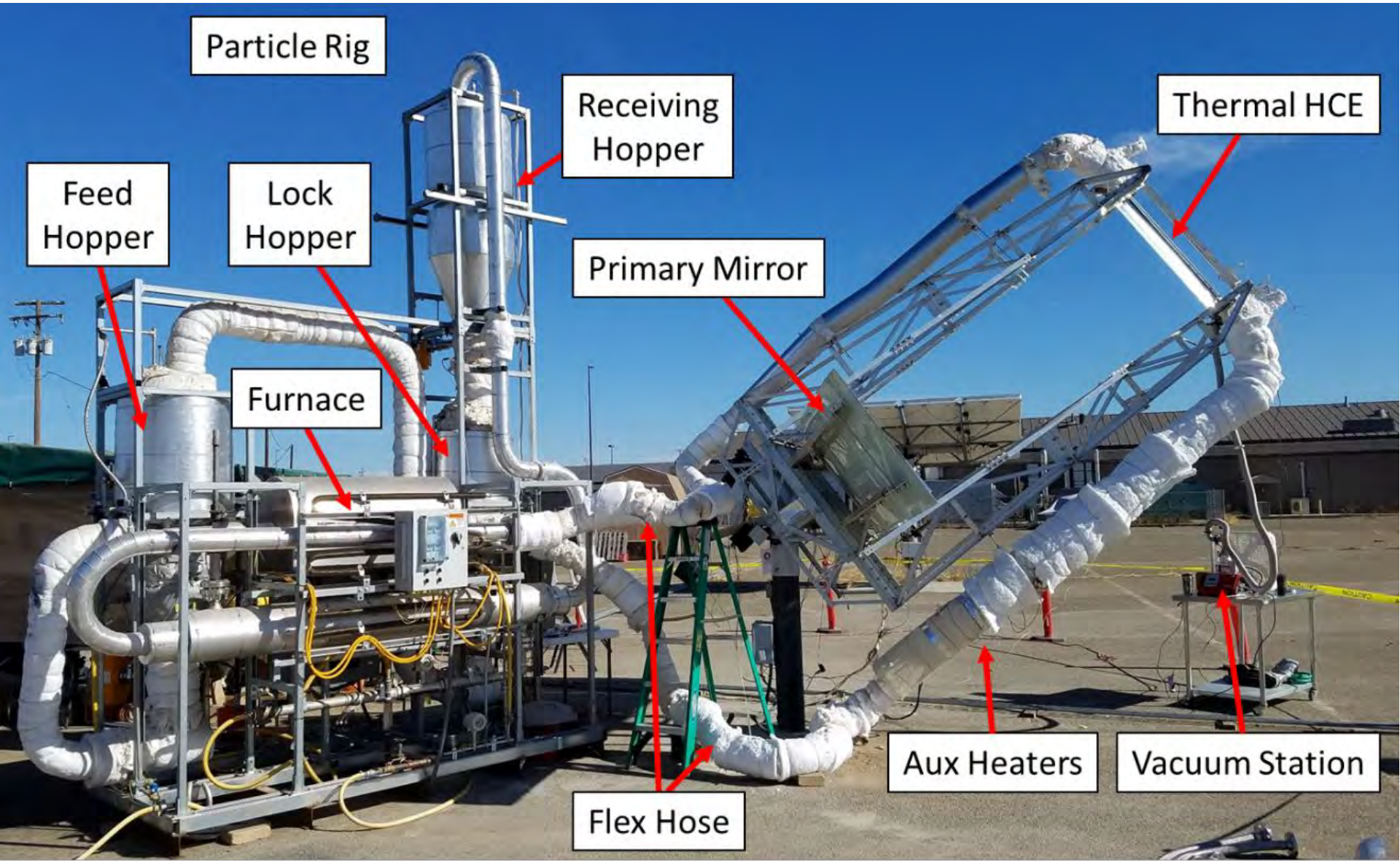
$$I * V = A\varepsilon\sigma T_{abs}^4$$

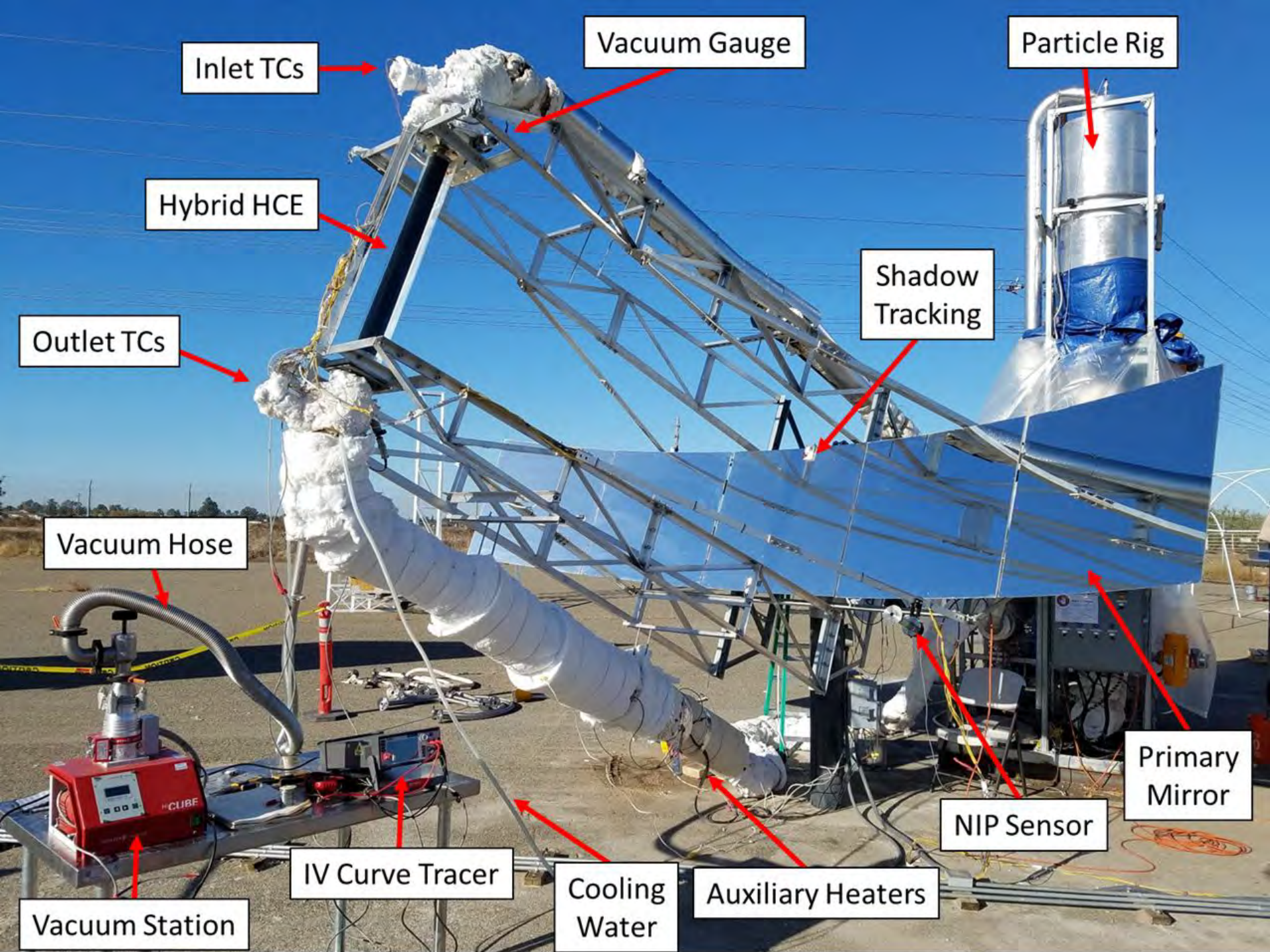


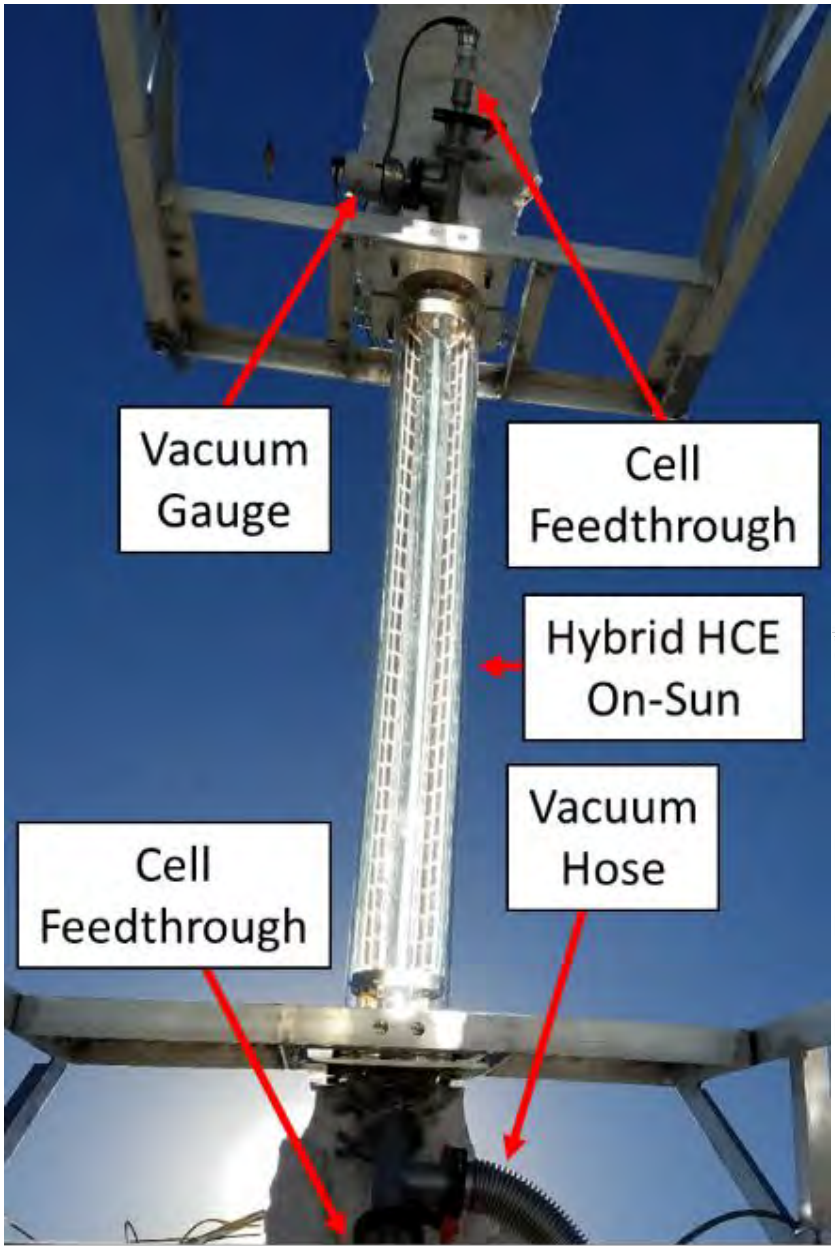
Coating undergoing 100 hours continuous testing at 650 °C

