Black Holes, Gravity, and Information Theory

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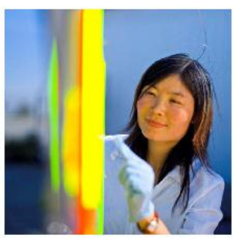
ABSTRACT

A particle physicist looks at new ideas about black holes and gravity. Already with some successful verification, the new ideas challenge long accepted views about the nature of the world. Disclaimer: these ideas are *not* due to me, I am just an experimentalist trying to make some sense of them.

Call for Papers

Special Section of the Journal of Photonics for Energy (JPE) on Nonimaging Optics: Efficient Design for Illumination and Solar Concentration



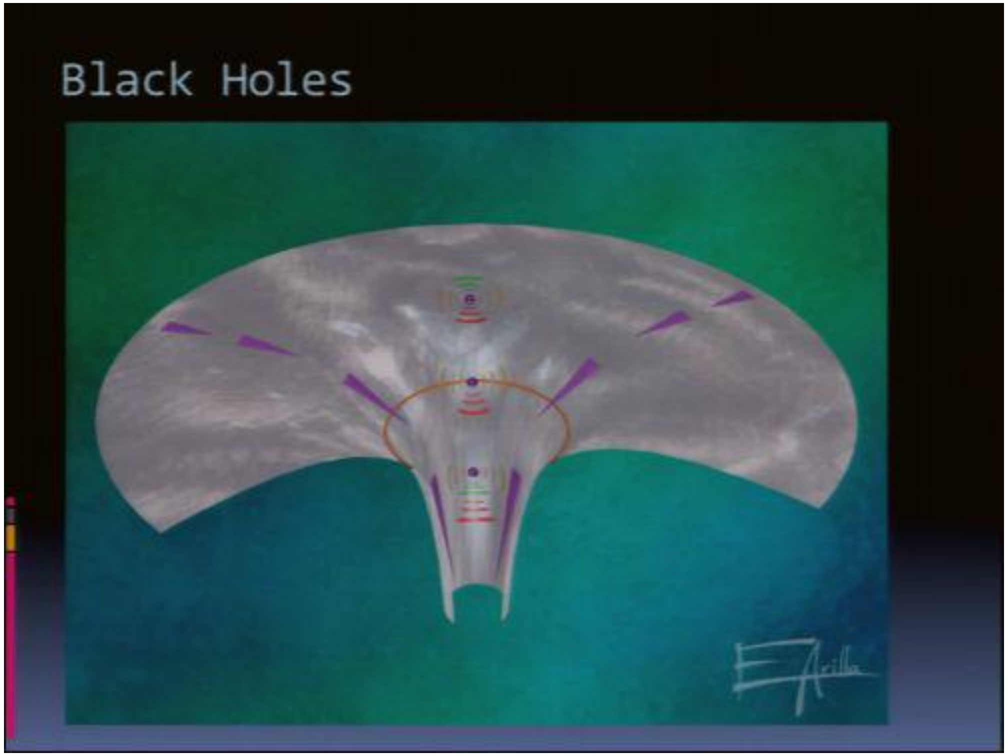
Guest Editors: **Roland Winston, Univ. of California, Merced (United States); Jeffrey M. Gordon, Ben-Gurion Univ. of the Negev (Israel)**

This Call for Papers is open to all interested applicants that have original and *not yet published* scientific work in the broad area of Nonimaging Optics: Efficient Design for Illumination and Solar Concentration.

This Special Section of JPE will center on fundamental studies to critical design issues and practical applications of nonimaging optics including theory and its application to the design and experimental realization of illumination and concentration systems, tailored freeform optics, display backlighting, condenser optics, high-flux solar and infrared concentration, day lighting, LED optical systems, laser pumping, and luminaires. Examples of research in these areas include but are not limited to radiative transfer near the étendue limit, concentrator optics, illumination and irradiation optics, solar photovoltaic and solar thermal concentration, fiber-optic and light-pipe optical systems, radiometry, day lighting, characterization of light-transfer devices, freeform optics, optical furnaces and radiative heating, infrared detection, LED applications, laser pumping, and condenser optics.

Manuscripts due January 12, 2012.

Black Hole Thermodynamics Informs Solar Energy Conversion

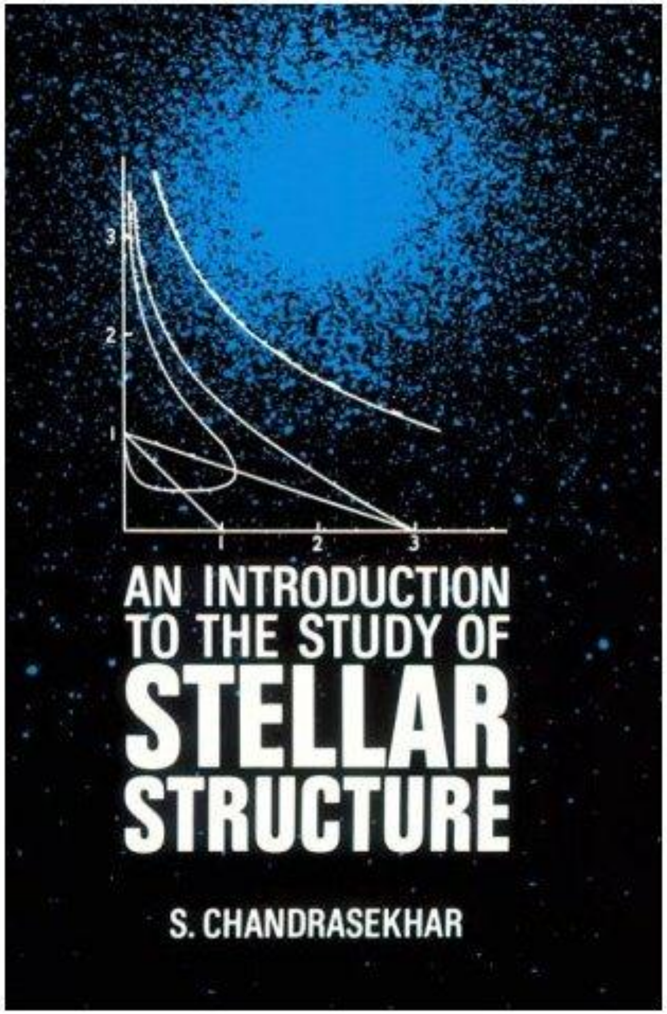


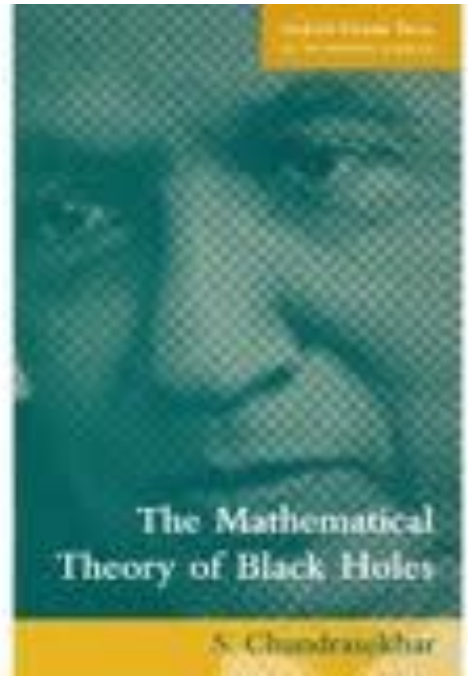
S. Chandrasekhar, the most distinguished astrophysicist of the 20th century discovered that massive stars collapse (neutron stars, even black hole)

On the Non-Radial Oscillations of a Star II. Further Amplifications

Subrahmanyan Chandrasekhar, Valeria Ferrari and Roland Winston

Proc. R. Soc. Lond. A 1991 **434**, 635-641
doi: 10.1098/rspa.1991.0117


AN INTRODUCTION TO THE STUDY OF
STELLAR STRUCTURE
S. CHANDRASEKHAR

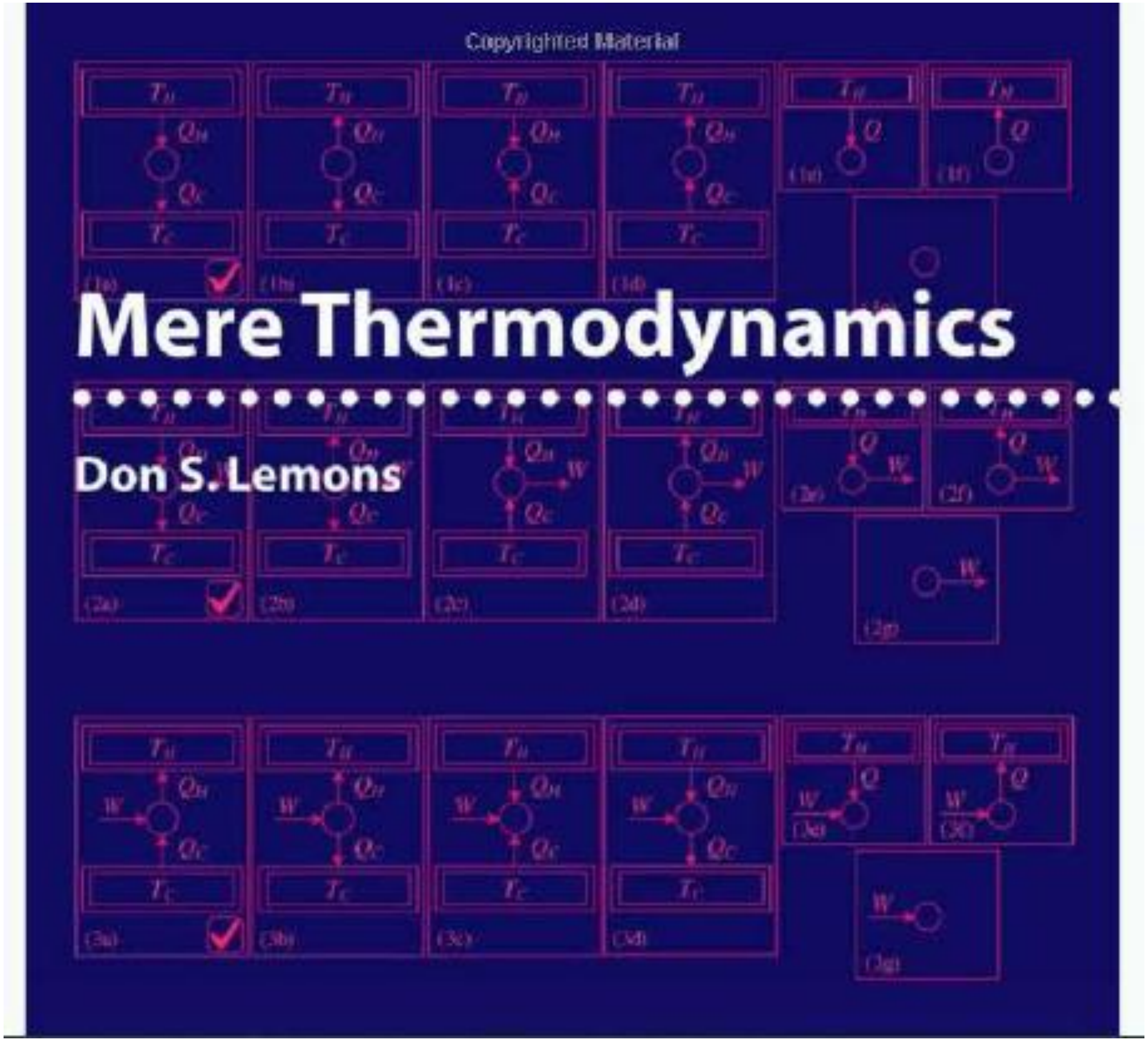

The Mathematical Theory of Black Holes
S. Chandrasekhar

Invention of the Second Law of Thermodynamics by Sadi Carnot

Invention of Entropy

(The Second Law of Thermodynamics)

- Sadi Carnot had fought with Napoleon, but by 1824 was a student studying physics in Paris. In that year he wrote:
- Reflections on the Motive Power of Heat and on Machines fitted to Develop that Power.
- The conservation of energy (the first law of thermodynamics) had not yet been discovered, heat was considered a conserved fluid-”caloric”
- So ENTROPY (the second law of thermodynamics) was discovered first.
- A discovery way more significant than all of Napoleon’s conquests! (personal bias)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Mere Thermodynamics
Don S. Lemons

TdS = dE + PdV

is arguably the most important equation in Science

If we were asked to predict what currently accepted principle would be valid 1,000 years from now,

The Second Law would be a good bet (personal bias)

From this we can derive entropic forces **F** = T **grad** S

The S-B radiation law (const. T^4)

Information theory (Shannon, Gabor)

Accelerated expansion of the Universe

Even Gravity!

And much more modestly----

The design of thermodynamically efficient optics

BLACK HOLE THERMODYNAMICS

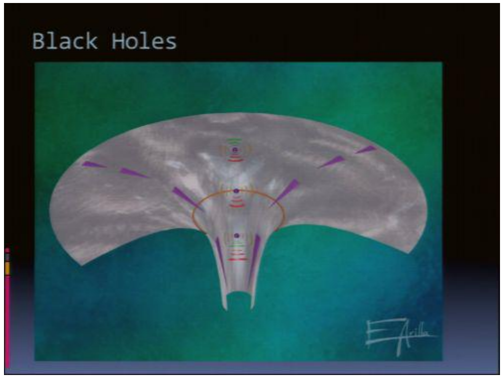
THE HORIZON FROM WHICH LIGHT CAN'T ESCAPE

(½ mv^2) = $G\ Mm/R$ G is Newton's gravitational constant

$The\ horizon\ radius\ is\ R = 2MG/v^2$

Change $2MG/v^2$ to $2MG/c^2$ and hope for the best

At least the units are right, and so is the value!



THE SCHARZSCHILD RADIUS

Is this some exotic place, out of Star Trek?

The fact is, we could be at the horizon and not even notice!

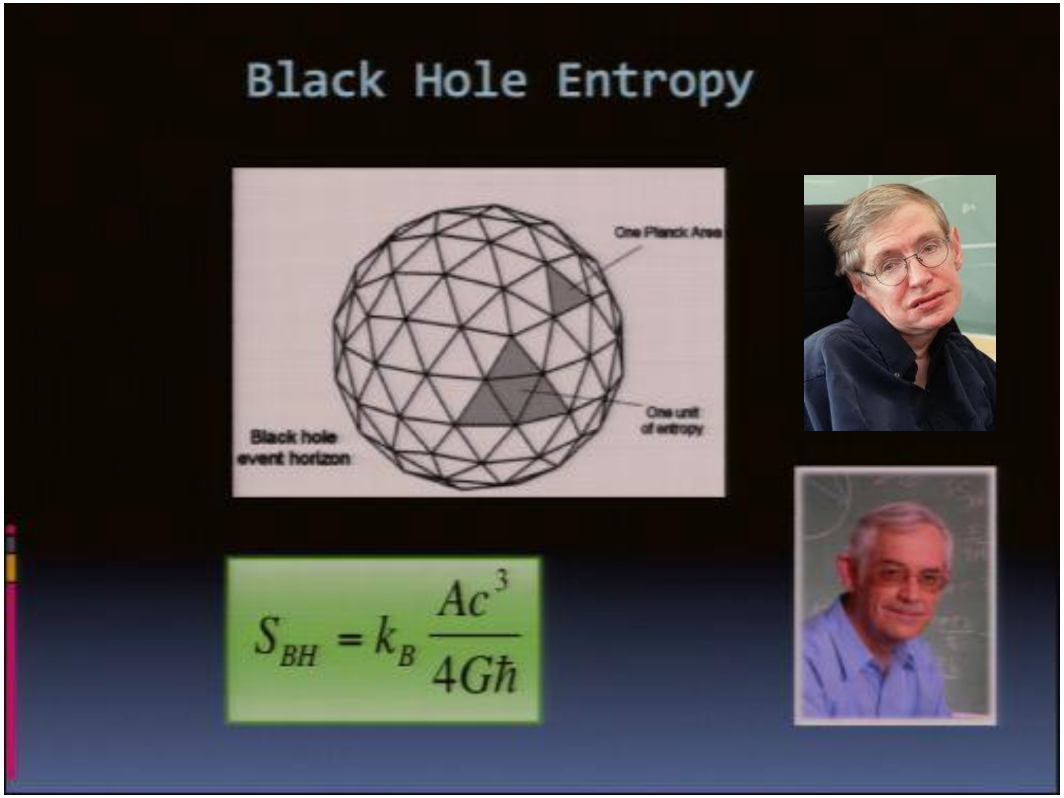
Just place a sufficient mass at the center of the Milky way (~ 27,000 LY from us)