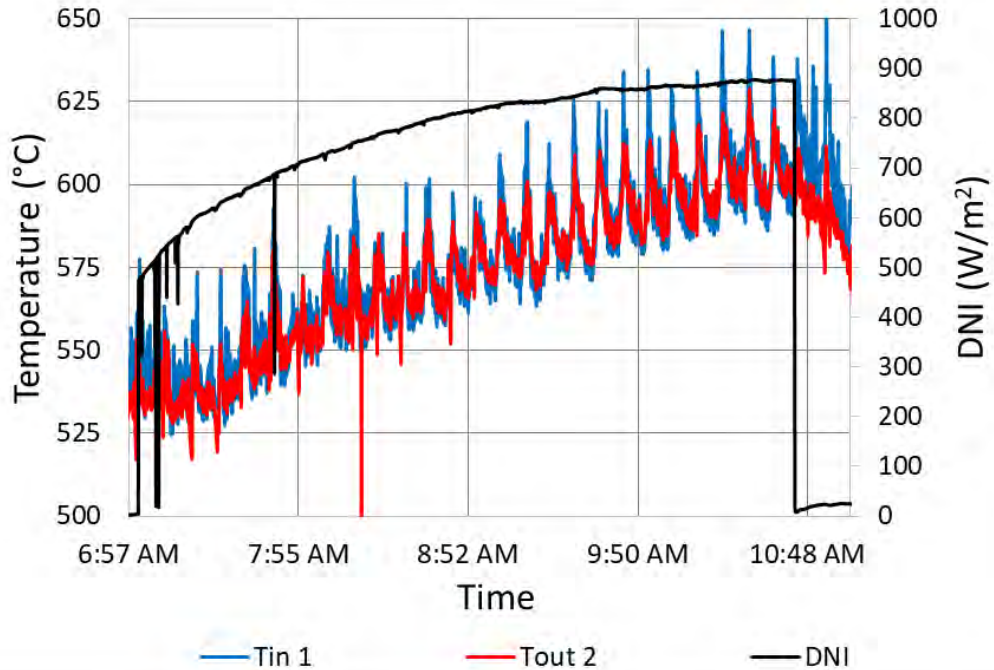

Beam Splitting Secondary
Secondary Reflector
Support Ring
InGaP/GaAs Cells
Cell Strip Leads
Copper Minichannels

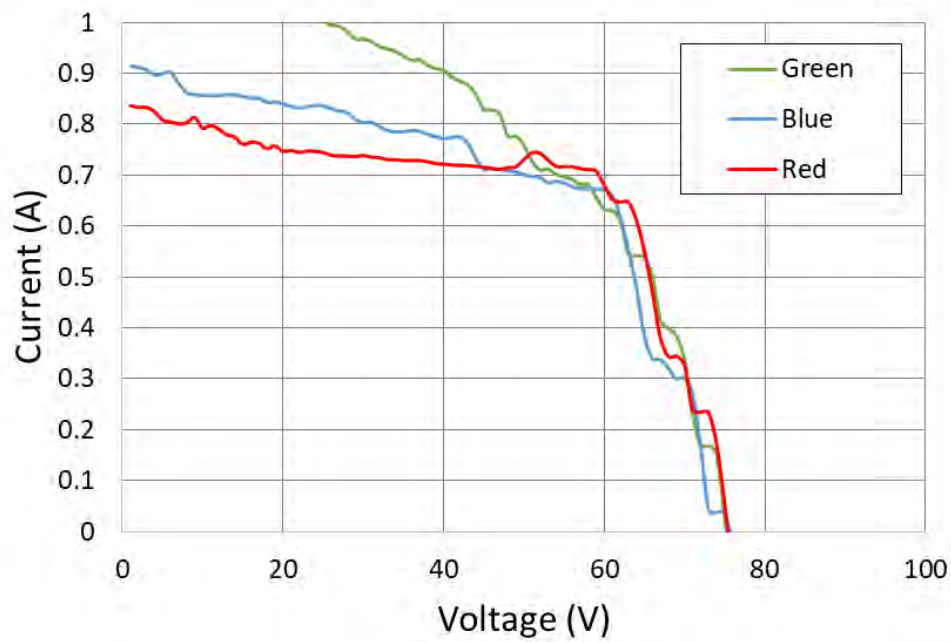

Hybrid HCE
Clamps
Cell Strips
Vacuum Port
Cell Strips
Support Ring
Copper/Steel Transition Ring
End Plate
Bellows
Cooling Connections

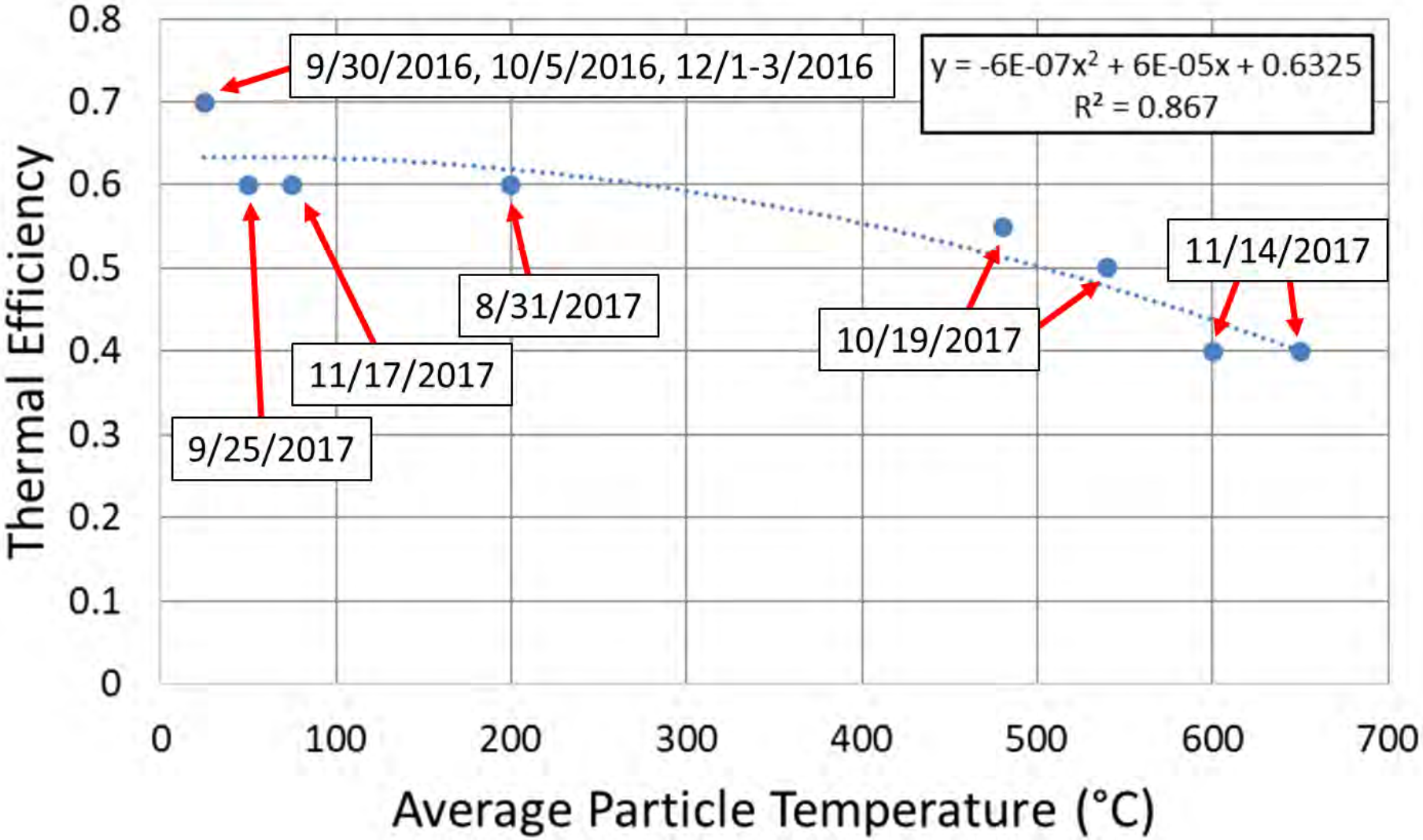

Particle Rig
Receiving Hopper
Thermal HCE
Feed Hopper
Lock Hopper
Primary Mirror
Furnace
Aux Heaters
Vacuum Station
Flex Hose


Inlet TCs
Vacuum Gauge
Particle Rig
Hybrid HCE
Shadow Tracking
Outlet TCs
Vacuum Hose
Primary Mirror
NIP Sensor
IV Curve Tracer
Cooling Water
Auxiliary Heaters
Vacuum Station


Vacuum Gauge
Cell Feedthrough
Hybrid HCE On-Sun
Vacuum Hose
Cell Feedthrough


Temperature (°C)
650
625
600
575
550
525
500
DNI (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
6:57 AM
7:55 AM
8:52 AM
9:50 AM
10:48 AM
Time
Tin 1
Tout 2
DNI


Current (A)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
Voltage (V)
Green
Blue
Red


9/30/2016, 10/5/2016, 12/1-3/2016
y = -6E-07x² + 6E-05x + 0.6325
R² = 0.867
11/14/2017
8/31/2017
10/19/2017
11/17/2017
9/25/2017
Thermal Efficiency
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
600
700
Average Particle Temperature (°C)

Filling the Hopper

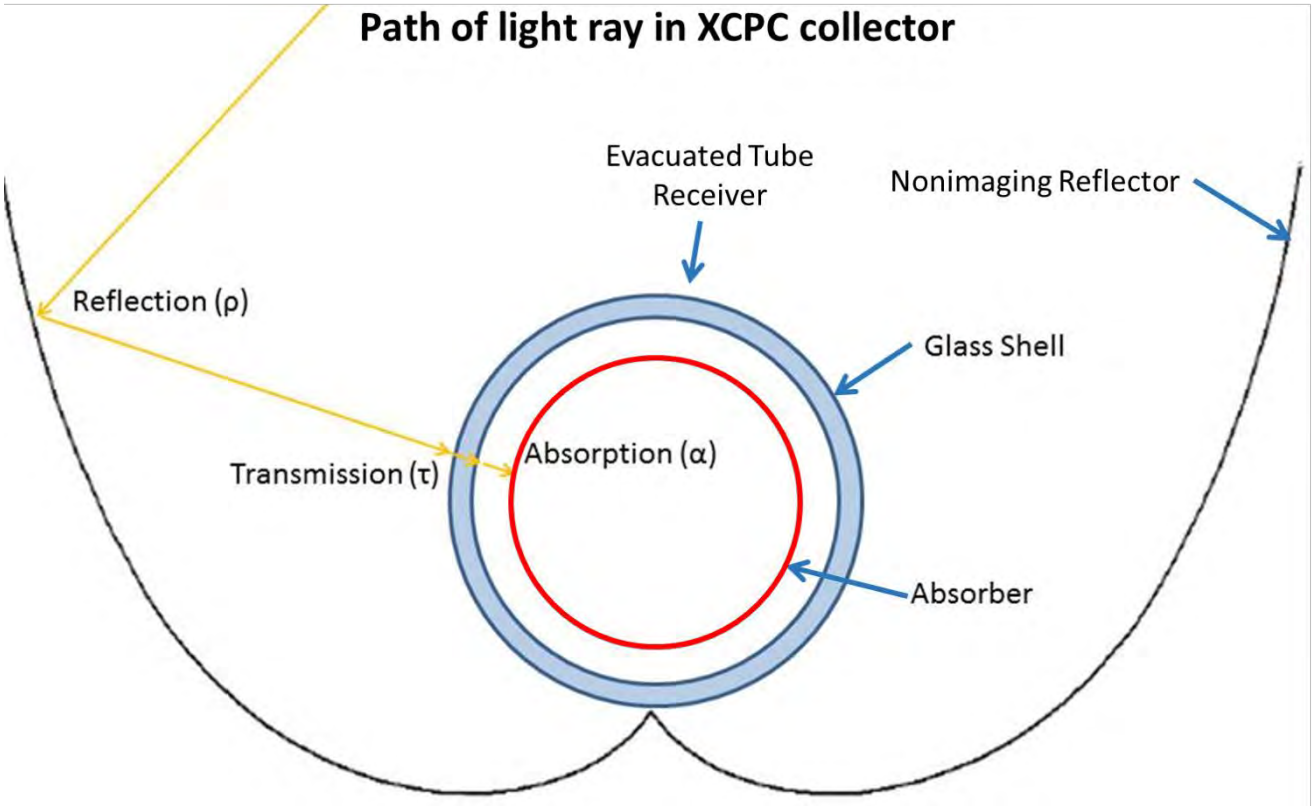
Filling the Hopper


Hybrid Solar Energy System
OVERVIEW
BENEFITS
FORWARD

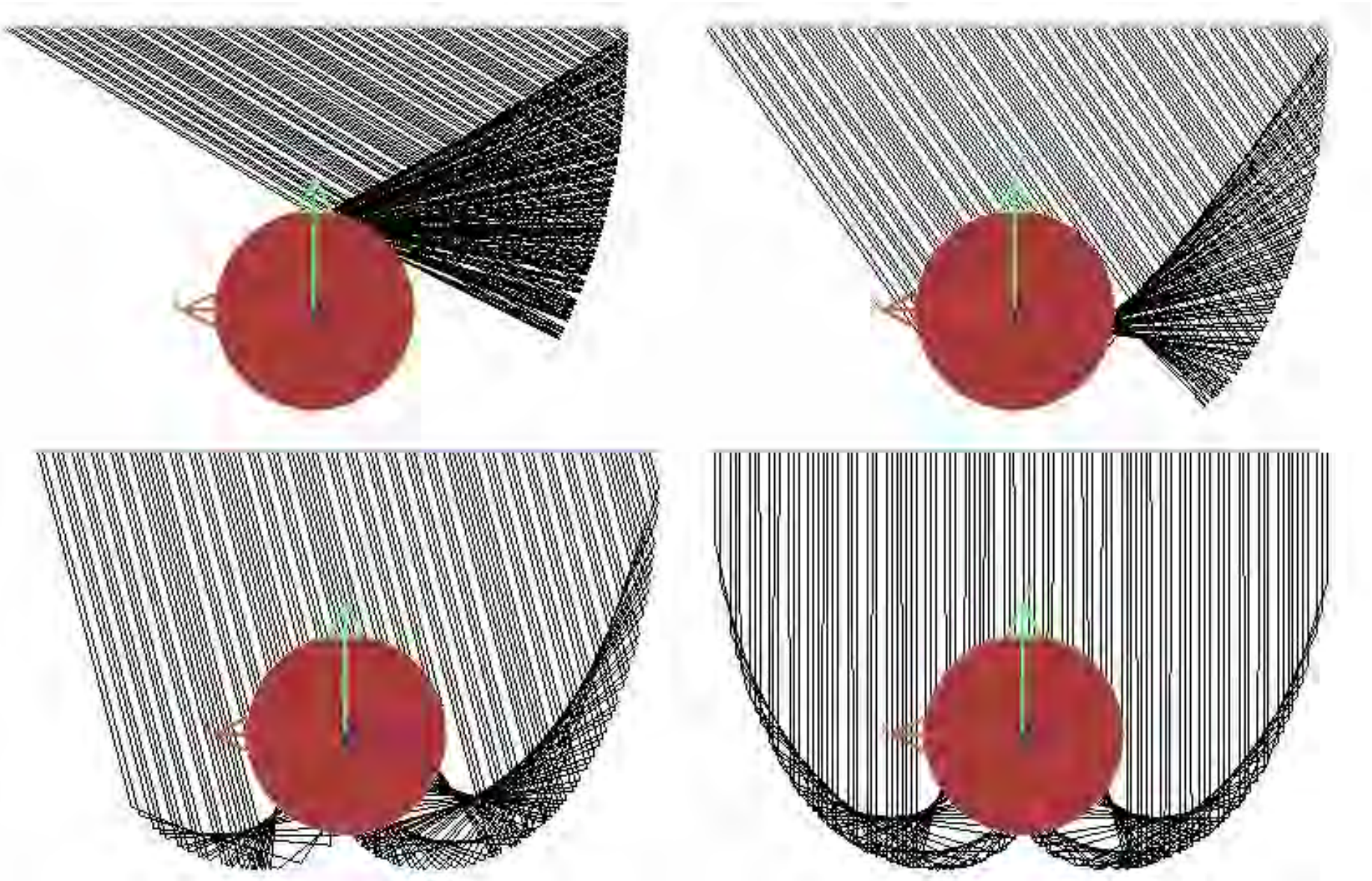
At Dirksen Senate Office Bldg aides to Sen Tammy Duckworth 3.14.18


W Evan Hewes Hwy
SBD
Osterkamp Trucking, Inc
W Evan Hewes Hwy
SBD
W Evan Hewes Hwy
W Evan Hewes Hwy
USG Corporation
Next Stop USG!
Google

The external compound parabolic concentrators (XCPC)



The XCPC uses non-imaging optics to track the sun, while the XCPC hardware remains stationary

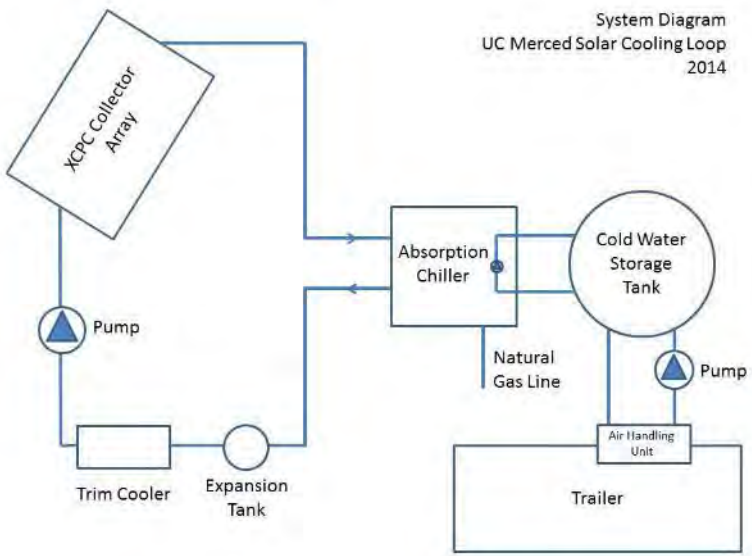


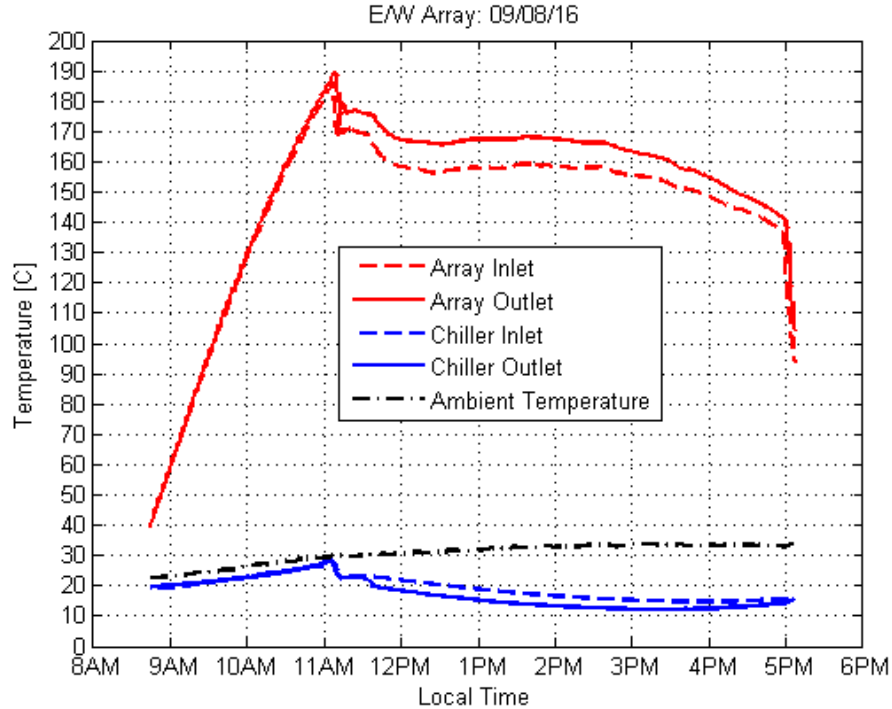
The XCPC

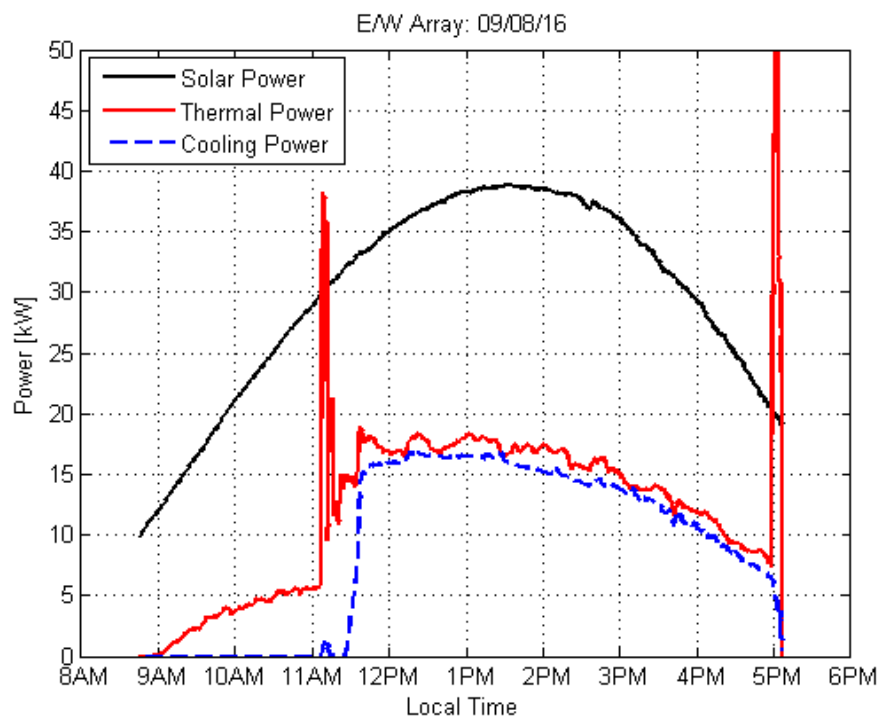
- With CEC & private donor support, researchers at UC Merced have designed, tested and demonstrated the External Compound Parabolic Concentrator (XCPC), a novel non-tracking solar thermal collector for industrial process heat (100º-250ºC)