M = Rc²/2G

$$g = \frac{MG}{R^2} = 0.5\frac{c^2}{R} = 0.5\frac{c^2}{27{,}000LY} = \frac{5}{27{,}000} \sim 0.0002\ meters/\sec^2$$

$$(\ LY = |c^2/10|\ meters)$$

compared to terrestrial g ~ 9.8 $meters/\sec^2$

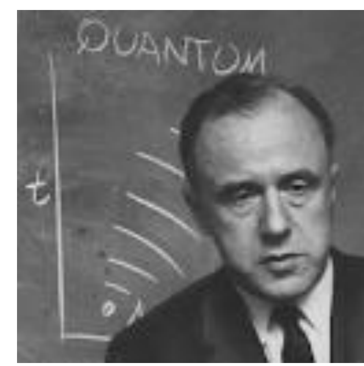


Finding the temperature

$$½\, kT \times N \; = \; Mc^2$$

$$kT \; = \; 2Mc^2/N \; = \hbar c^3/(8\pi GM)$$

Stephen Hawking
Jacob Bekenstein
John Wheeler
Max Planck



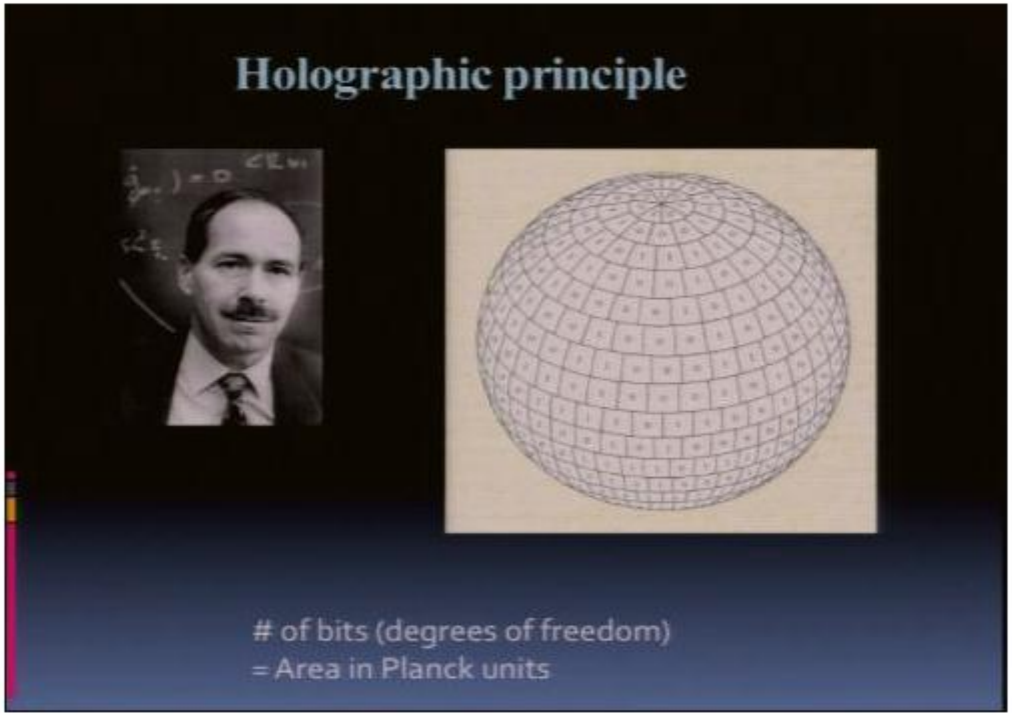
PLANCK AREA $A_P = \frac{G\hbar}{c^3} = 2.7 \times 10^{-70} \quad Meter^2$

½ kT per degree of freedom

N = number of degrees of freedom = A/Ap = $4\pi R^2 c^3/G\hbar \; = \; 16\pi \, GM^2/\hbar c$

Total Energy = Mc^2 = ½ kT × N

Gerardus 't Hooft



$A_P = 1$ pixel on horizon surface or 1 bit of information –Holographic Principle t'Hooft

1 planck area = 2.61209 × 10^{-70} m^{2}

Erik Verlinde (Spinoza Prize 2011) lecturing at the Perimeter Institute
5.12.2010 Home of Lee Smolin and colleagues

A_P= one degree of freedom on horizon surface (1 pixel)
All information is stored on this surface (holographic principle, ‘t Hooft)

Equipartition of normal matter $\frac{1}{2}kT/degree\ of\ freedom\ = \frac{1}{2}kT/N$

$N = number\ of\ degrees\ of\ freedom = \frac{A}{A_p} = \frac{4\pi R^2 c^3}{G\hbar}$ recall $(R = 2MG/c^2)$

$N\ = 16\pi GM^2/\hbar c$

Finding the temperature

$$\frac{1}{2}\ kT \times N\ =\ Mc^2\ \ then\ \ kT\ =\ 2Mc^2/N\ = \hbar c^3/(8\pi GM)$$

Later we will need $1/kT\ =\ 8\pi GM/\hbar c^3 = 4\pi R/\hbar c$

Deriving the Black Hole entropy purely from thermodynamics

Build up the black hole my adding mass in small increments

Use the second law $TdS = dE = c^2 dM$

$$dS/k = c^2 dM/kT = 8\pi c^2\, GMdM/\hbar c^3$$
$$S/k = 4\pi\, GM^2/\hbar c^3$$

Recall $R = 2GM/c^2$, so

$S/k = \pi R^2\, c^3/G\hbar = \frac{1}{4}\, A/A_p$ (we recover Hawking's factor of 4)

I was so happy with his result, I emailed it to our "cosmo club" last November
Even Eli Yablonovitch (UC Berkeley) liked it!

Entropy of a string of zero’s and one’s
01110010101110000011101011010101

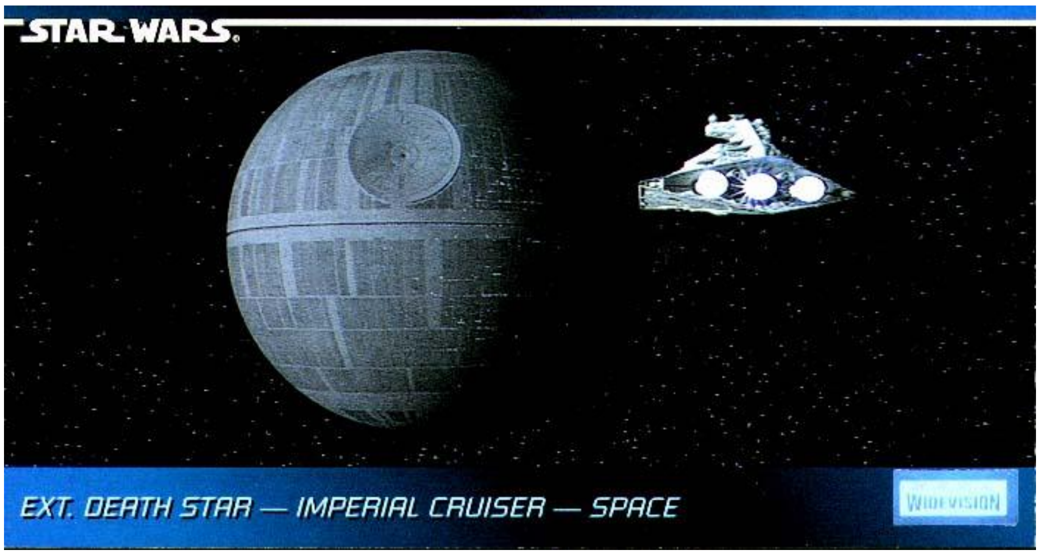
The connection between entropy and the information is well known. The entropy of a system measures one’s uncertainty or lack of information about the actual internal configuration of the system, suppose that all that is known about the internal configuration of a system is that it may be found in any of a number of states with probability p_n for the *n*th state. Then the entropy associated with the system is given by Shannon’s formula:

$$S = -k \sum_n p_n \ln(p_n)$$

The conventional unit of information is the "bit" which may be defined as the information available when the answer to a yes-or-no question is precisely known (zero entropy). According to the scheme (11) a bit is also numerically equal to the maximum entropy that can be associated with a yes-or-no question, i.e., the entropy when no information whatsoever is available about the answer. One easily finds that the entropy function (10) is maximized when $p_{\text{yes}} = p_{\text{no}} = \frac{1}{2}$. Thus, in our units, one bit is equal to ln2 of information.

S = k (ln2) N or as modified by Hawking
S = k(1/4) N for a Black Hole

“Gravity is moving information around” Erik Verlinde



As we fall into the death star, information we send decreases due to red shift
Like the lower frequency of the horn sound from a receeding train

On board the rocket ship 0111001010111000011101011010101

Further away 0 1 1 1 0 *0 1 0 1 0 1 1 1 0 0 0 0 1* 1 1 0 1 0 1 1
Still further away 0 1 1 1 0 0 1
Still further 0 1 1 1

Finally, behind the horizon goodbye

Information content of the world

Notice Shannon's entropy maximizes for all Pn = ½ (total ignorance)
Maximum S/k = N log 2 where N is the number of bits.
So 1 bit (1 degree of freedom) is log 2 of information.

Seth Lloyd[10] generated a formula the number of operations N [1] or events that can have taken place in volume with radius r over a time t is

$$N = \frac{rt}{\ell_{Pl} t_{Pl}} = \frac{10^{26}\ m \times 4.32 \times 10^{17}\ sec}{1.616252(81) \times 10^{-35}\ m \times 5.3924(27) \times 10^{-44} s} = 0.5 \times 10^{122} \qquad (1)$$

We can compare this to the number of bits set by the entropy of a horizon

$$S_H = \frac{k_B c^3}{G\hbar}\frac{A}{4} = \frac{k_B c^3}{G\hbar}\pi R_H^2 = \frac{k_B c^3}{G\hbar}\pi\left(\frac{c}{H}\right)^2 \sim (2.6 \pm 0.3) \times 10^{122} k_B \qquad (2)$$

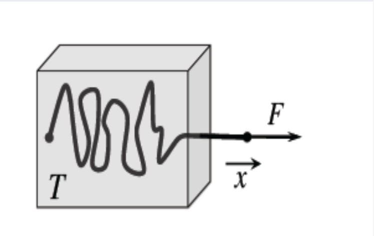
Note that these two agree to an amazing factor of order unity. The relationship one expects is that $S = N ln(2) k_B$ where $ln(2) = 0.693$, so that the factor is $F = 2.6/(0.693 \times 0.5) = 7.5$.

Seth Lloyd was Lin Tian's advisor

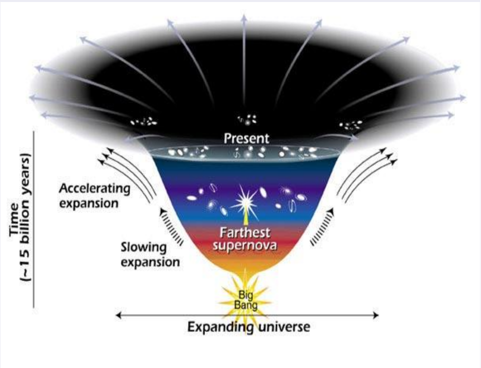
Acceleration of the World

From $TdS = Fdx$ (entropic force)

direction of an entropic force is increase S or R



$F = T\,\nabla S$ (recall $\frac{S}{k} = \frac{1}{4}\frac{A}{A_p} = \pi R^2 \frac{c^3}{G\hbar}$)



$kT = \frac{\hbar c}{4\pi R}$

$F = \frac{c^4}{2G}$ (outward to horizon)

"Pressure" = $Tension = \frac{F}{4\pi R^2} = \frac{1}{8\pi G R^2}$ $(\sim \frac{1}{3}\rho_{critical}\, c^2)$

$\rho_{critical} = \frac{3C^2}{8\pi G R^2}$ $R = R_H$ (Hubble radius) ~ c 13.7×10^9 LY

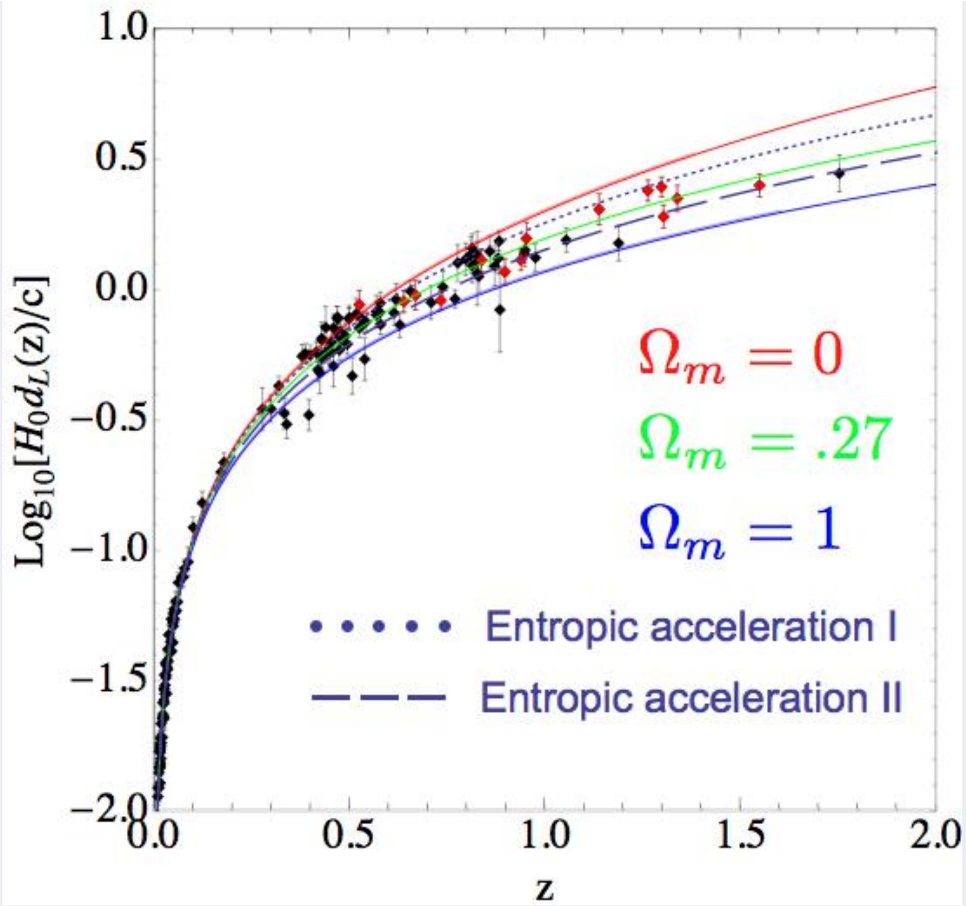
Connection with Unruh Temperature

- $kT = a/2\pi$ At R_H (horizon)
- a = 0.5 c^2/R_H = 5/LY ~ $5/13.7\times 10^9$ ~$0.4x10^{-9} meters/sec^2$
- kT = $\hbar c/(4\pi$R)
- T ~ 10^{-30} Kelvin At R_H (horizon)

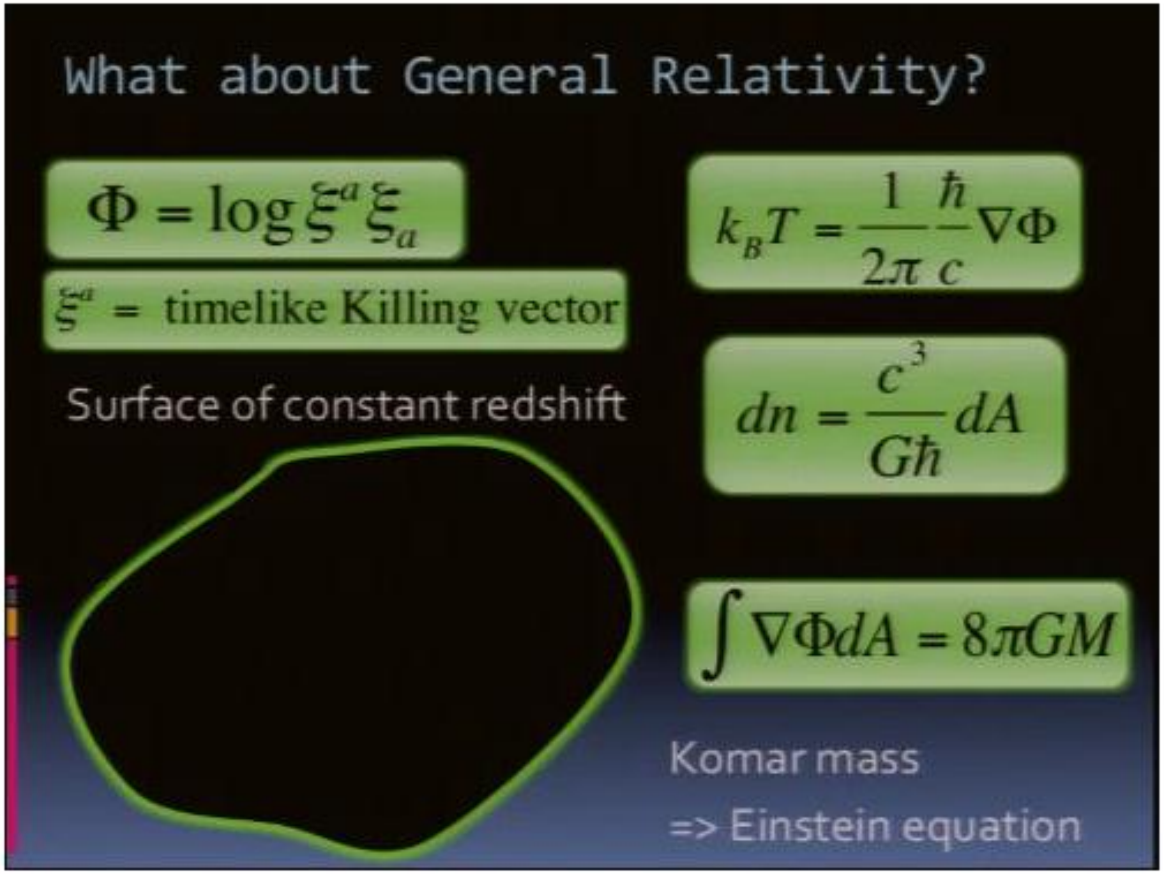
Some scaling laws

T ~ R
a ~ R
N ~ R^2
S ~ R^2

From G. Smoot *et al*, 2010



George Smoot, Nobel Prize 2006,$1M quiz show prize Are You Smarter than a 5th Grader? 2009


What about General Relativity?
$\Phi = \log \xi^a \xi_a$
ξ^a = timelike Killing vector
Surface of constant redshift
$k_B T = \frac{1}{2\pi} \frac{\hbar}{c} \nabla\Phi$
$dn = \frac{c^3}{G\hbar} dA$
$\int \nabla\Phi dA = 8\pi GM$
Komar mass
=> Einstein equation

EPILOGUE

In case you have been wondering,
WHERE IS UC MERCED???