Solar Cooling

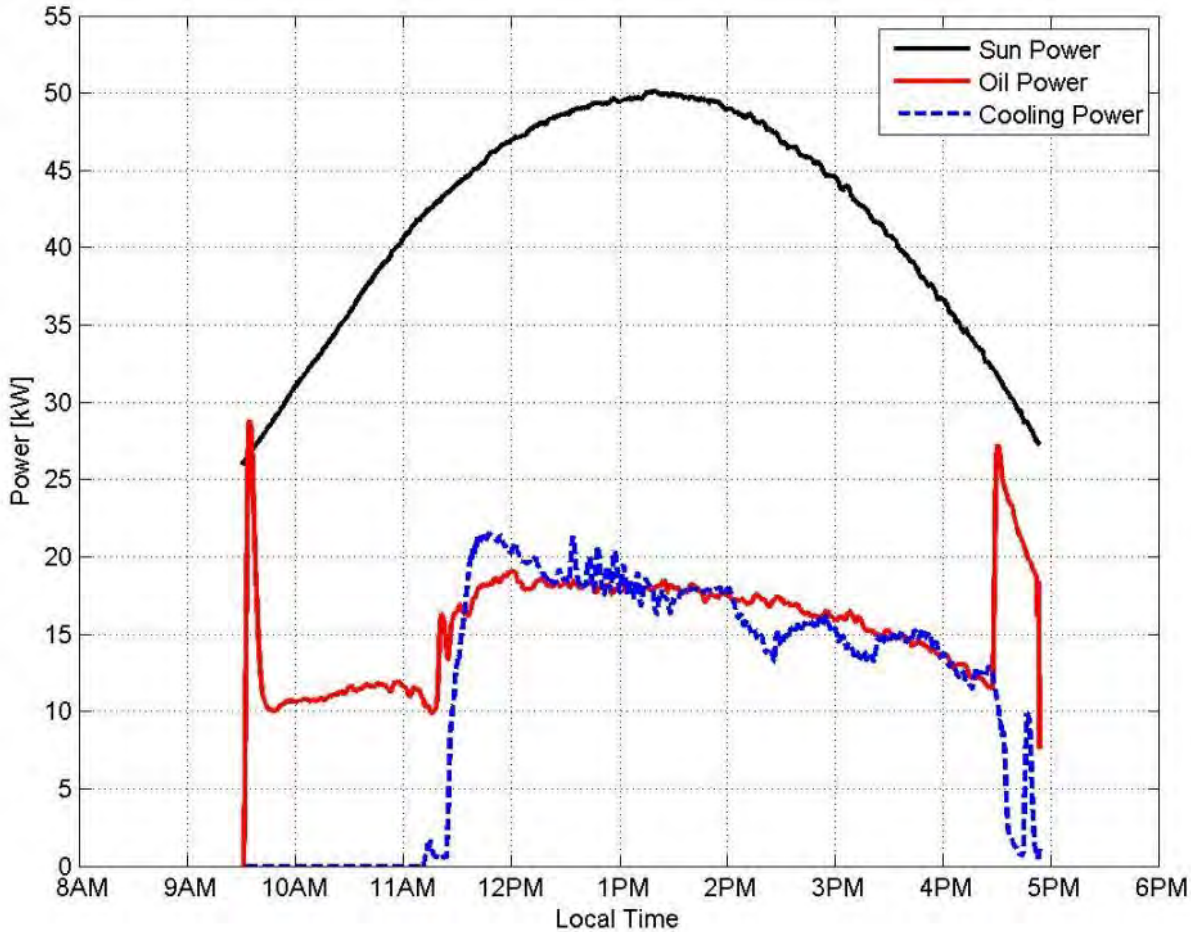
- 4 year demonstration
- 160 N/S XCPC collectors produce 20 kWth
- Power a 6.5 ton 2e absorption chiller
- Expanded to working IT trailer for 2015 tests



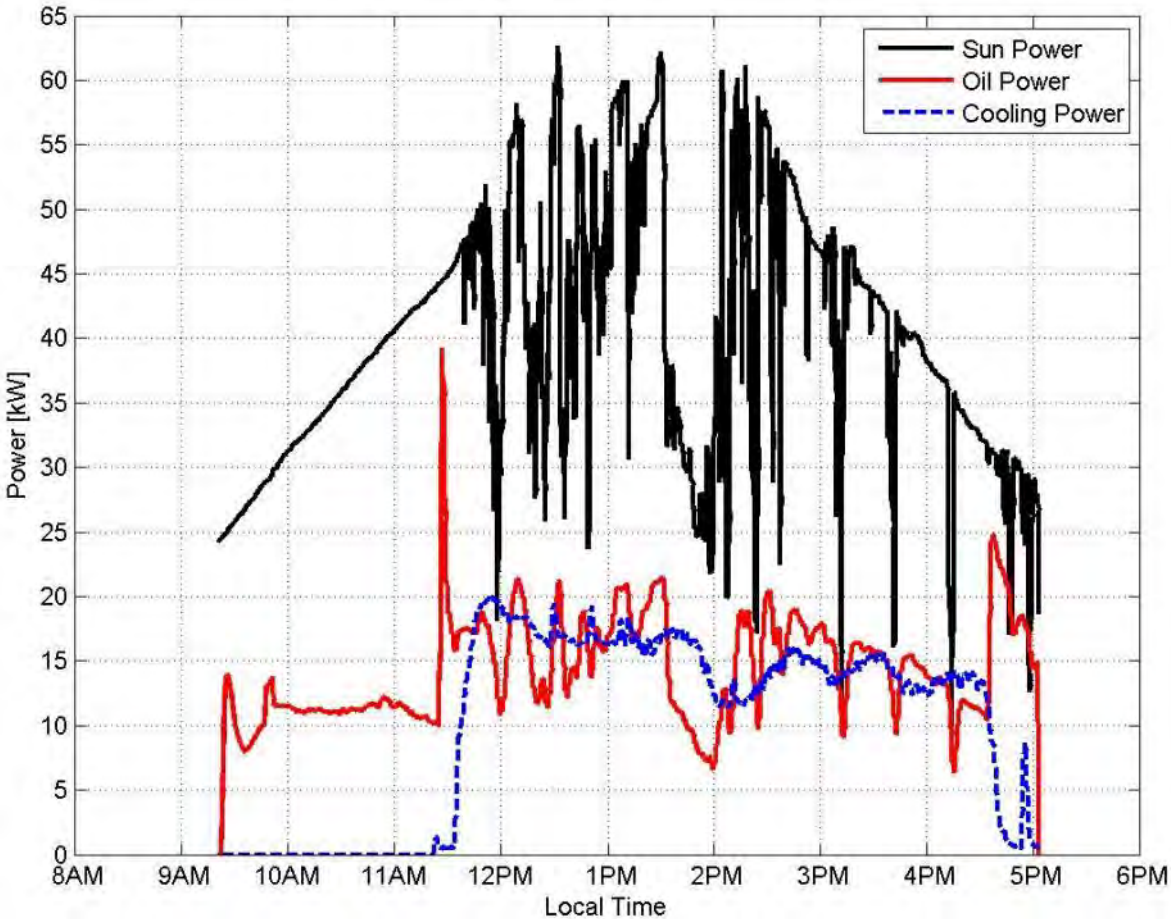


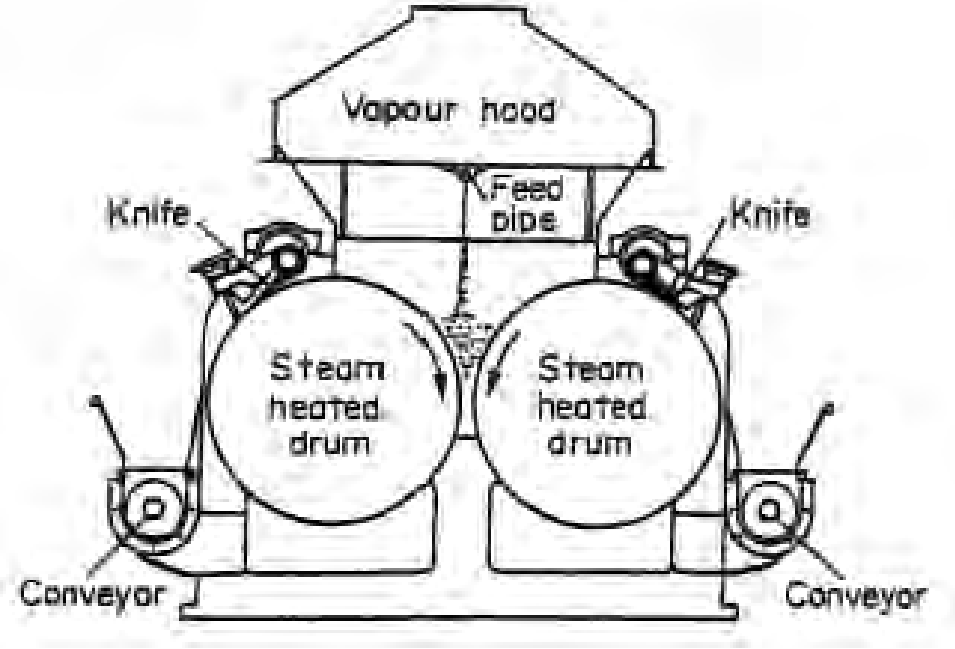


Solar cooling performance (sunny day)



Solar cooling performance (cloudy day)