Where we are

TUOLUMNE
MARIPOSA
MERCED
STANISLAUS
SAN JOAQUIN
TULARE
KINGS
KERN
INYO
SAN BERNARDINO
LOS ANGELES
SANTA BARBARA
VENTURA
RIVERSIDE


UC Merced Campus
Under Construction January 2004
Photo By Hans Marsen

Thank you…

Thermodynamically Efficient Solar Concentration

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City University of Hong Kong 3/27/2012

ABSTRACT

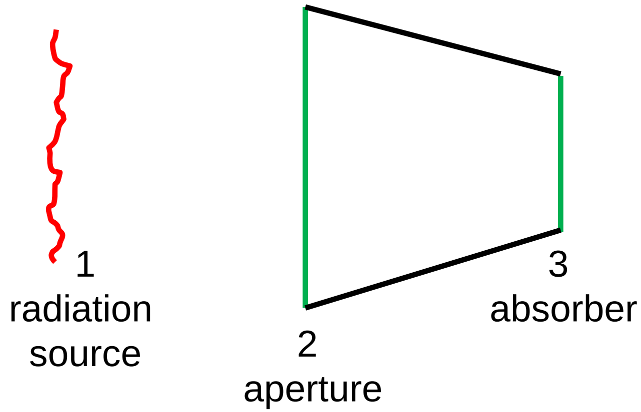
Thermodynamically efficient optical designs are dramatically improving the performance and cost effectiveness of solar concentrating and illumination systems.

UC Solar Research Innovation Education

University of California Advanced Solar Technologies Institute

UCMERCED

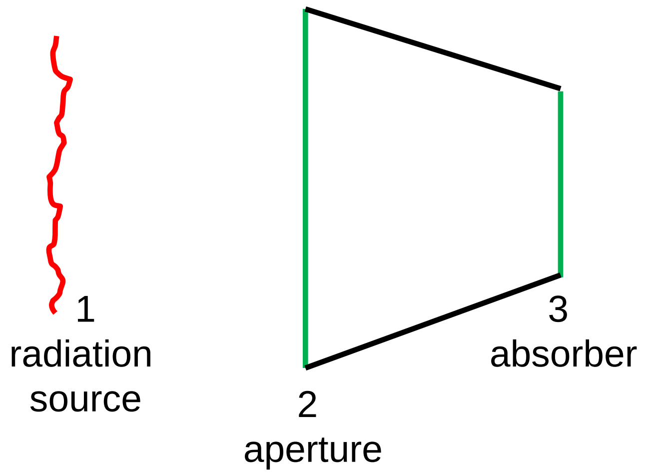
The general concentrator problem



Concentration C is defined as A2/A3

What is the "best" design?

Characteristics of an optimal concentrator design



Let Source be maintained at T1 (sun)

Then T_3 will reach $T_1 \leftrightarrow P_{31} = 1$

Proof: $q_{13} = \sigma T_1^4 A_1 P_{13} = \sigma T_3^4 A_3 P_{31}$

But $q_3 total = \sigma T_3^4 \times A3 \geq q_{13}$ at steady state

$T_3 \leq T_1$ (second law)$\rightarrow P_{31}=1 \leftrightarrow T_3 = T_1$

Summary:
For a thermodynamically efficient design

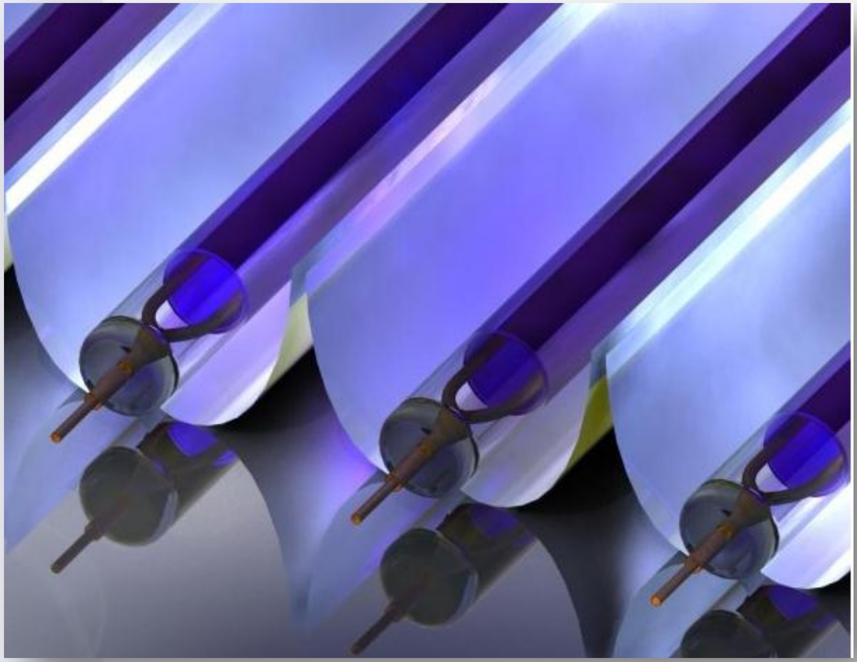
1. P_{31} (where P_{31} = probability of radiation from receiver to source) = 1
Second Law

2. C = $1/P_{21}$ where P_{21} = probability of radiation from receiver to source

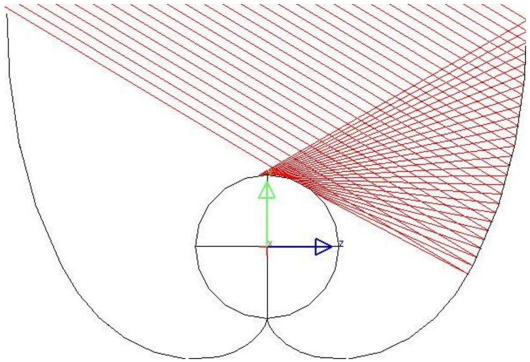
I am frequently asked- Can this possibly work?

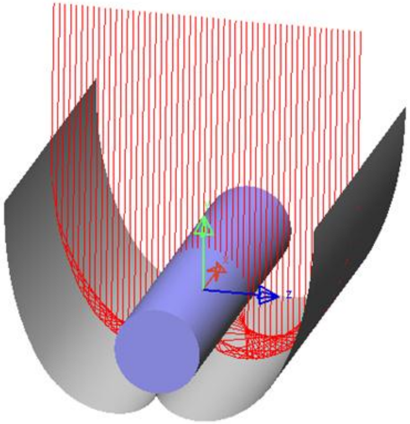
How?

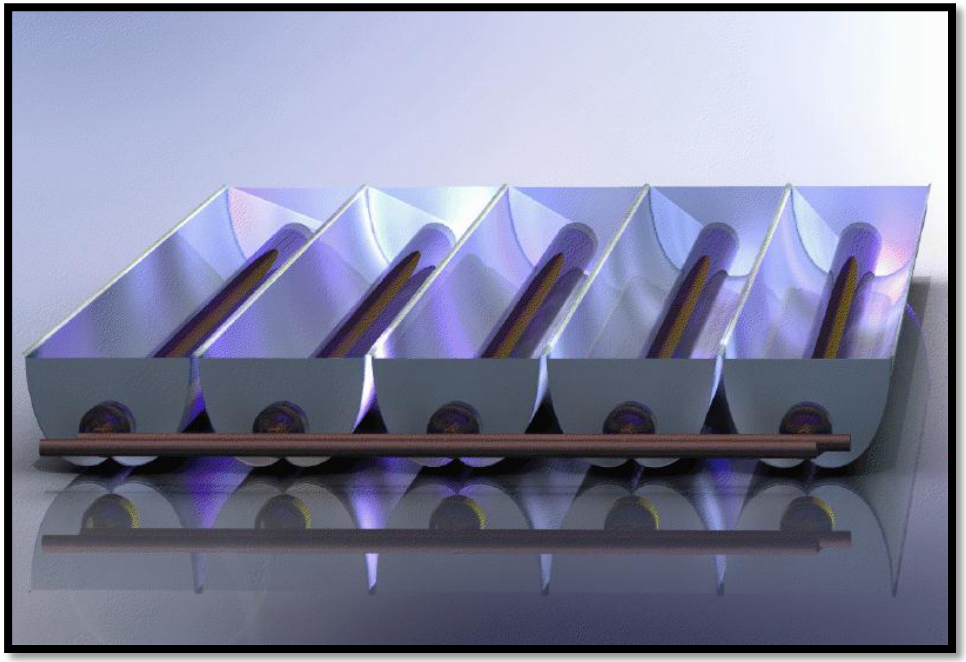
- Non-imaging optics:
  - External Compound Parabolic Concentrator (XCPC)
  - Non-tracking
  - Thermodynamically efficient
  - Collects diffuse sunlight