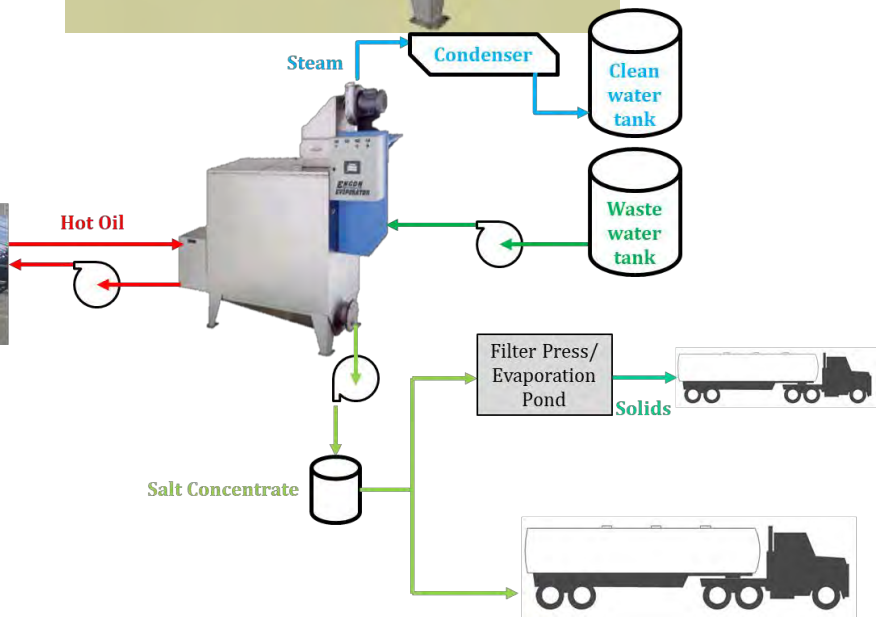
Drum Drying

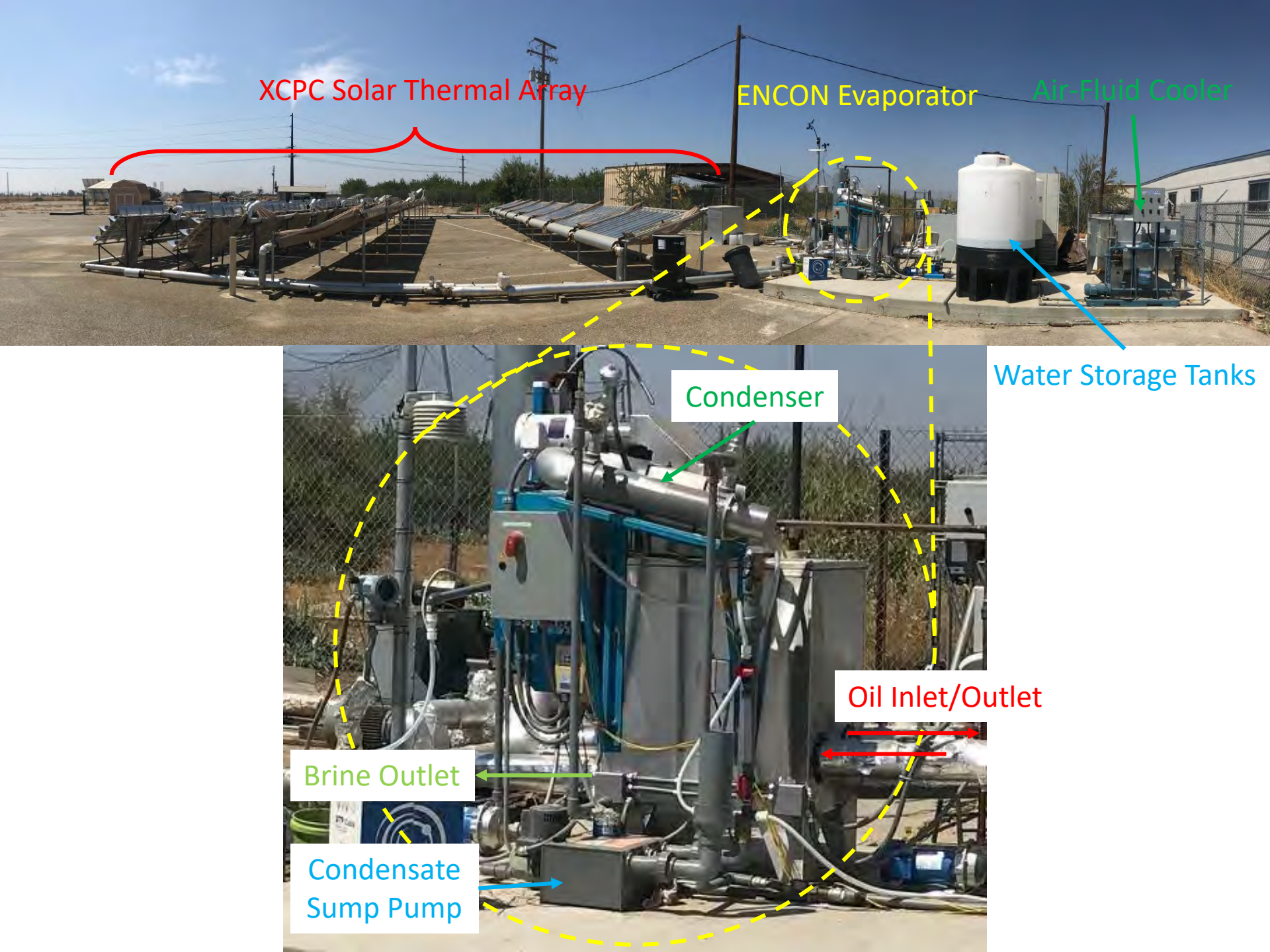
- XCPC collectors generate heat to mineral oil heat transfer fluid
  - 100-150 C
- Drum dryer uses steam (100-130 psig) to heat exterior surface of the drums.
- Retrofitted existing steam powered double drum dryer to use direct flow of mineral oil.

United States Department of Agriculture
Agricultural Research Service
the in-house research arm of the USDA

Evaporation

- XCPC collectors can provide heat (150 °C) to power commercial evaporators
  - Up to 90% waste stream volume reduction
  - 6-13 GPH evaporation
  - Test using heat transfer oil instead of steam or a natural gas burner
- Test effectiveness in processing valley waste streams:
  - RO discharge
  - Industrial and food processing waste streams
  - Agricultural drainage




XCPC Solar Thermal Array
ENCON Evaporator
Air-Fluid Cooler
Water Storage Tanks
Condenser
Oil Inlet/Outlet
Brine Outlet
Condensate
Sump Pump

Boiler Pre-heating in The UAE

XCPC boiler pre-heating at sugar refinery plant in Dubai, UAE

XCPC Steam Generation in Beijing

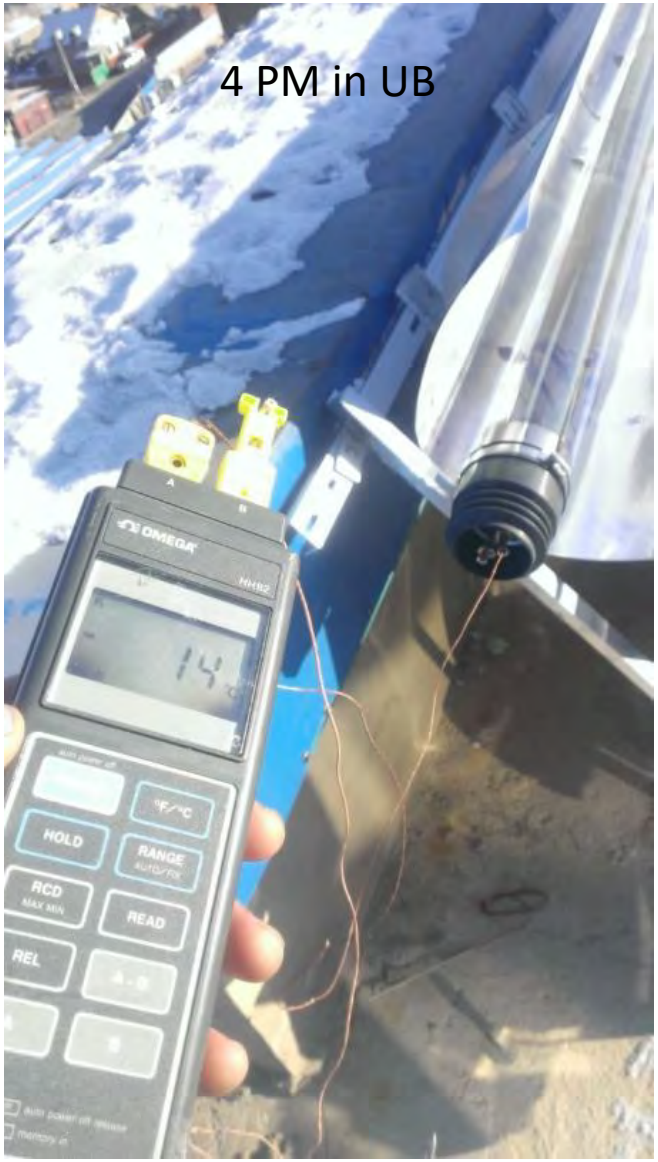
XCPC Heating in Mongolia

(space, water, cooking, toilet)

Bennett in Ulan Bator

Initial Testing

310 °C



-14 °C

Project Launch

XCPC in Mongolia

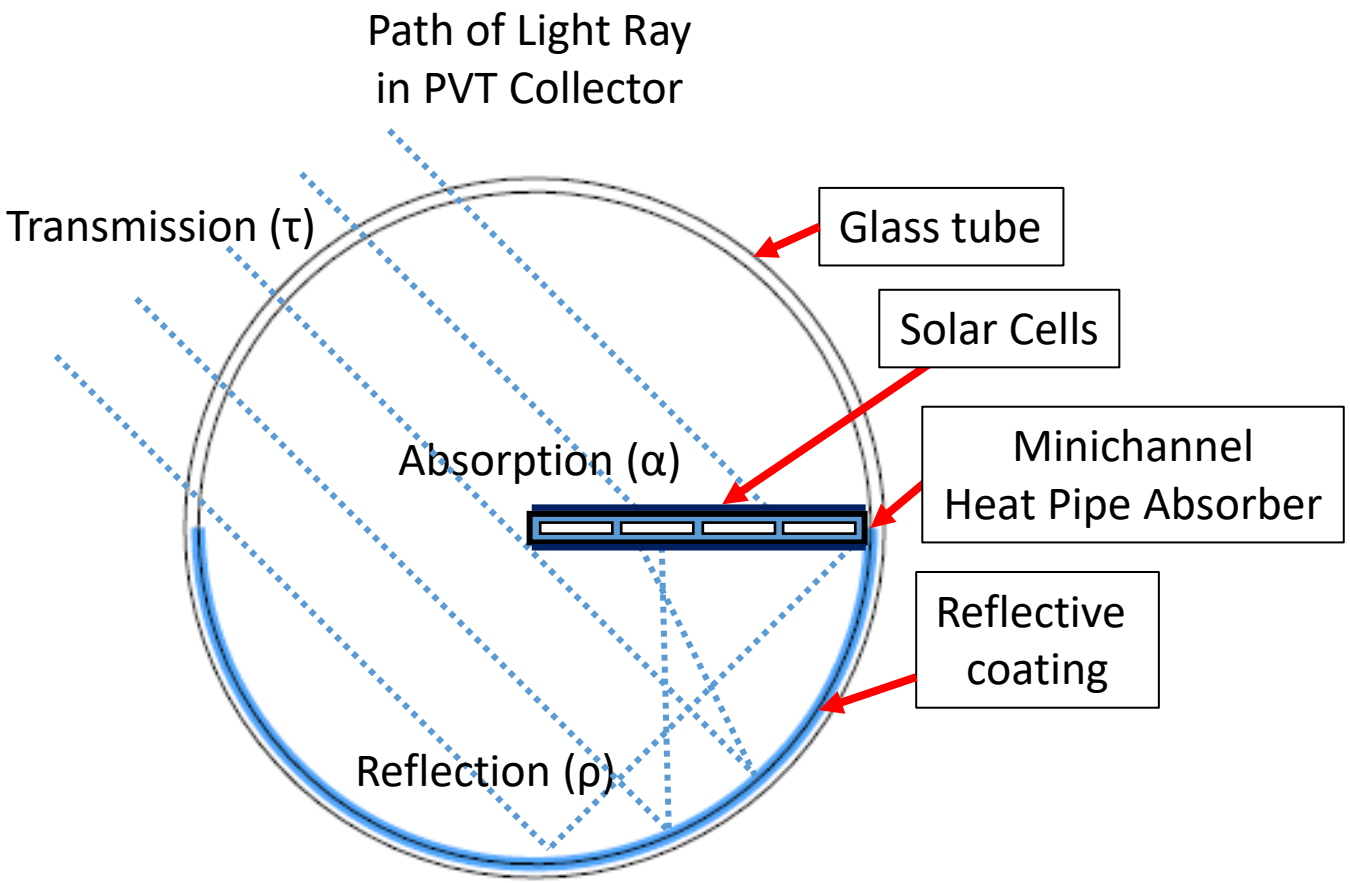
Solar array outside ger @ BogdKhan Resort, UB – May 2015