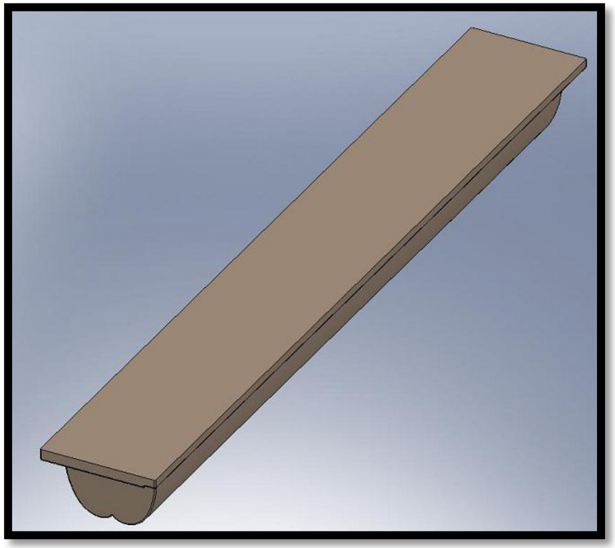


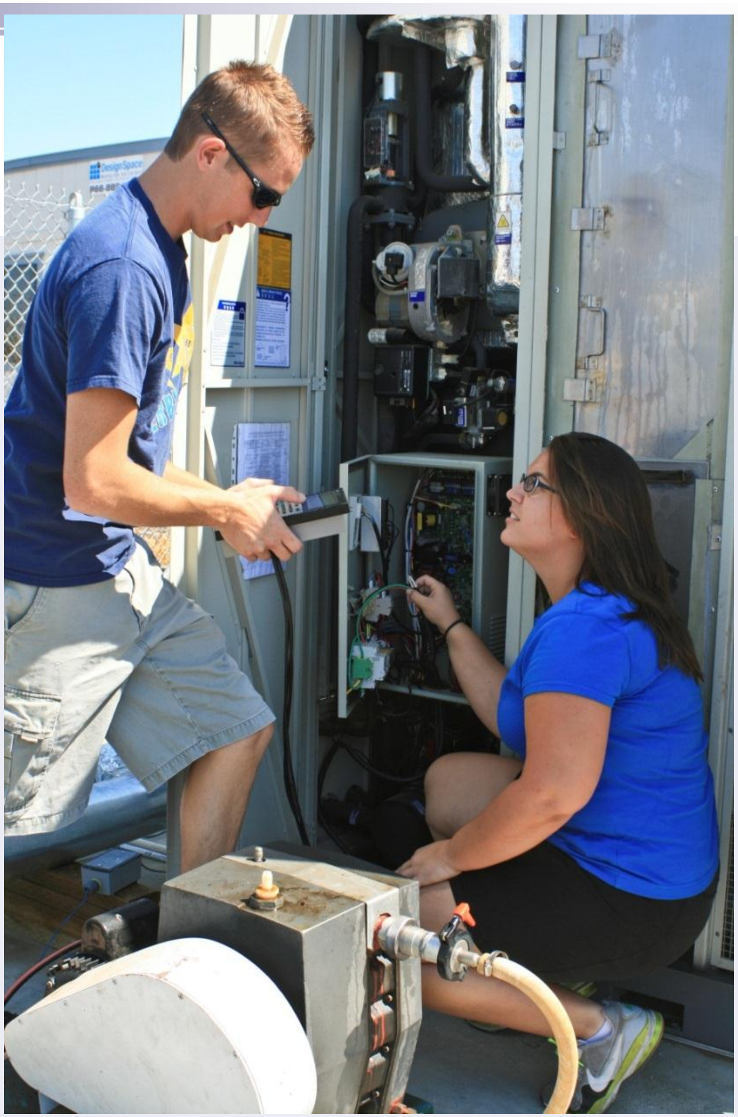
The Design: Solar Collectors



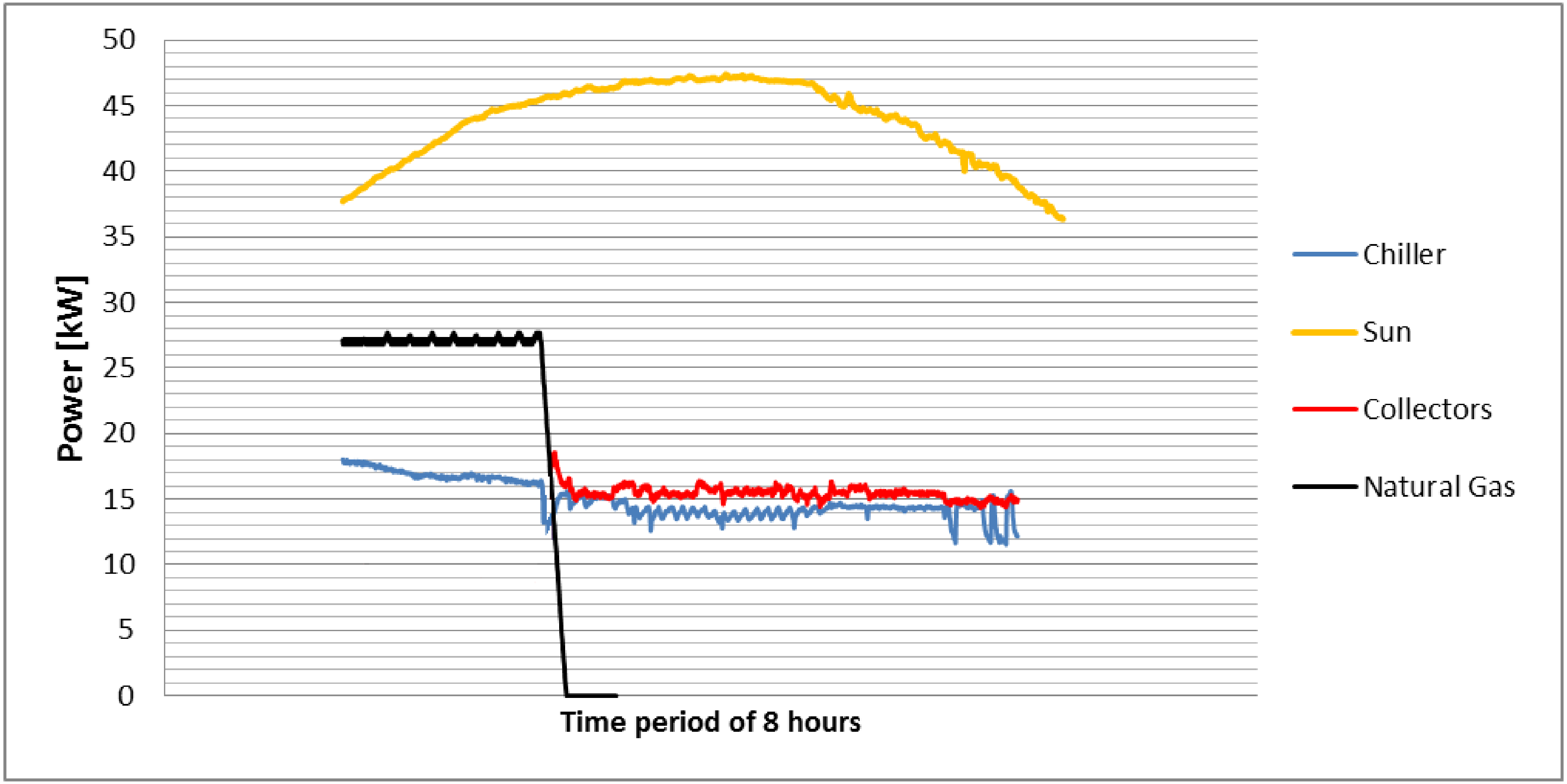


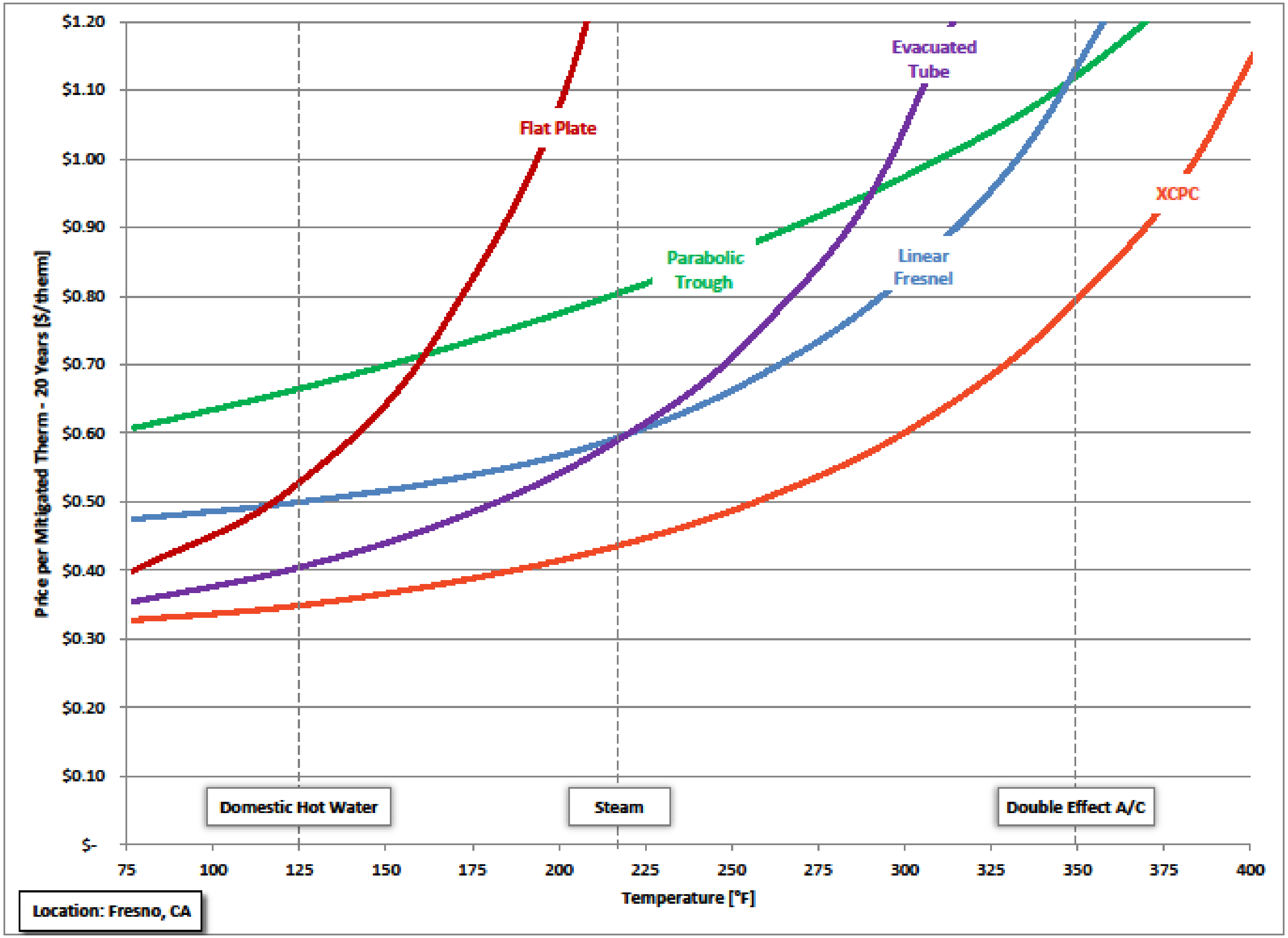




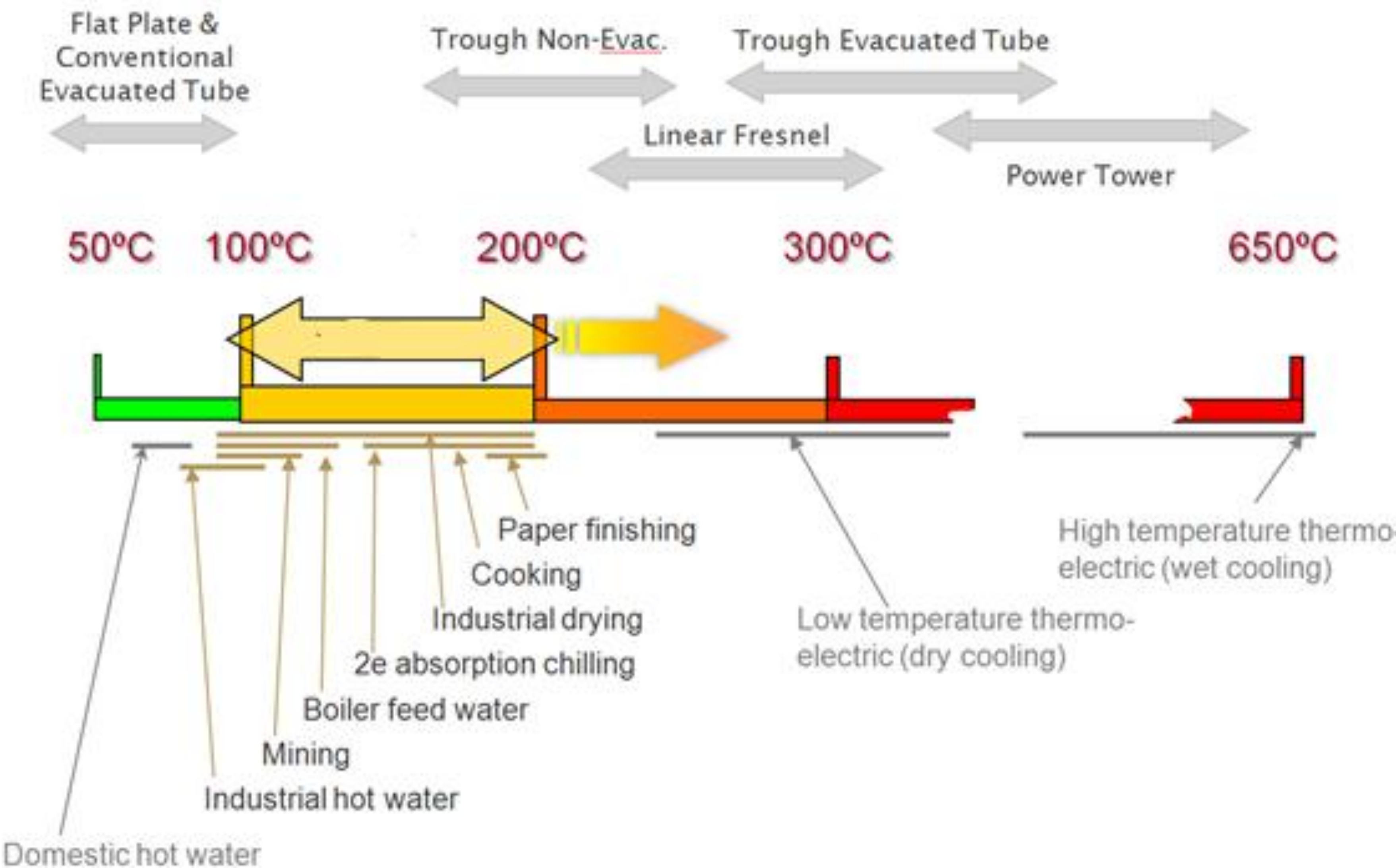


Power Output of the Solar Cooling System





Price per Mitigated Therm - 20 Years [$/therm]
$1.20
$1.10
$1.00
$0.90
$0.80
$0.70
$0.60
$0.50
$0.40
$0.30
$0.20
$0.10
$-
75
100
125
150
175
200
225
250
275
300
325
350
375
400
Temperature [°F]
Flat Plate
Evacuated Tube
Parabolic Trough
Linear Fresnel
XCPC
Domestic Hot Water
Steam
Double Effect A/C
Location: Fresno, CA



Flat Plate & Conventional Evacuated Tube
Trough Non-Evac.
Trough Evacuated Tube
Linear Fresnel
Power Tower
50ºC
100ºC
200ºC
300ºC
650ºC
Paper finishing
Cooking
Industrial drying
2e absorption chilling
Boiler feed water
Mining
Industrial hot water
Domestic hot water
High temperature thermo-electric (wet cooling)
Low temperature thermo-electric (dry cooling)

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Roland, I hope Shanghai went well Hit 200C yesterday with just 330W DNI. Gary D. Conley~*Ancora Imparo*
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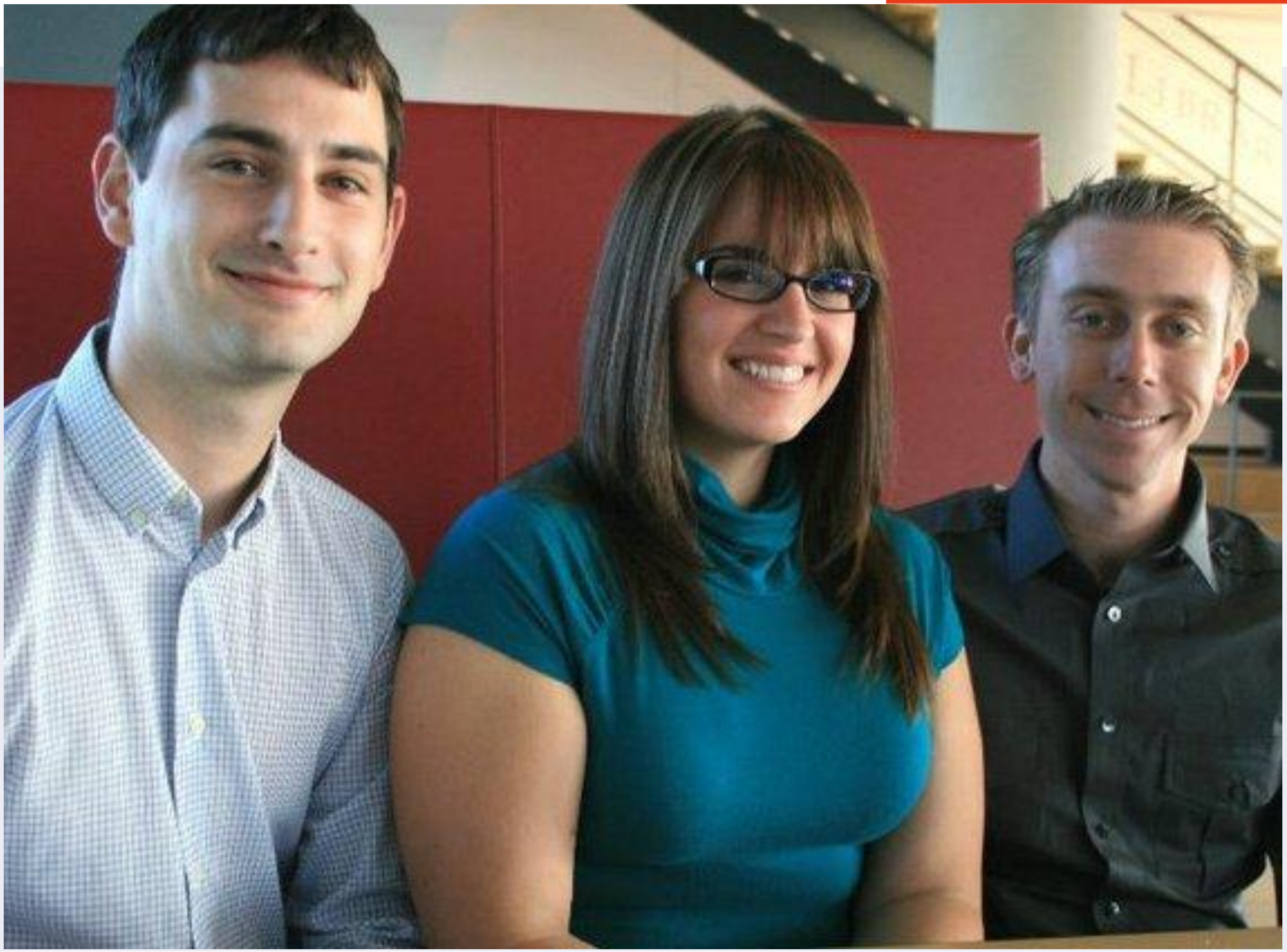
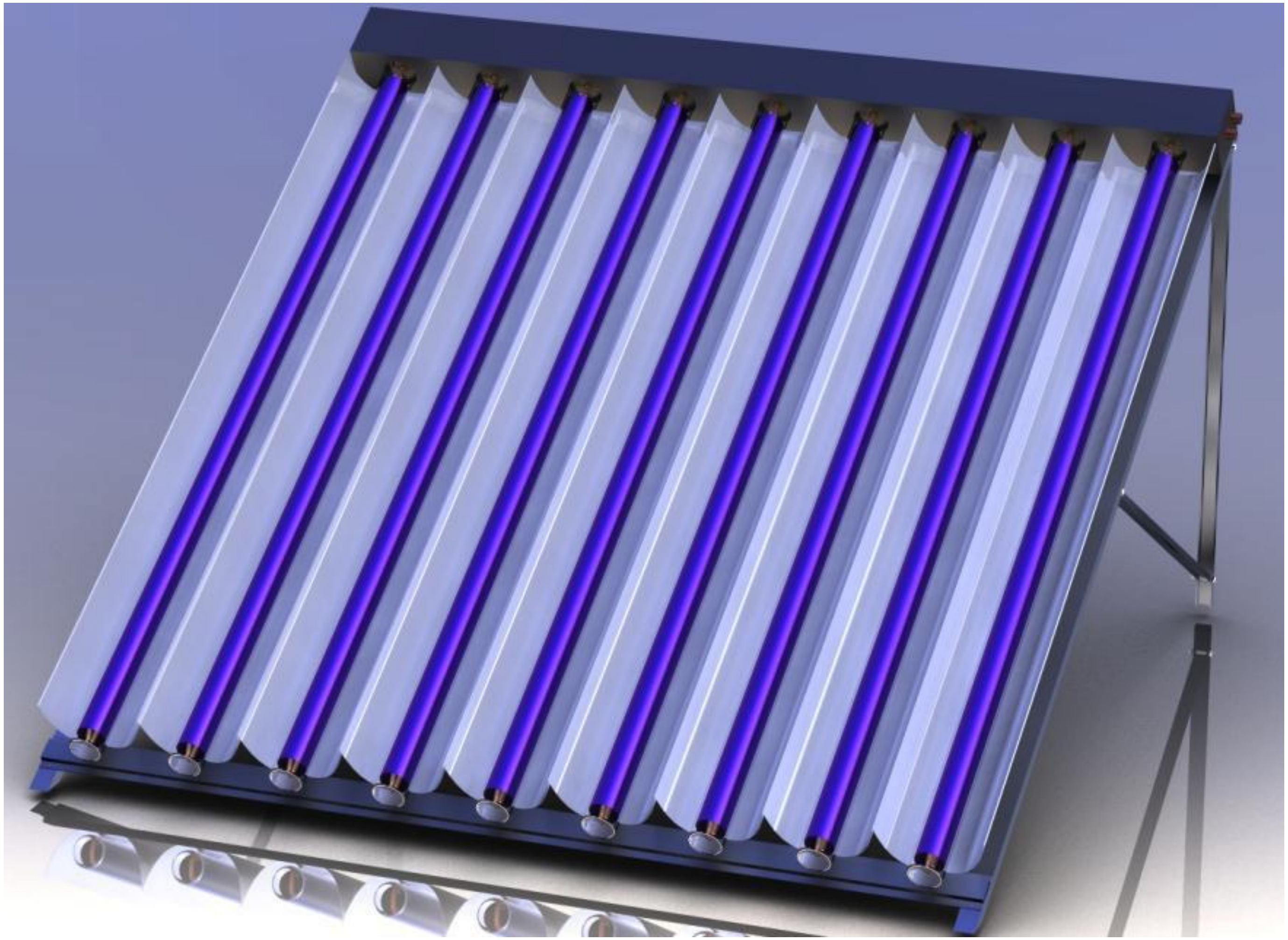


Sun-Therm Collector



EPILOGUE

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VENTURA
SANTA BARBARA
SAN LUIS OBISPO
RIVERSIDE
ORANGE
SAN DIEGO
SACRAMENTO
SONOMA
NAPA
YOLO
COLUSA
GLENN
LAKE
TEHAMA
SHASTA
LASSEN
PLUMAS
TRINITY
ALAMEDA
CONTRA COSTA
SANTA CLARA

Thank You


UC Merced Campus
Under Construction January 2004
Photo By Hans Marsen

What is the best efficiency possible? When we pose this question, we are stepping outside the bounds of a particular subject. Questions of this kind are more properly the province of thermodynamics which imposes limits on the possible, like energy conservation and the impossible, like transferring heat from a cold body to a warm body without doing work.   And that is why the fusion of the science of light (optics) with the science of heat (thermodynamics), is where much of the excitement is today. During a seminar I gave some ten years ago at the Raman Institute in Bangalore, the distinguished astrophysicist Venkatraman Radhakrishnan famously asked “how come geometrical optics knows the second law of thermodynamics?” This provocative question from C. V. Raman’s son serves to frame our discussion.

Limits to Concentration

- from λ $_{max\ sun}$ ~ 0.5 μ

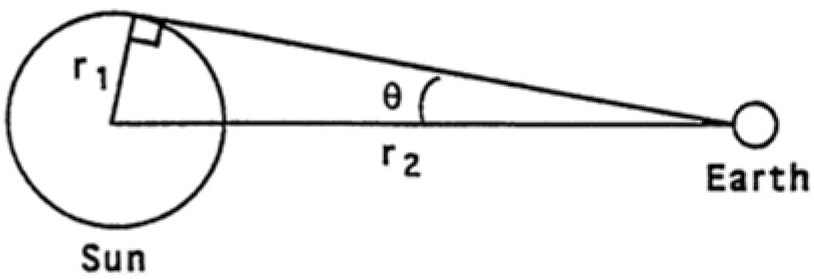
  we measure T_{sun} ~ 6000° (5670°)

  Without actually going to the Sun!

- Then from $\sigma\ T^4$ - 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

$1/\sin^2\theta$ 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)

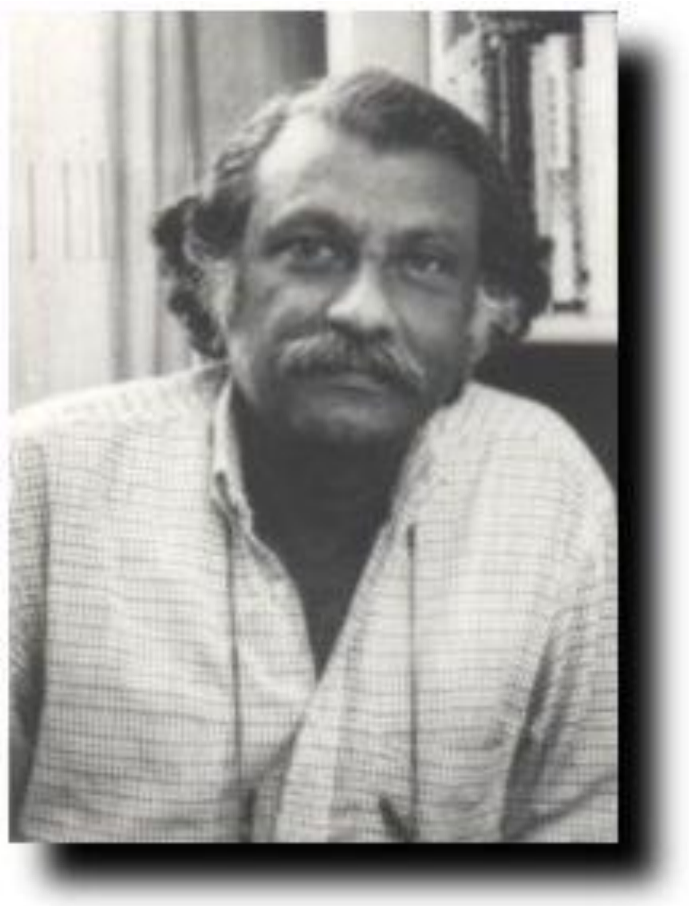
Maximum Concentration $C = 1/\sin^2\theta = 46{,}000$

- The irradiance, of sunlight, I, falls off as $1/r^2$ so that at the orbit of earth, I_2 is $1/\sin^2\theta \; x I_1$, the irradiance emitted at the sun's surface.
- The 2nd Law of Thermodynamics forbids concentrating I_2 to levels greater than I_1, since this would correspond to a brightness temperature greater than that of the sun.
- In a medium of refractive index n, one is allowed an additional factor of n^2 so that the equation can be generalized for an absorber immersed in a refractive medium as $C_{\max} = \dfrac{n^2}{\sin^2\theta_s}.$

During a seminar at the Raman Institute (Bangalore) in 2000,

Prof. **V. Radhakrishnan** asked me:

How does geometrical optics know the second law of thermodynamics?



Invention of the Second Law of Thermodynamics by Sadi Carnot

Invention of Entropy

(The Second Law of Thermodynamics)

- Sadi Carnot had fought with Napoleon, but by 1824 was a student studying physics in Paris. In that year he wrote:
- Reflections on the Motive Power of Heat and on Machines fitted to Develop that Power.
- The conservation of energy (the first law of thermodynamics) had not yet been discovered, heat was considered a conserved fluid-”caloric”
- So ENTROPY (the second law of thermodynamics) was discovered first.
- A discovery way more significant than all of Napoleon’s conquests!

$$TdS = dE + PdV$$

is arguably the most important equation in Science
If we were asked to predict what currently accepted principle would be valid 1,000 years from now,
The Second Law would be a good bet
From this we can derive entropic forces **F** = T **grad** S
The S-B radiation law (const. T^4)
Information theory (Shannon, Gabor)
Accelerated expansion of the Universe
Even Gravity!
And much more modestly----
The design of thermodynamically efficient optics

Failure of conventional optics

$P_{AB} << P_{BA}$ where P_{AB} is the probability of radiation starting at A reaching B--- etc

Nonimaging Concentrators

- It was the desire to bridge the gap between the levels of concentration achieved by common imaging devices, and the *sine law of concentration limit* that motivated the invention of nonimaging optics.

First and Second Law of Thermodynamics

Nonimaging Optics is the theory of maximal efficiency **radiative transfer**

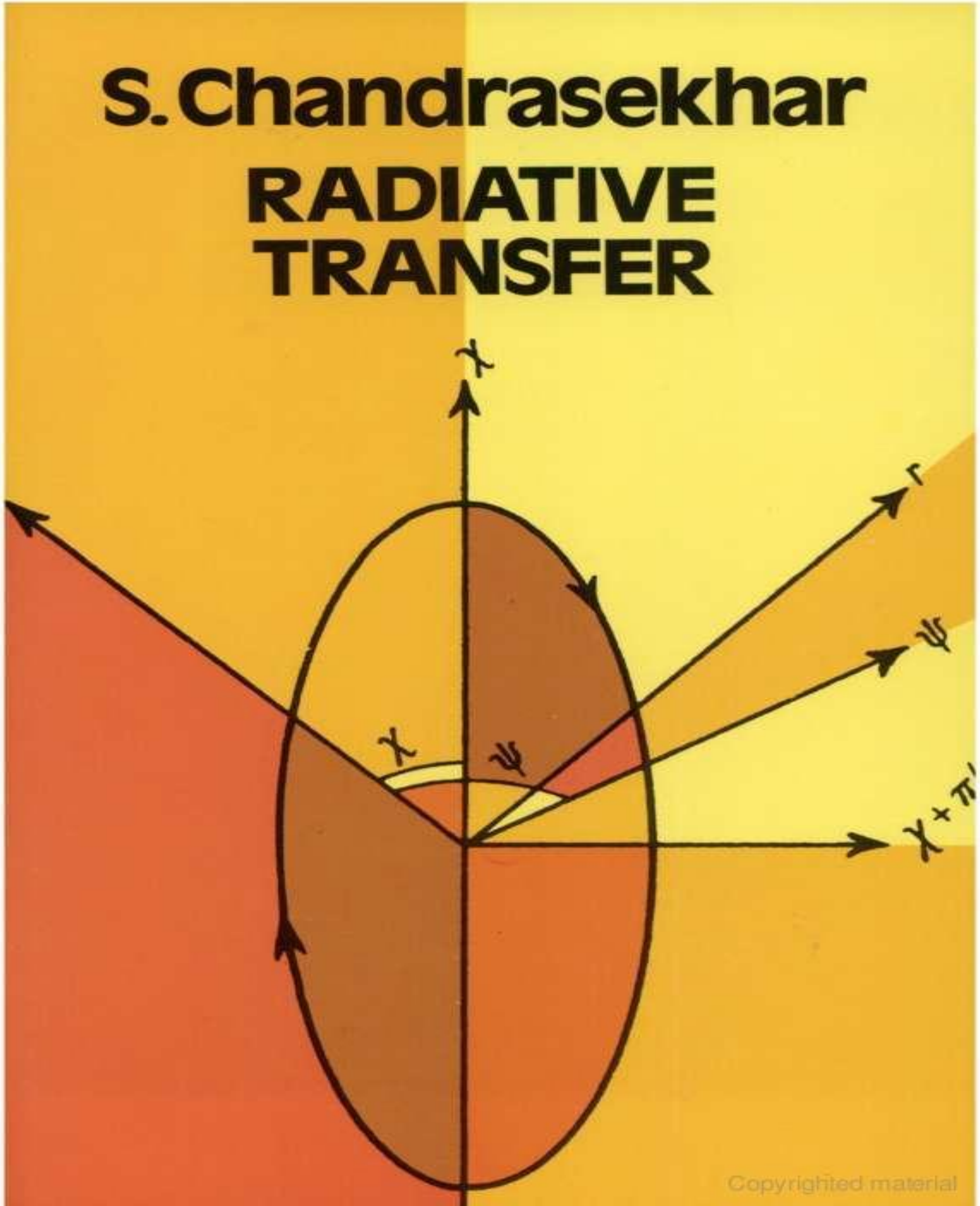
It is axiomatic and algorithmic based

As such, the subject depends much more on thermodynamics than on optics

To learn efficient optical design, first study the theory of furnaces.

`

Chandra


S. Chandrasekhar
RADIATIVE
TRANSFER
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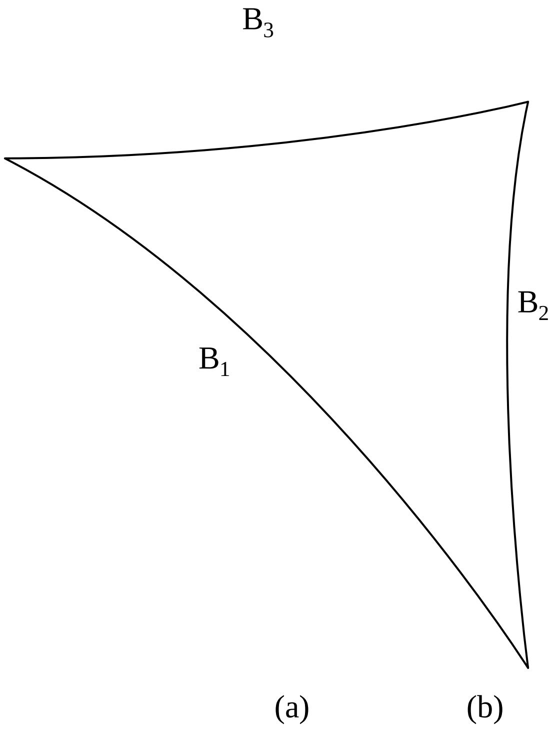
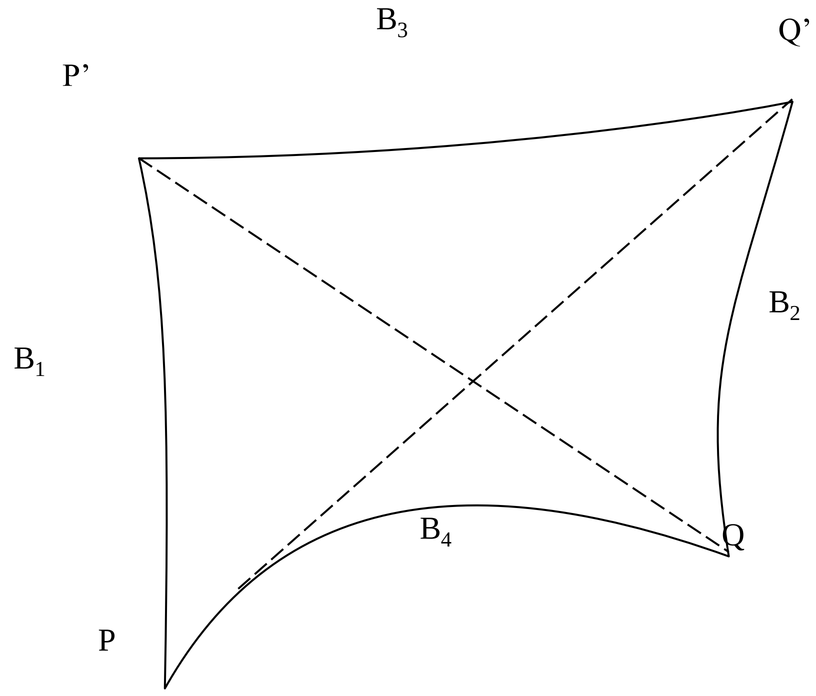
Copyrighted material





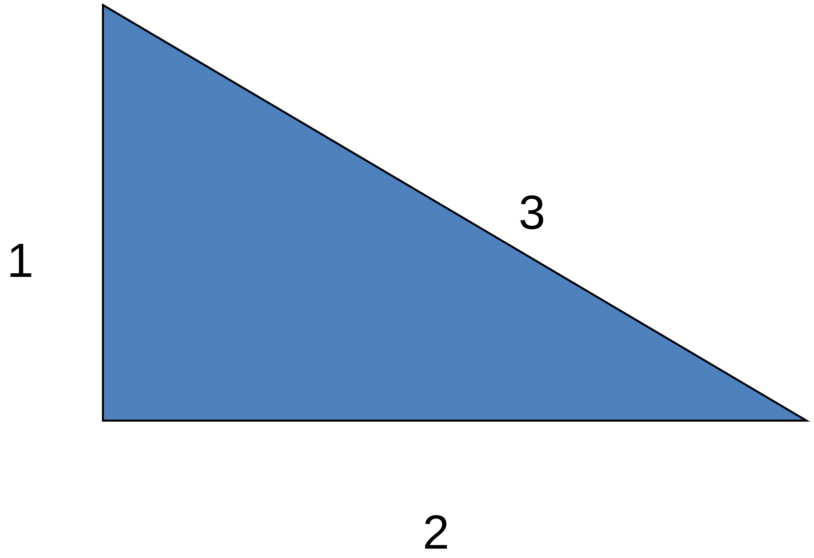
Radiative transfer between walls in an enclosure