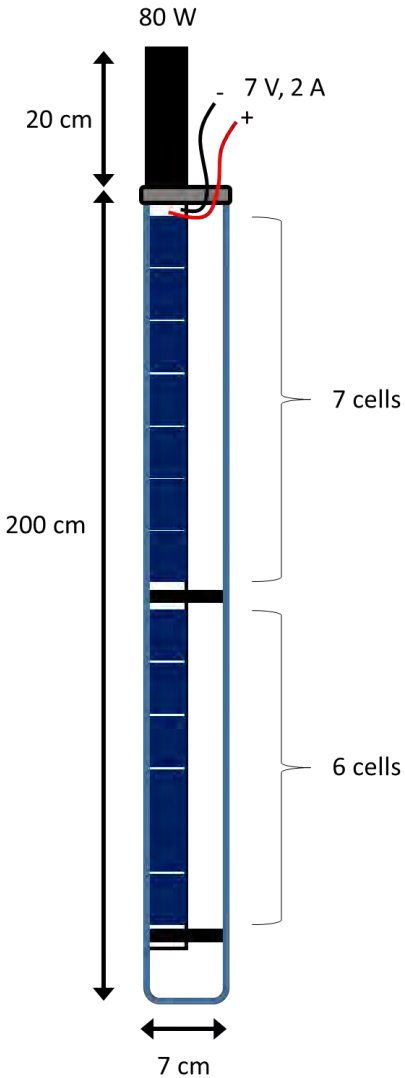
A Novel Low-Cost, High-Efficiency Solar Powered Micro-CHP System for Electricity, Hot Water, and Space Heating

- Hybrid PV/T Collector Generates
  - Electricity
  - Hot water (60 °C)
- Operates at same efficiency as solar PV panel *and* generates solar heat with minimal additional cost

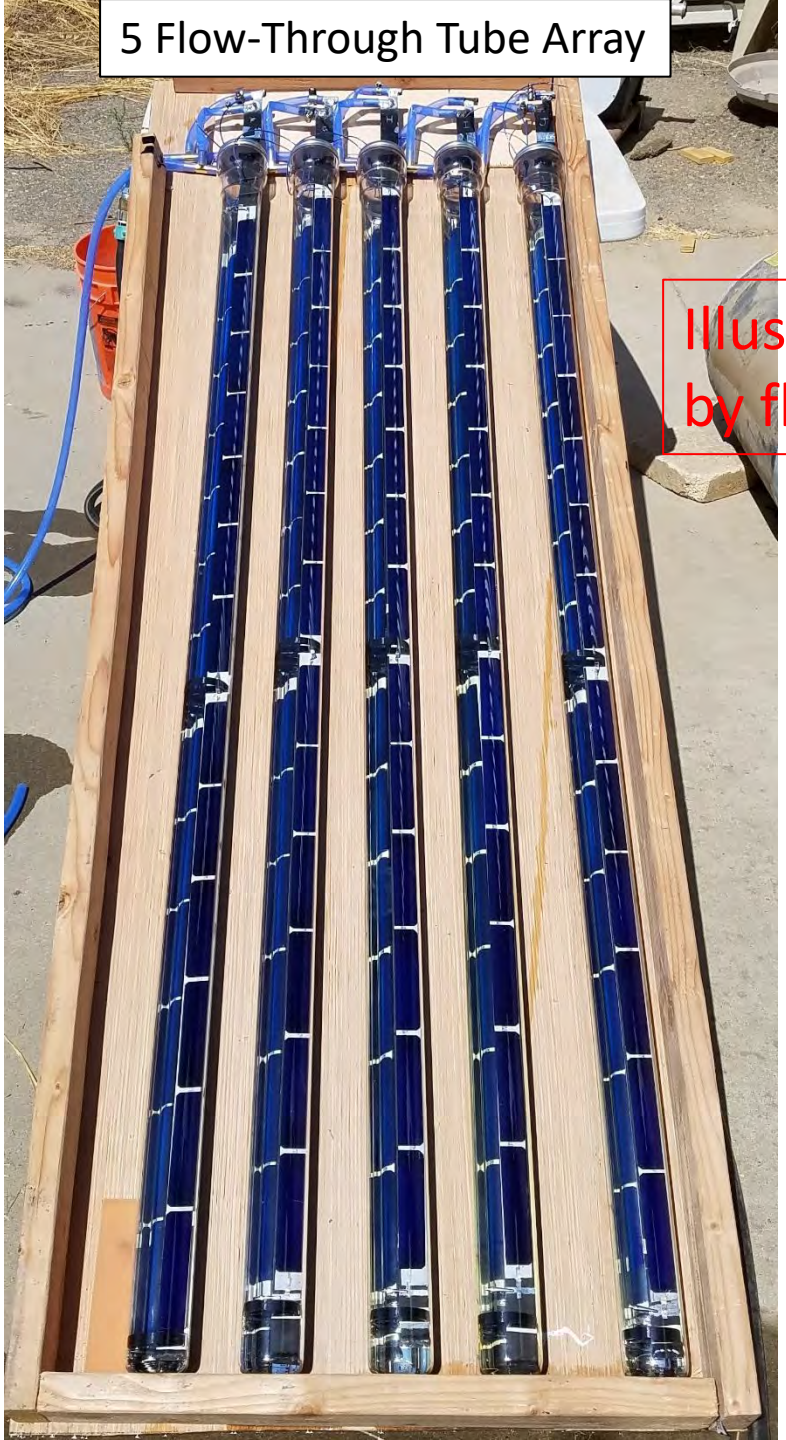
CALIFORNIA ENERGY COMMISSION

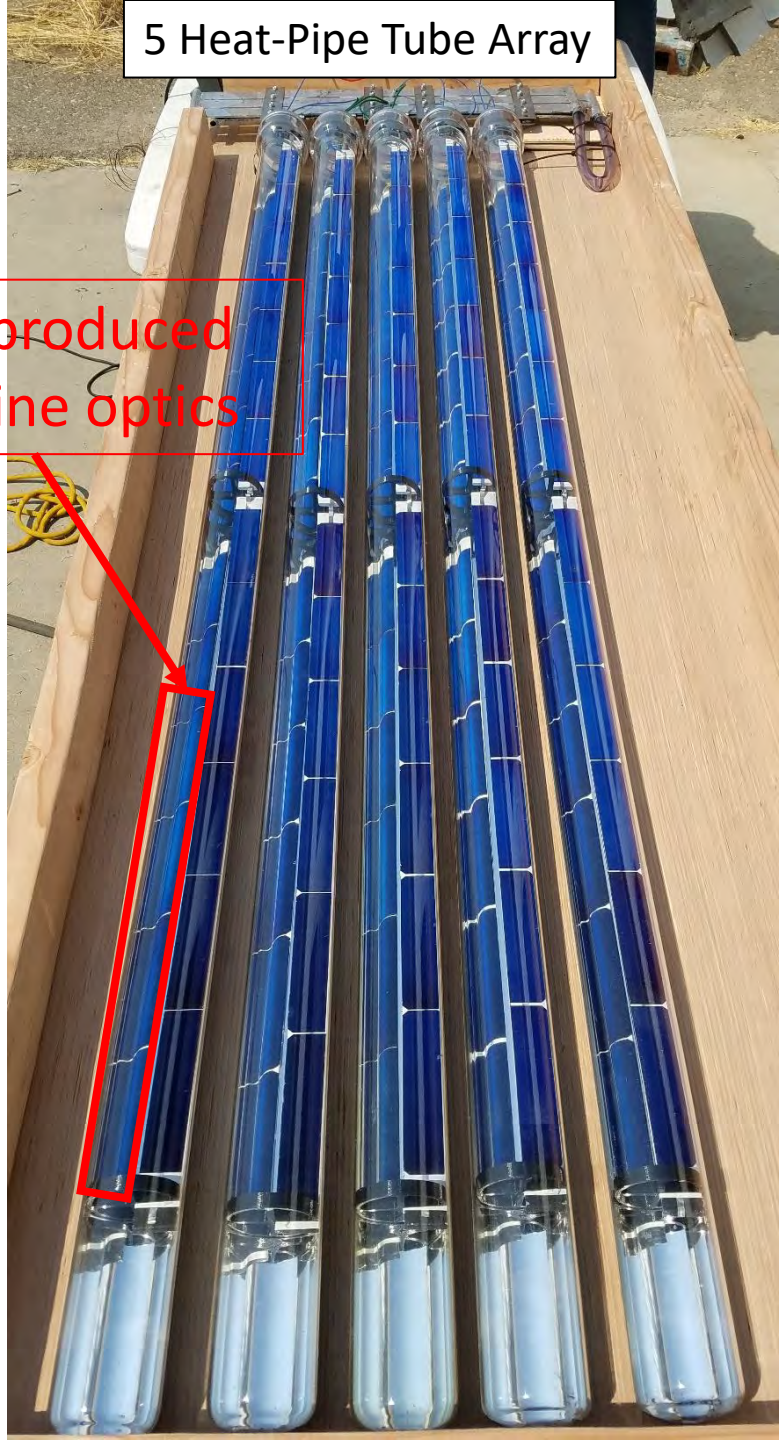
Combined Heat and Power (CHP) for Domestic / Commercial Hot Water