HOTTEL STRINGS

Michael F. Modest, Radiative Heat Transfer, Academic Press 2003

Hoyt C. Hottel, 1954, Radiant-Heat Transmission, Chapter 4 in
William H. McAdams (ed.), *Heat Transmission,* 3rd ed. McGRAW-HILL

Strings 3-walls



$P12 = (A1 + A2 - A3)/(2A1)$

$P13 = (A1 + A3 - A2)/(2A1)$

$P23 = (A2 + A3 - A1)/(2A2)$

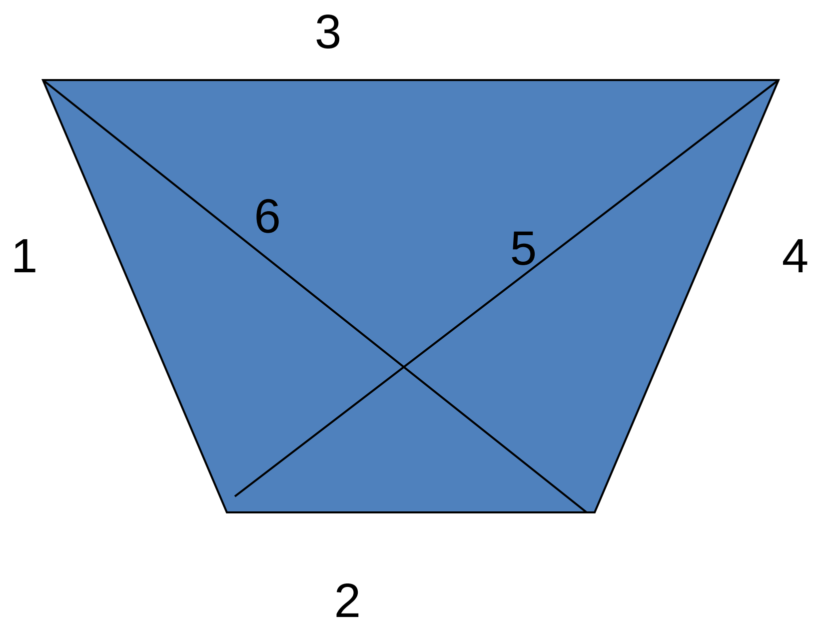
$qij = AiPij$

$Pii = 0$

$P12 + P13 = 1$
$P21 + P23 = 1$ 3 Eqs
$P31 + P32 = 1$

$Ai\ Pij = Aj\ Pji$ 3 Eqs

Strings 4-walls



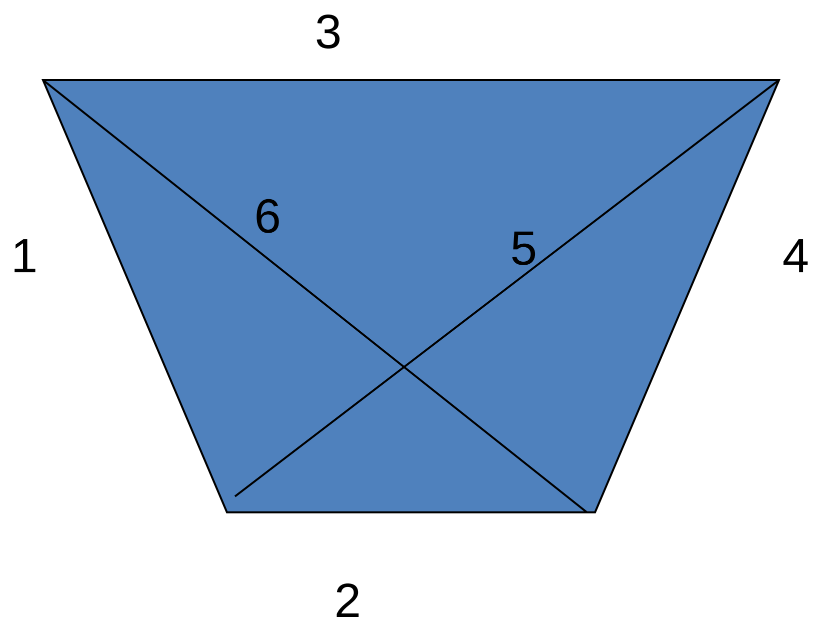
P12 + P13 + P14 = 1

P21 + P23 + P24 = 1

P14 = [(A5 + A6) – (A2 + A3)]/(2A1)

P23 = [(A5 + A6) – (A1 + A4)]/(2A2)

Limit to Concentration



P23 = [(A5 + A6) – (A1 + A4)]/(2A2)S

P23= sin(θ) as A3 goes to infinity

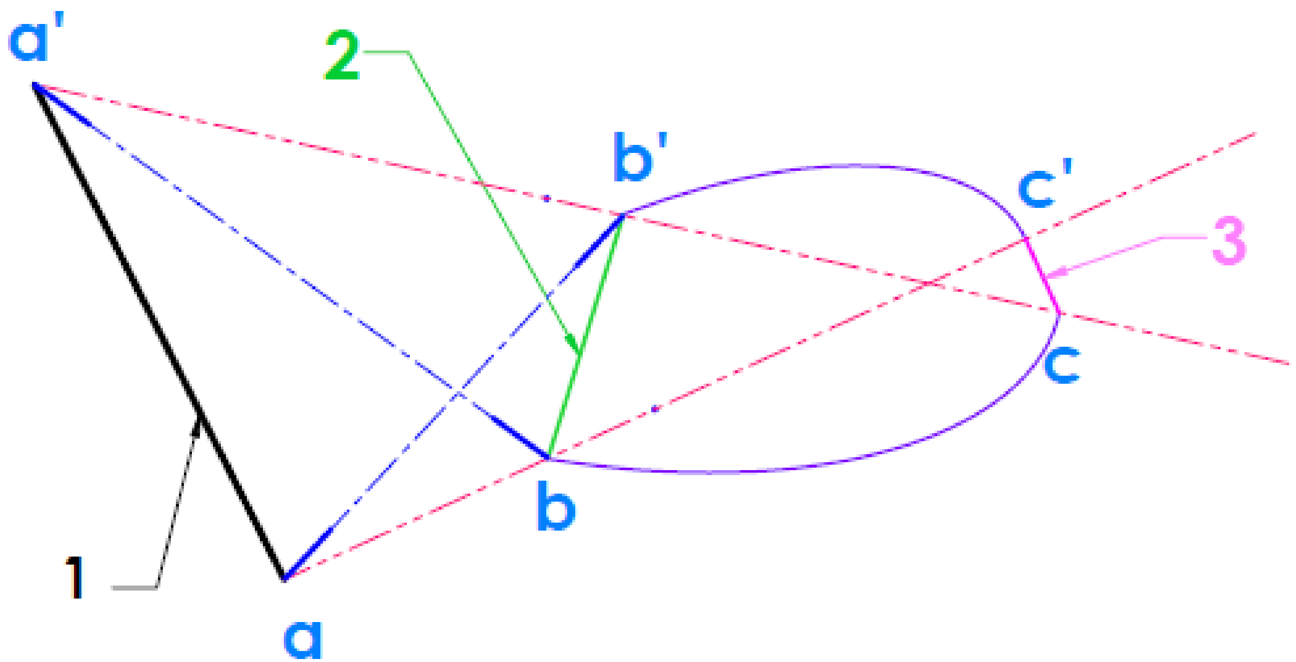
- This rotates for symmetric systems to sin ^{2}(θ)

String Method

- We explain what strings are by way of example.
- We will proceed to solve the problem of attaining the sine law limit of concentration for the simplest case, that of a flat absorber.

String method deconstructed

1. Choose source
2. Choose aperture
3. Draw strings
4. Work out $P_{12}A_1$

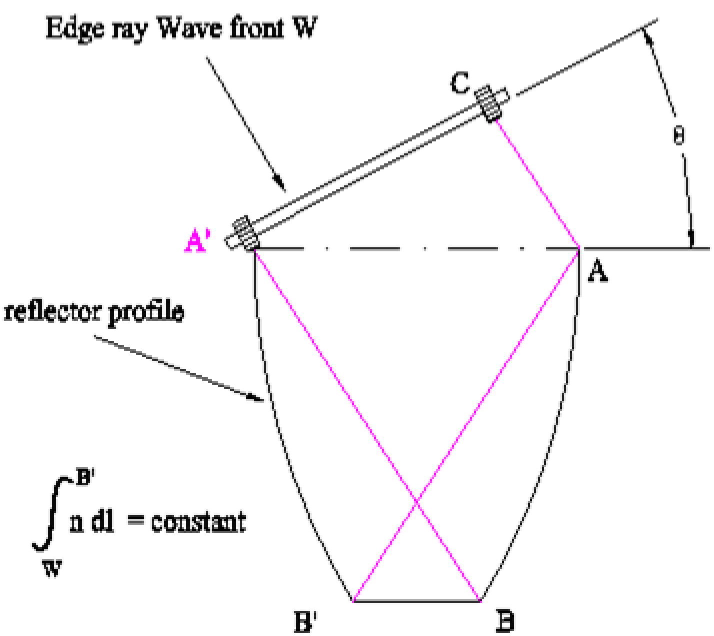


5. $P_{12}A_1 = \frac{1}{2}[\sum long\ strings - \sum short\ strings] = A_3 = 0.55A_1 = 0.12A_1$
6. Fit A_3 between extended strings => 2 degrees of freedom, Note that

$$A_3 = cc' = \frac{1}{2}[(ab' + a'b - (ab + a'b')]$$

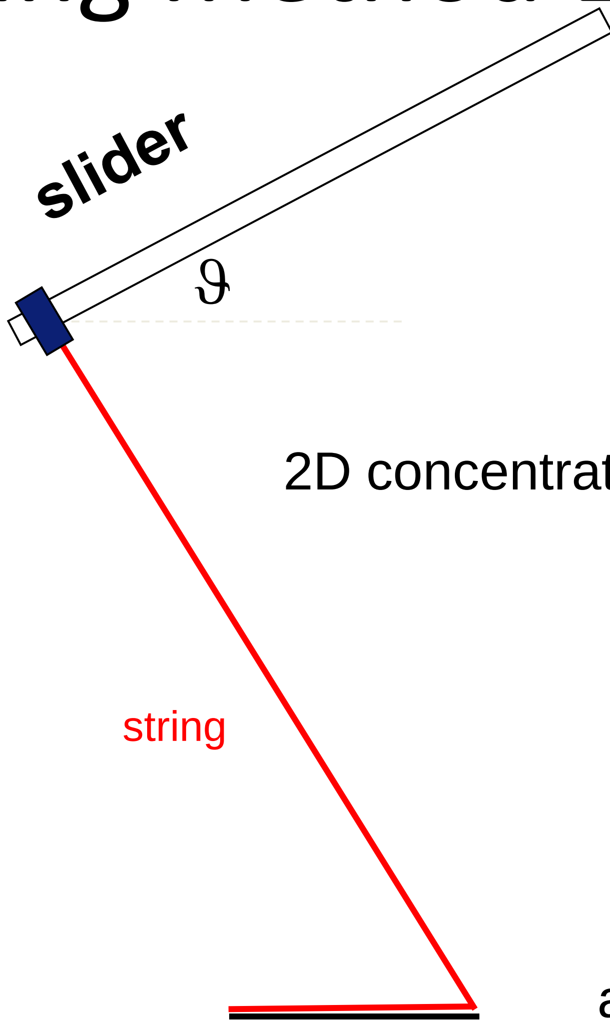
7. Connect the strings. That's all there is to it!

String Method Example: CPC



- We loop one end of a "string" to a "rod" tilted at angle θ to the aperture AA' and tie the other end to the edge of the exit aperture B'.
- Holding the length fixed, we trace out a reflector profile as the string moves from C to A'.

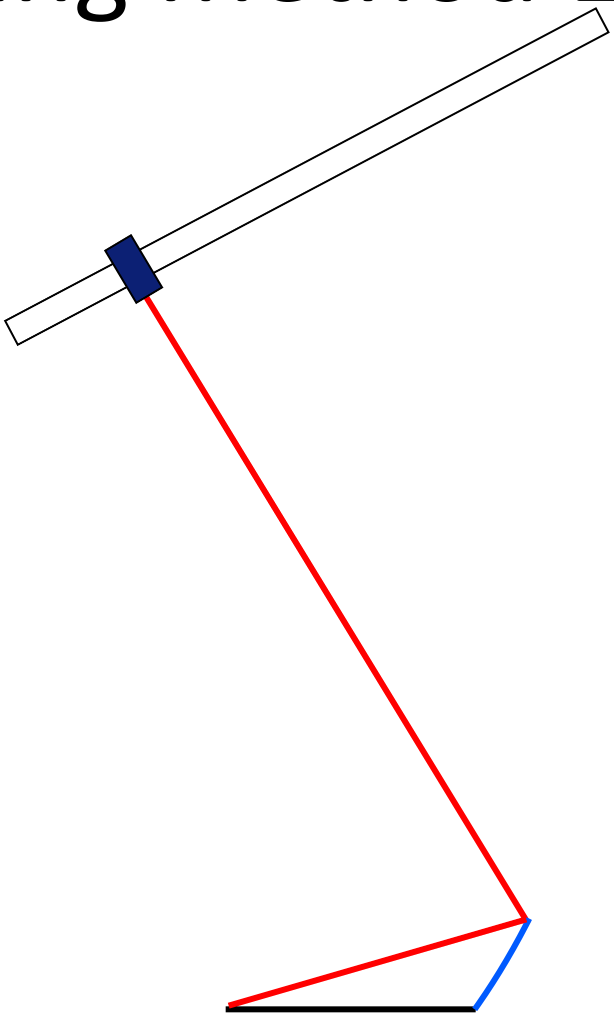
String Method Example: CPC



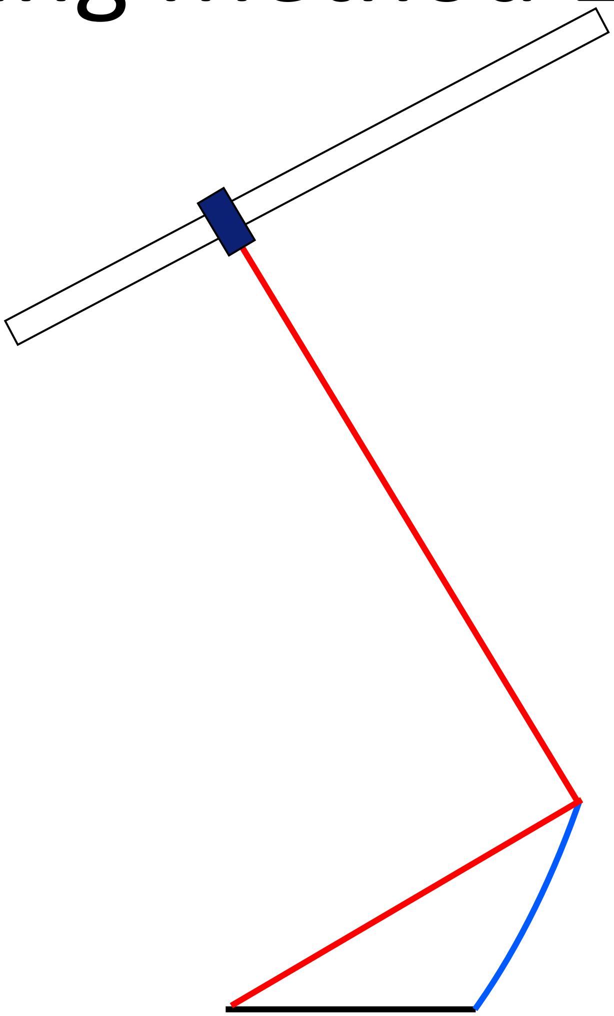
2D concentrator with acceptance (half) angle ϑ

absorbing surface

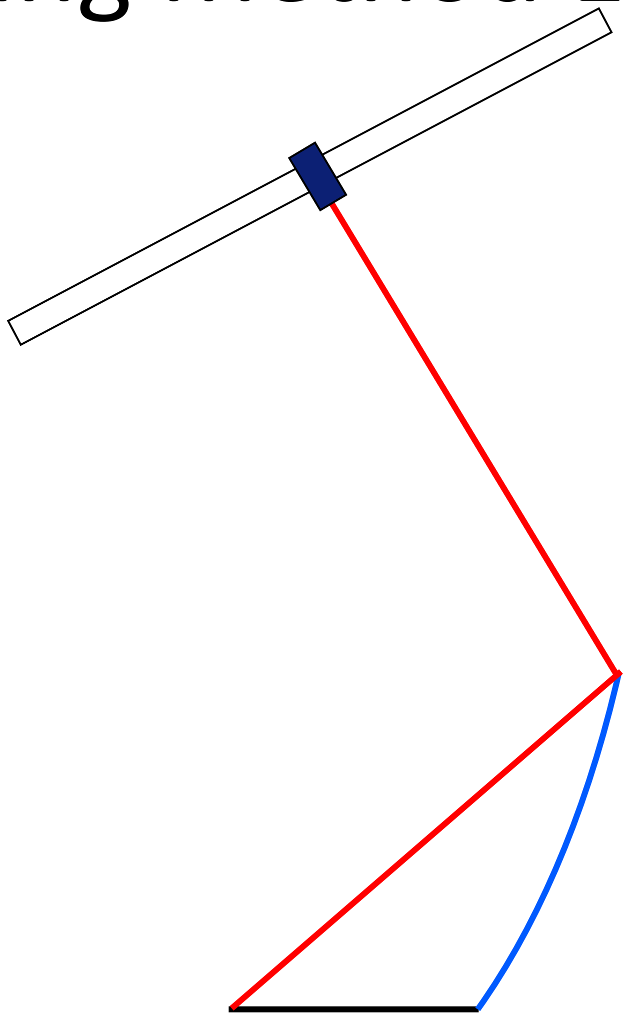
String Method Example: CPC



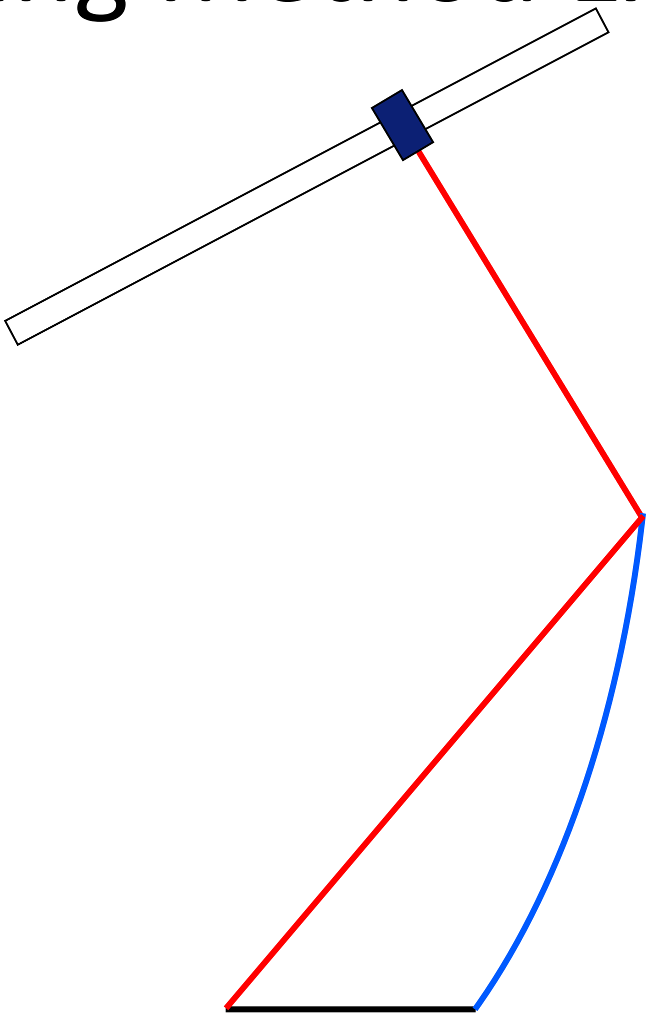
String Method Example: CPC



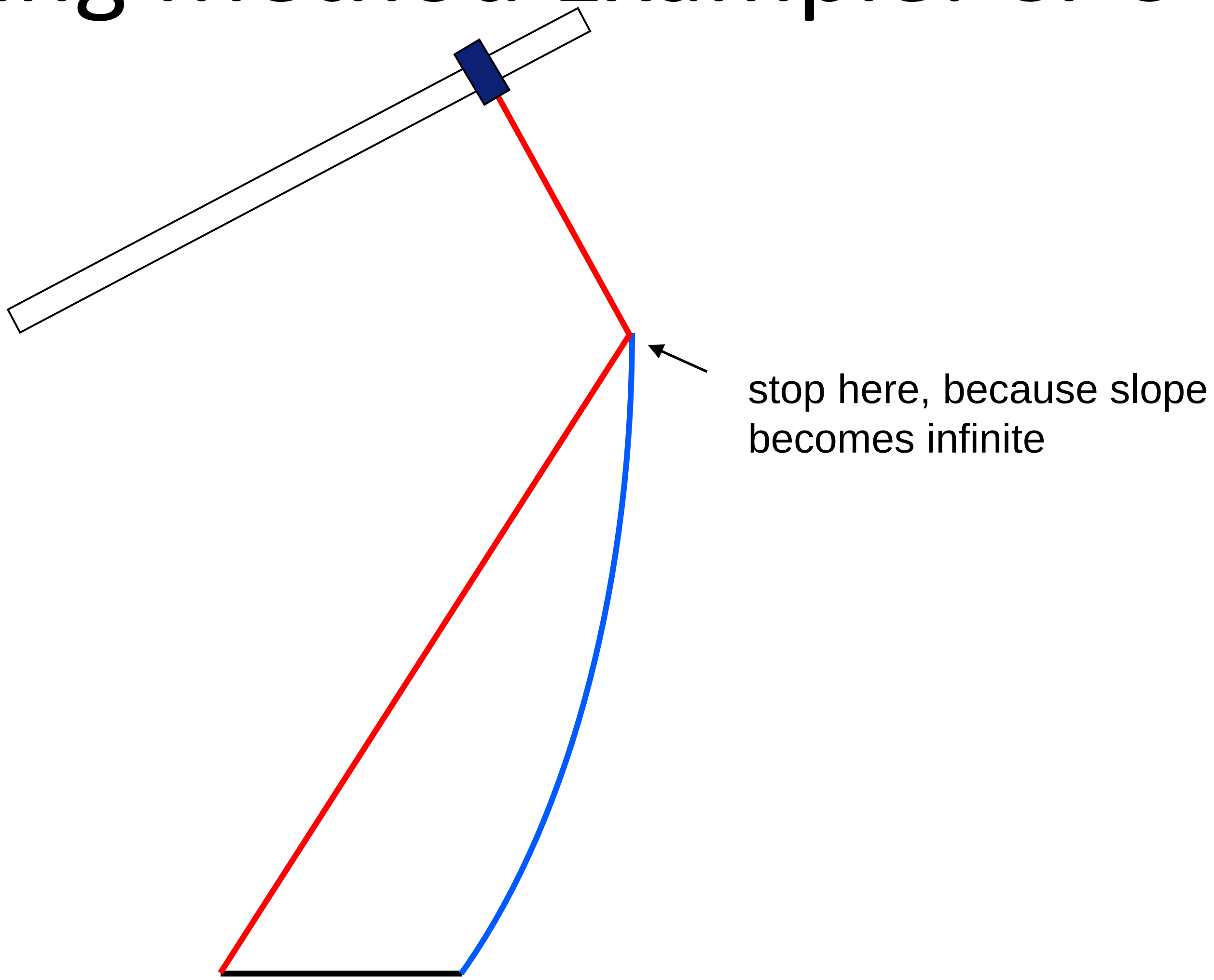
String Method Example: CPC



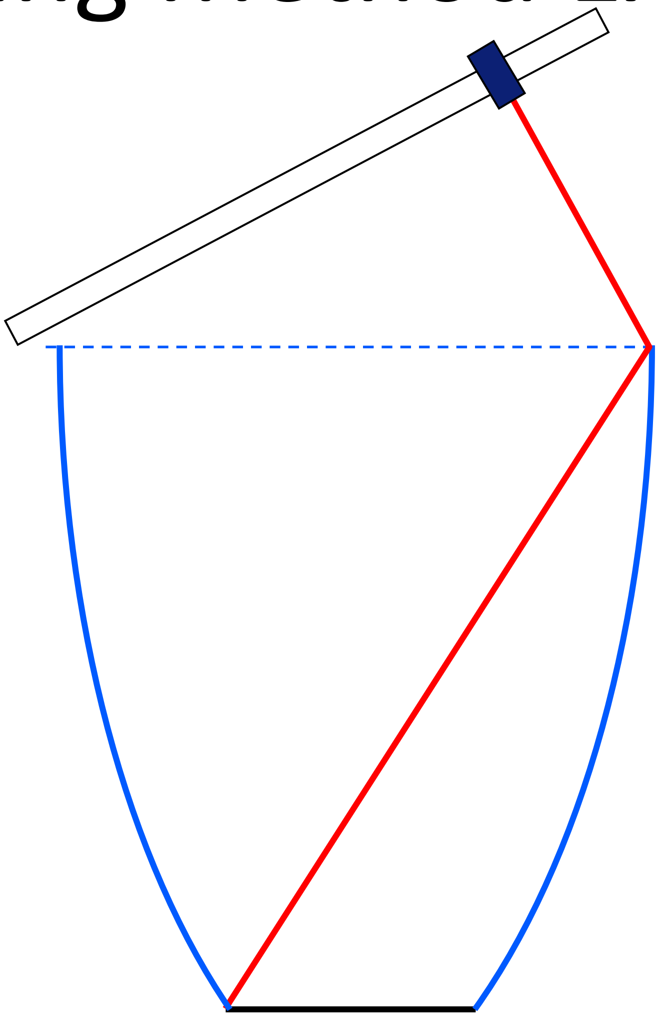
String Method Example: CPC



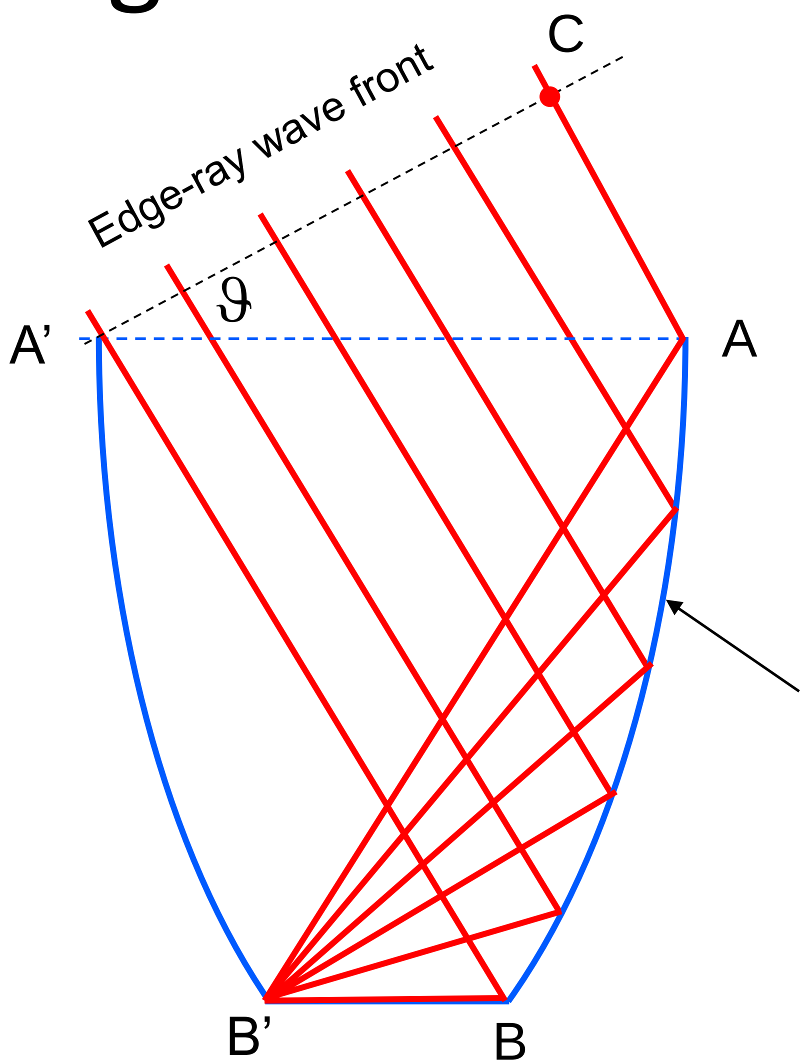
String Method Example: CPC



String Method Example: CPC



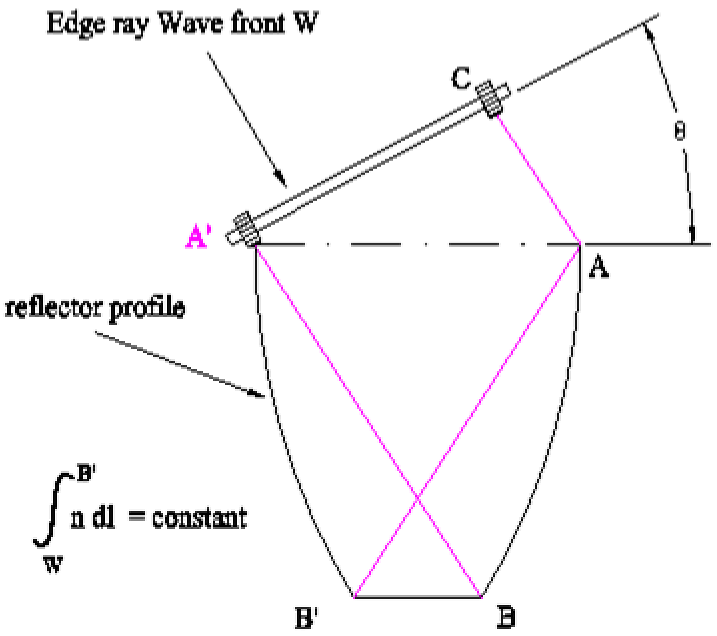
String Method Example: CPC



Compound Parabolic Concentrator (CPC)

(tilted parabola sections)

String Method Example: CPC



$$B'A + AC = B'B + BA'$$

$$B'A = BA'$$

$$BB' = AC = AA' \sin\vartheta$$

$$\Rightarrow AA' \sin\vartheta = BB'$$

$$\boxed{\begin{array}{l} C = \dfrac{AA'}{BB'} = \dfrac{1}{\sin\vartheta} \\[2ex] C(\text{cone}) = \left(\dfrac{AA'}{BB'}\right)^2 = \dfrac{1}{\sin^2\vartheta} \end{array}}$$

sine law of concentration limit!

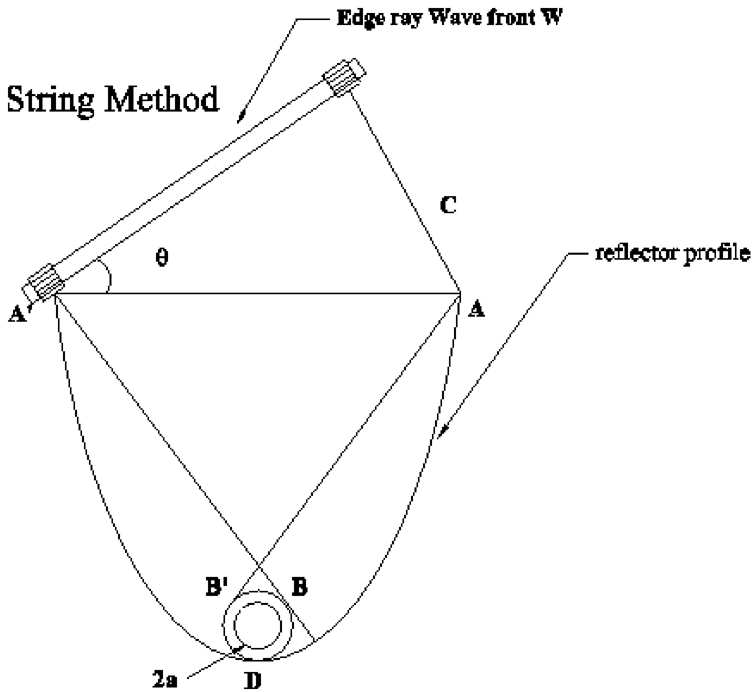
String Method Example: CPC

- The 2-D CPC is an ideal concentrator, i.e., it works perfectly for all rays within the acceptance angle θ,
- Rotating the profile about the axis of symmetry gives the 3-D CPC
- The 3-D CPC is very close to ideal.