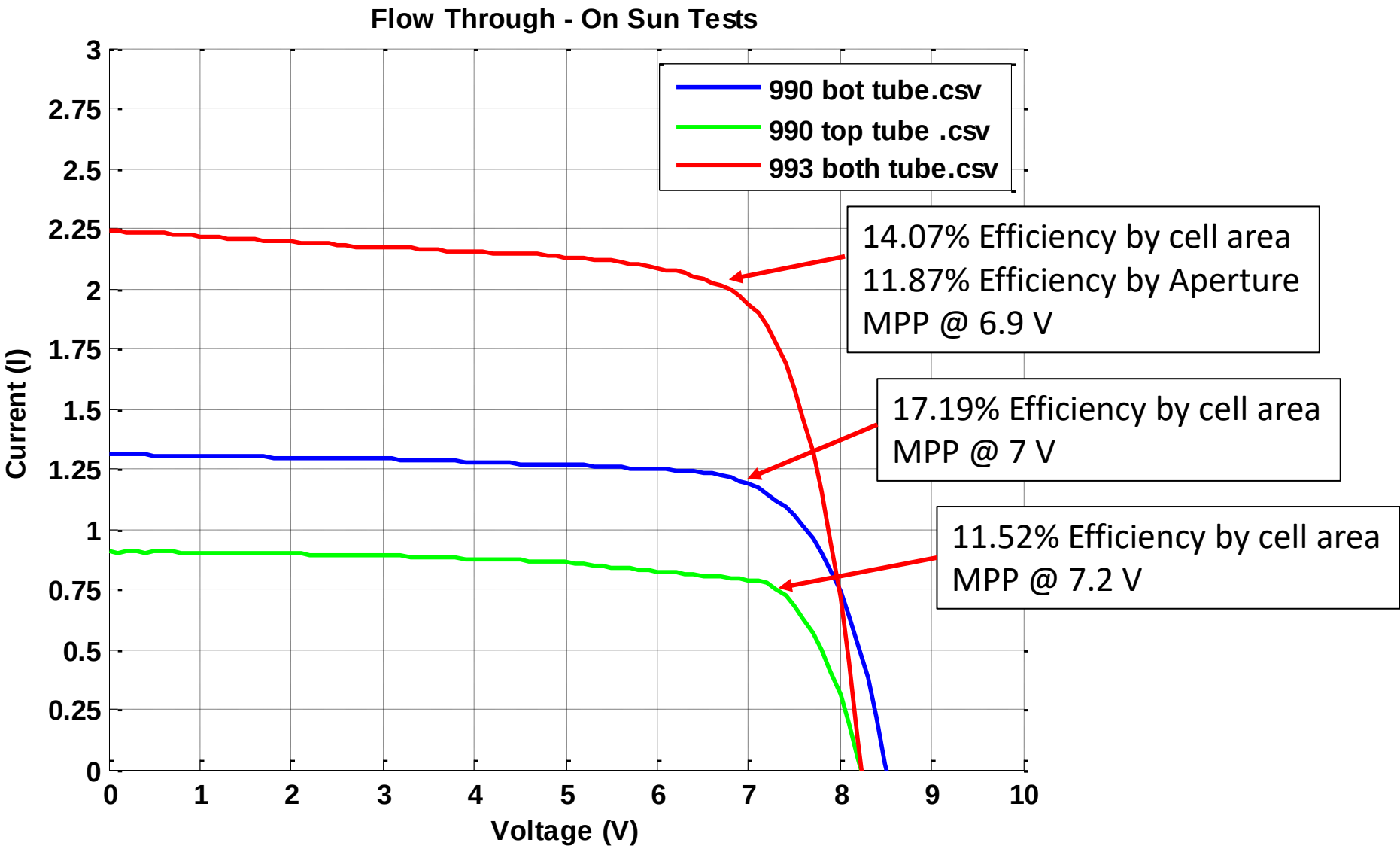
5 Flow-Through Tube Array


5 Flow-Through Tube Array


5 Heat-Pipe Tube Array
Illusion produced
by flowline optics


TRUST
ME
I'M
THE
DOCTOR

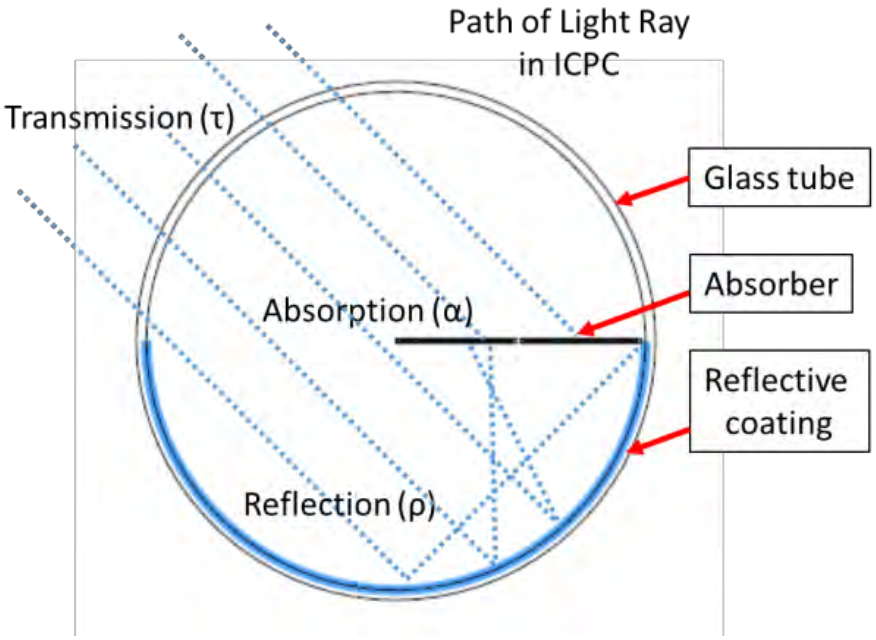
Full Flow Through Tube Tests w/ Glass

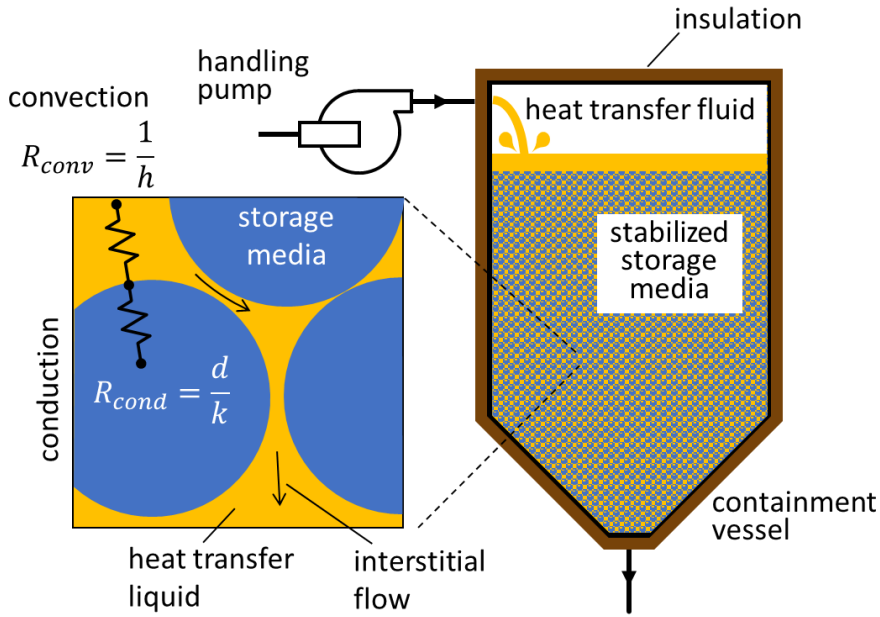


Topic Area 2: Low-cost solar thermal heat

SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

The Internal Compound Parabolic Concentrator (ICPC)—A Novel Low Cost Solar Thermal Collection System for Desalination Processes

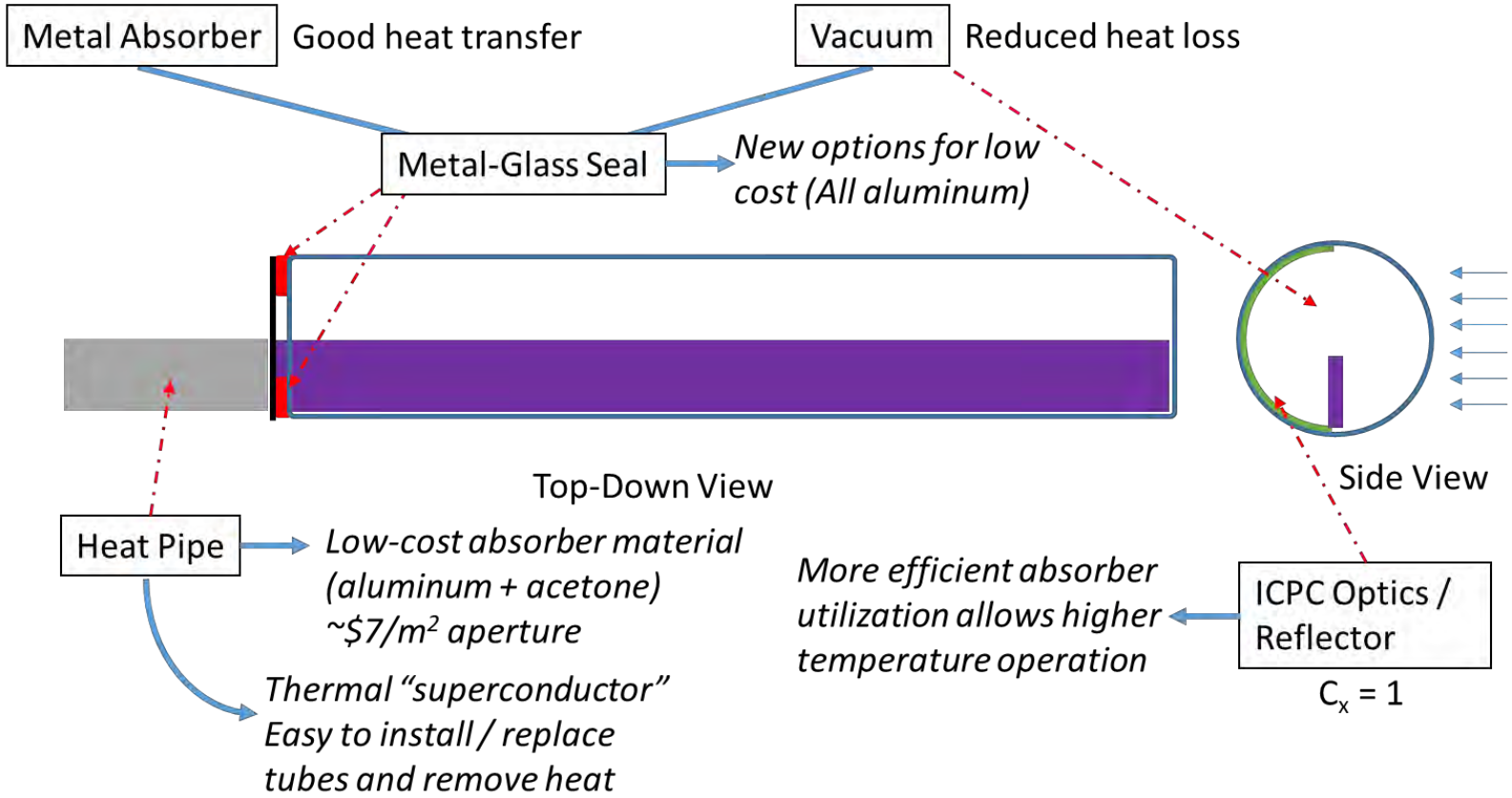


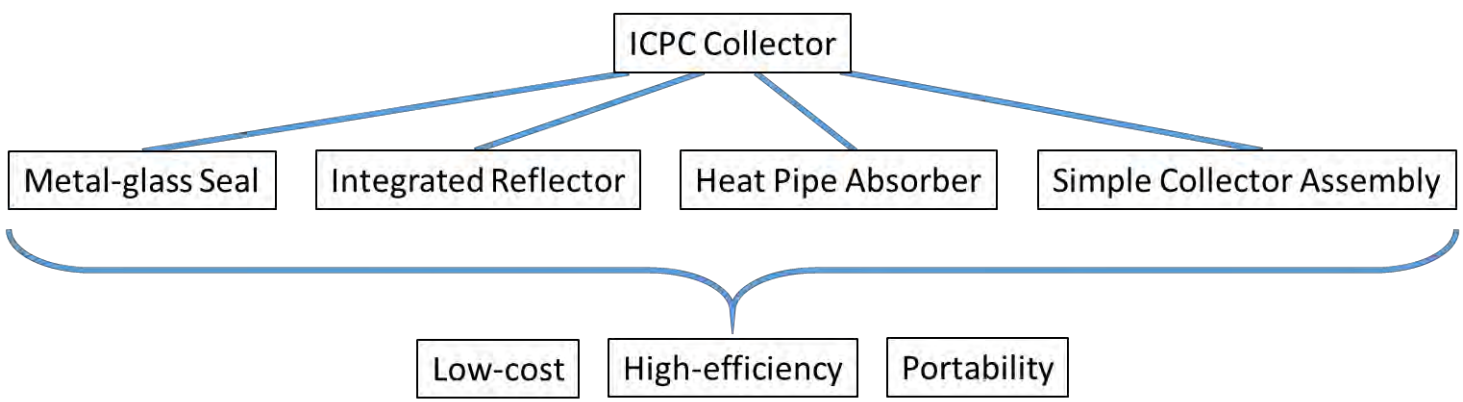


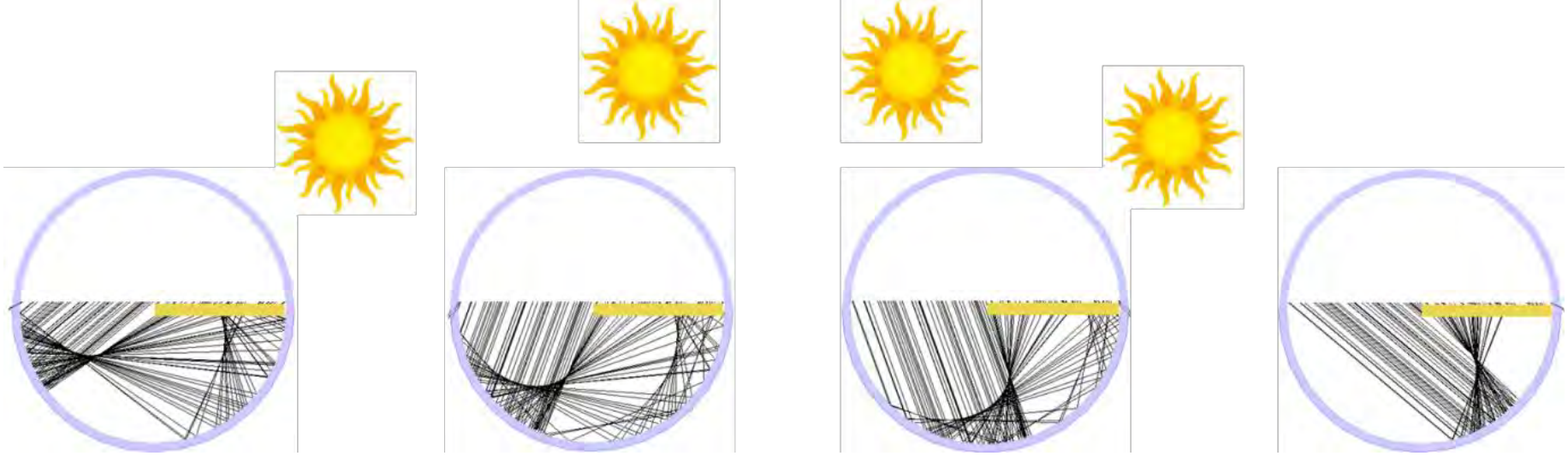
ICPC Collector

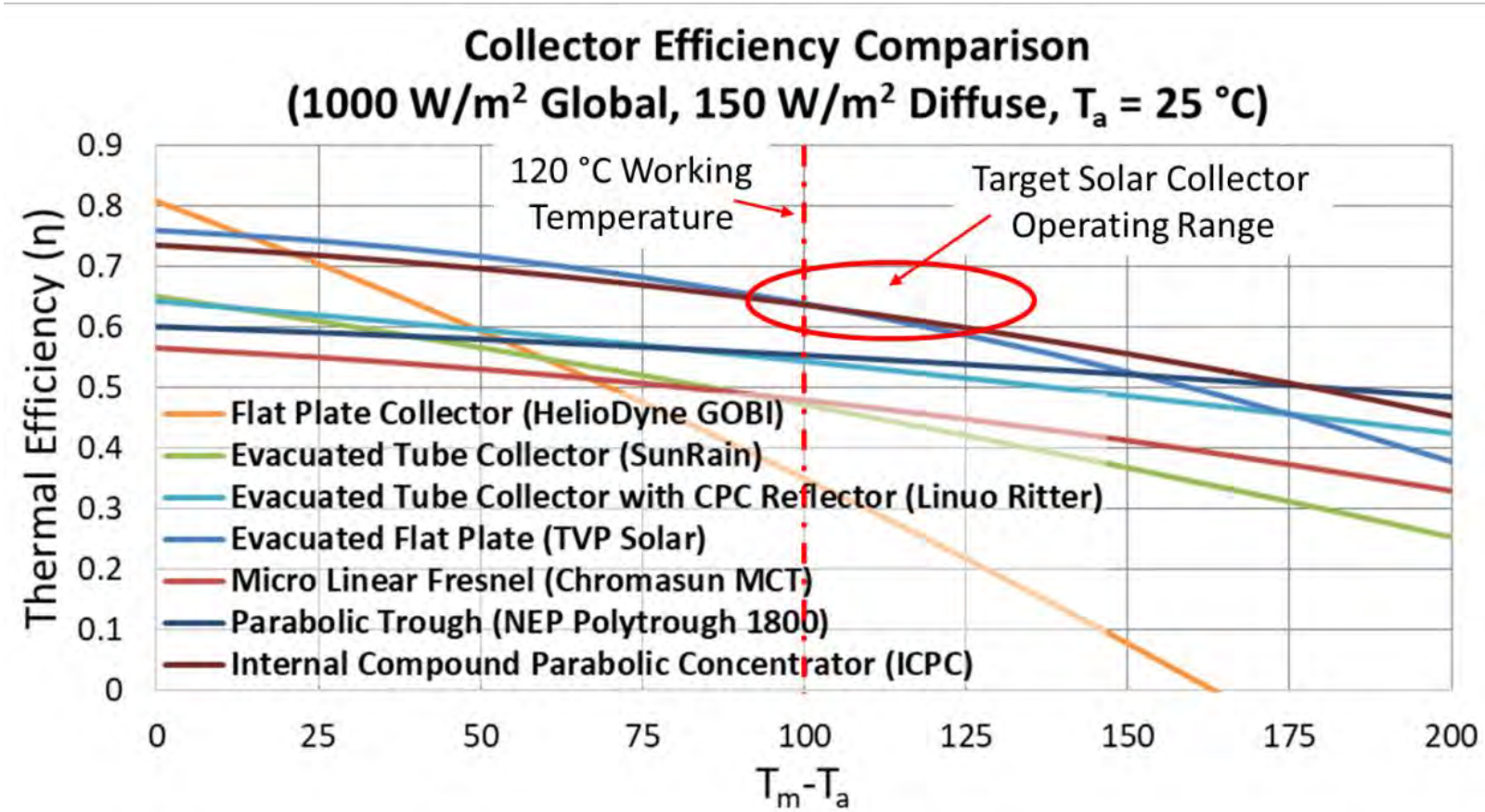
Direct-Contact Phase Change Thermal Storage

24/7 Low-Cost Dispatchable Solar Thermal for Desalination


Metal Absorber
Good heat transfer
Vacuum
Reduced heat loss
Metal-Glass Seal
New options for low cost (All aluminum)
Top-Down View
Side View
Heat Pipe
Low-cost absorber material (aluminum + acetone) ~$7/m² aperture
Thermal "superconductor" Easy to install / replace tubes and remove heat
More efficient absorber utilization allows higher temperature operation
ICPC Optics / Reflector
$C_x = 1$

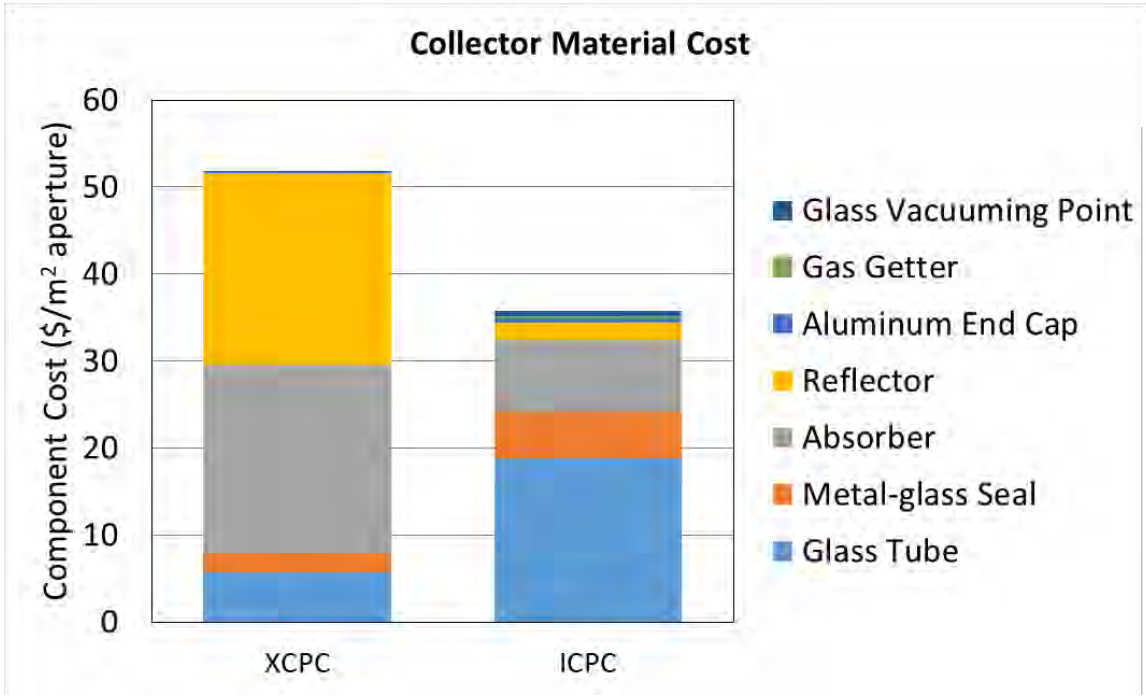

ICPC Collector
Metal-glass Seal
Integrated Reflector
Heat Pipe Absorber
Simple Collector Assembly
Low-cost
High-efficiency
Portability

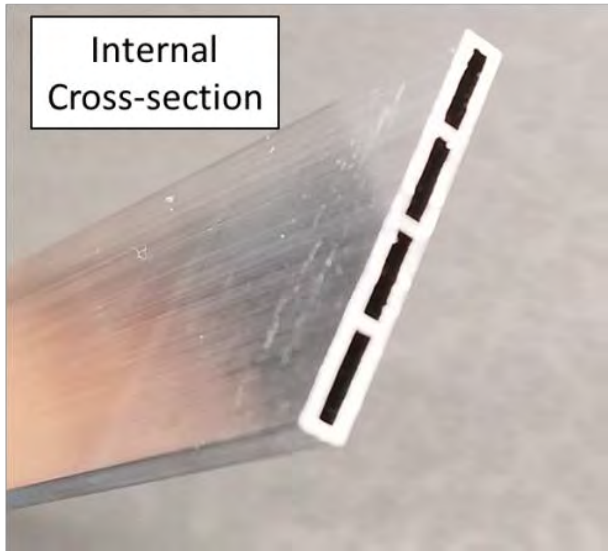



Collector Efficiency Comparison
(1000 W/m² Global, 150 W/m² Diffuse, Ta = 25 °C)
120 °C Working Temperature
Target Solar Collector Operating Range
Thermal Efficiency (η)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
25
50
75
100
125
150
175
200
Tm-Ta
Flat Plate Collector (HelioDyne GOBI)
Evacuated Tube Collector (SunRain)
Evacuated Tube Collector with CPC Reflector (Linuo Ritter)
Evacuated Flat Plate (TVP Solar)
Micro Linear Fresnel (Chromasun MCT)
Parabolic Trough (NEP Polytrough 1800)
Internal Compound Parabolic Concentrator (ICPC)

Cost reductions

- Glass tube
- Silver reflector coating
- Aluminum minichannel heat pipes
- Low cost metal-glass seal





Thank you