String Method Example: CPC

- Notice that we have kept the *optical length* of the string fixed.
- For media with varying index of refraction (n), the physical length is multiplied by n.
- The string construction is very versatile and can be applied to *any* convex (or at least non-concave) absorber…

String Method Example: Tubular Absorber



String Method : $\int_W^D n\,dl = \text{Constant}$

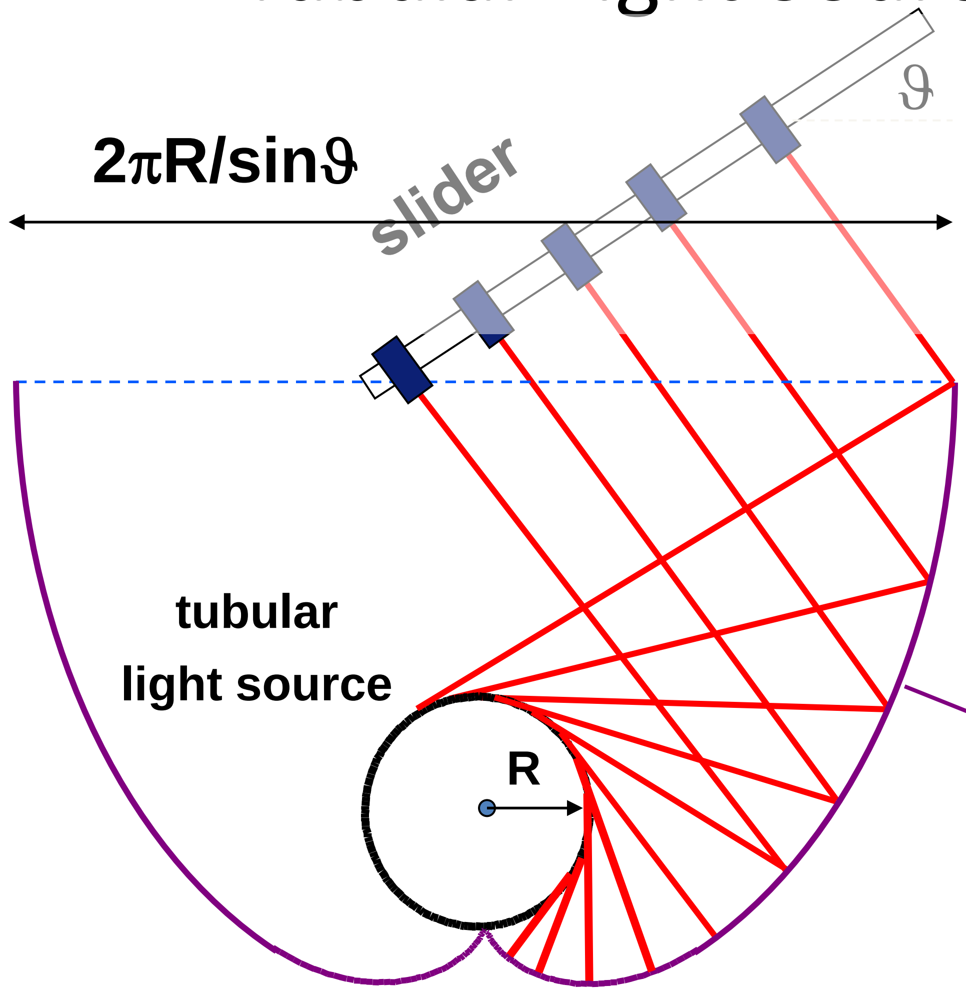
$AC + AB' + B'D = A'B + BD + 2\pi a$

$AA' \sin\theta = 2\pi a$

$$C = \frac{AA'}{2\pi a} = \frac{1}{\sin\vartheta}$$

- String construction for a tubular absorber as would be appropriate for a solar thermal concentrator.

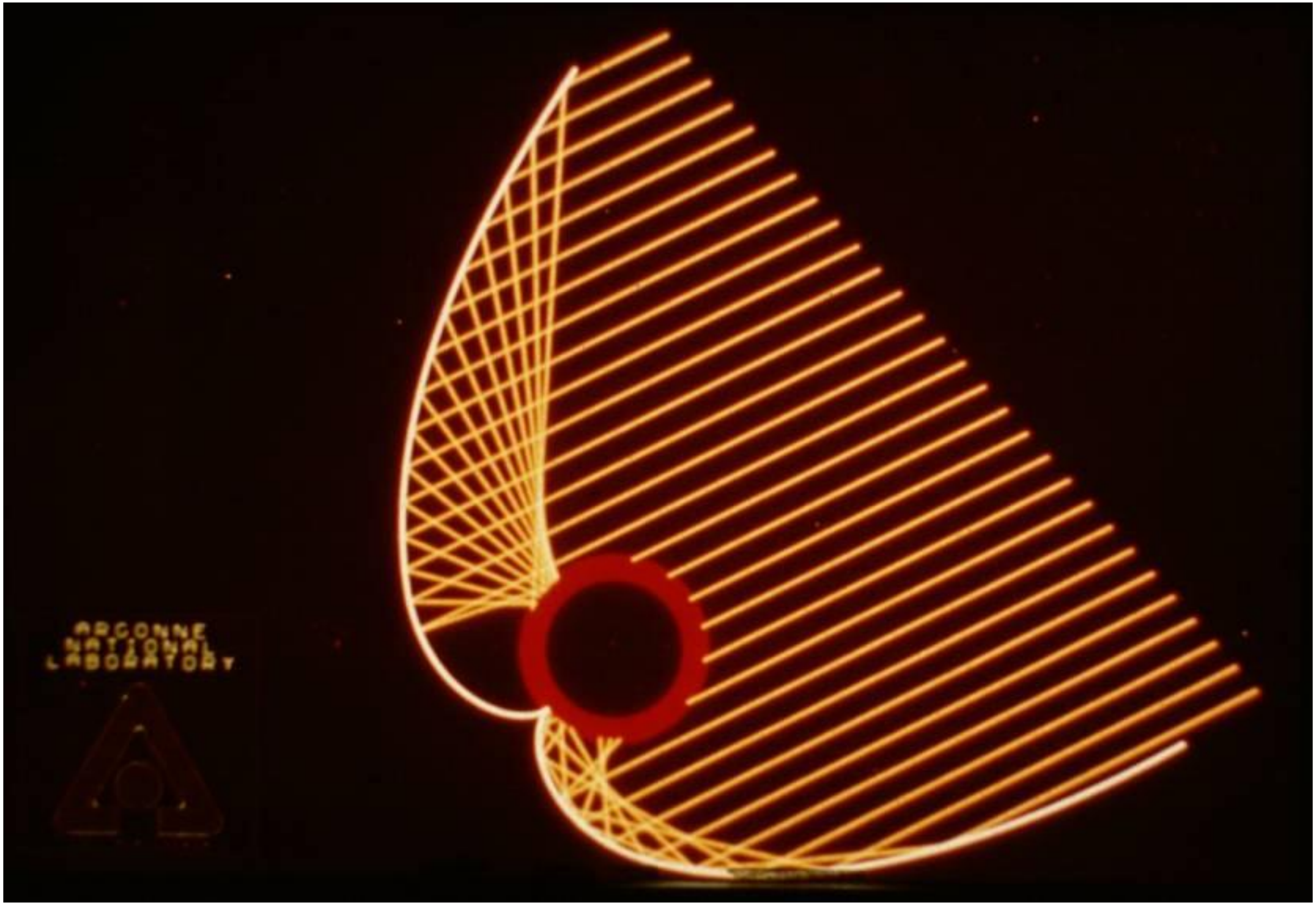
String Method Example: Collimator for a Tubular Light Source



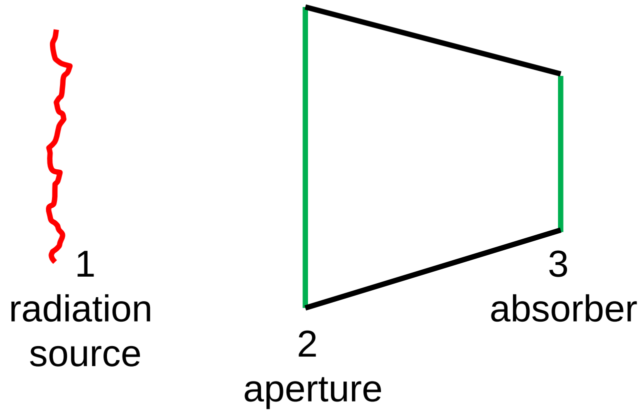
étendue
conserved
→ ideal design!

kind of "involute"
of the circle

Non-imaging Concentrator



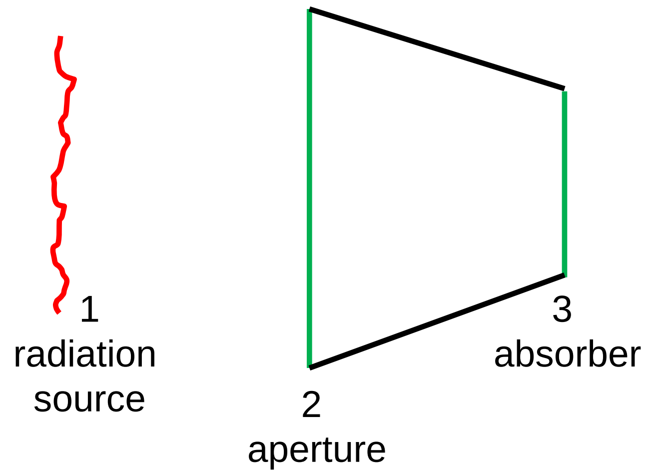
The general concentrator problem



Concentration C is defined as A2/A3

What is the "best" design?

Characteristics of an optimal concentrator design



Let Source be maintained at T1 (sun)

Then T_3 will reach $T_1 \leftrightarrow P_{31} = 1$

Proof: $q_{13} = \sigma T_1^4 A_1 P_{13} = \sigma T_3^4 A_3 P_{31}$

But $q_3 total = \sigma T_3^4 \times A3 \geq q_{13}$ at steady state

$T_3 \leq T_1$ (second law)$\rightarrow P_{31}=1 \leftrightarrow T_3 = T_1$

Summary:

For a thermodynamically efficient design

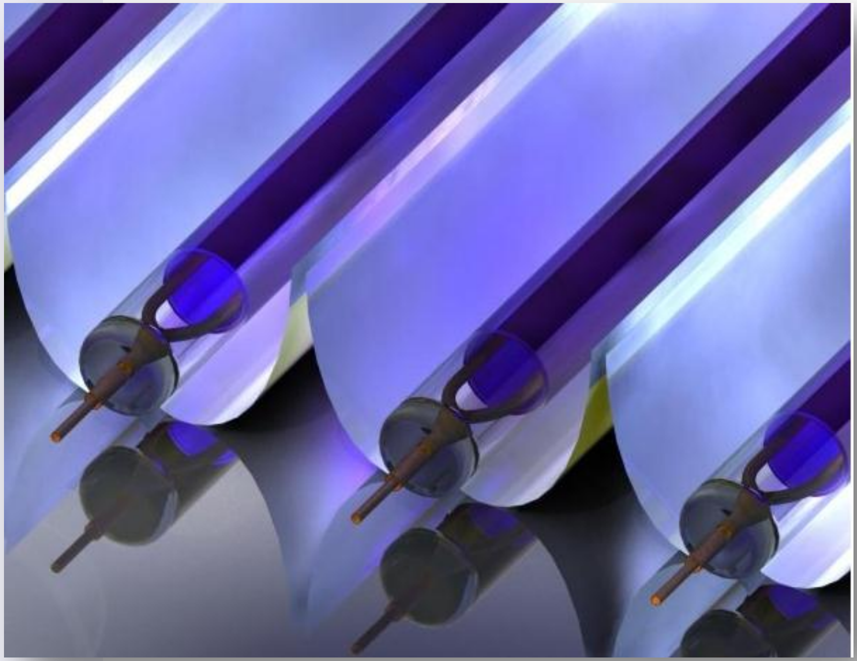
1. P_{31} (where P_{31} = probability of radiation from receiver to source) = 1

Second Law

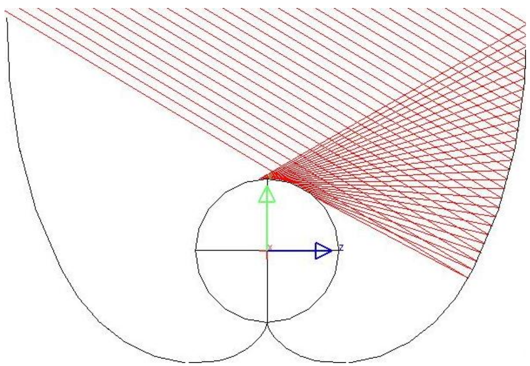
2. C = $1/P_{21}$ where P_{21} = probability of radiation from receiver to source

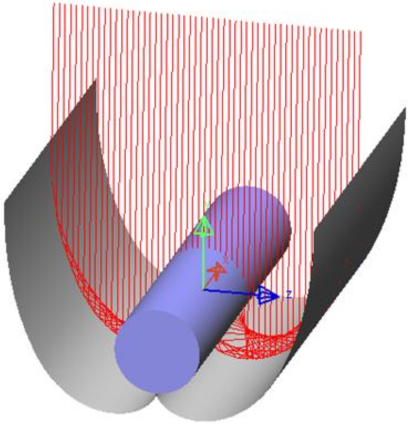
How?

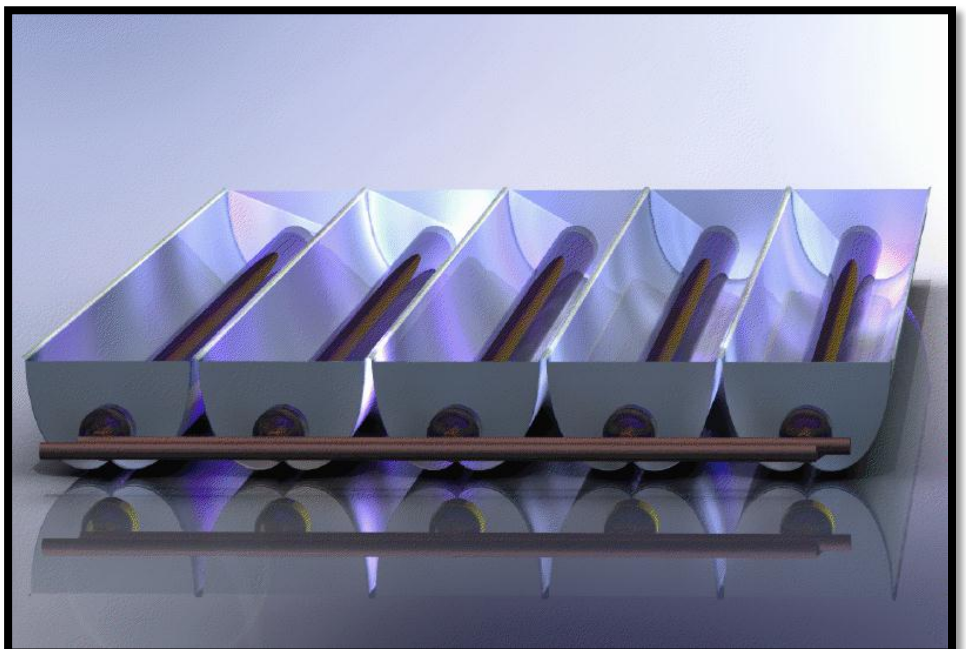
- Non-imaging optics:
  - External Compound Parabolic Concentrator (XCPC)
  - Non-tracking
  - Thermodynamically efficient
  - Collects diffuse sunlight

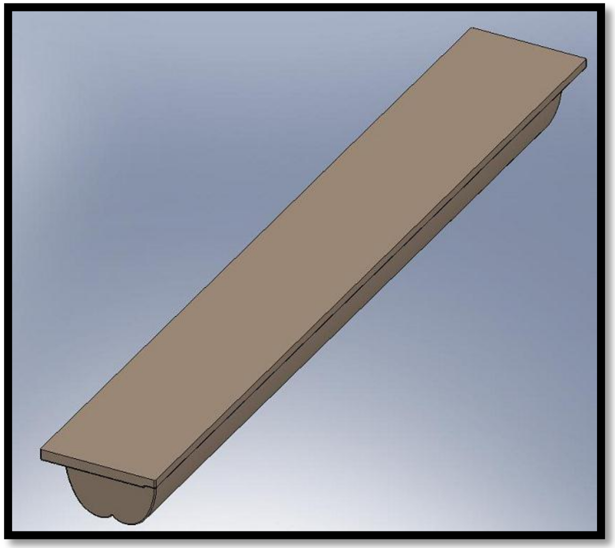


The Design: Solar Collectors









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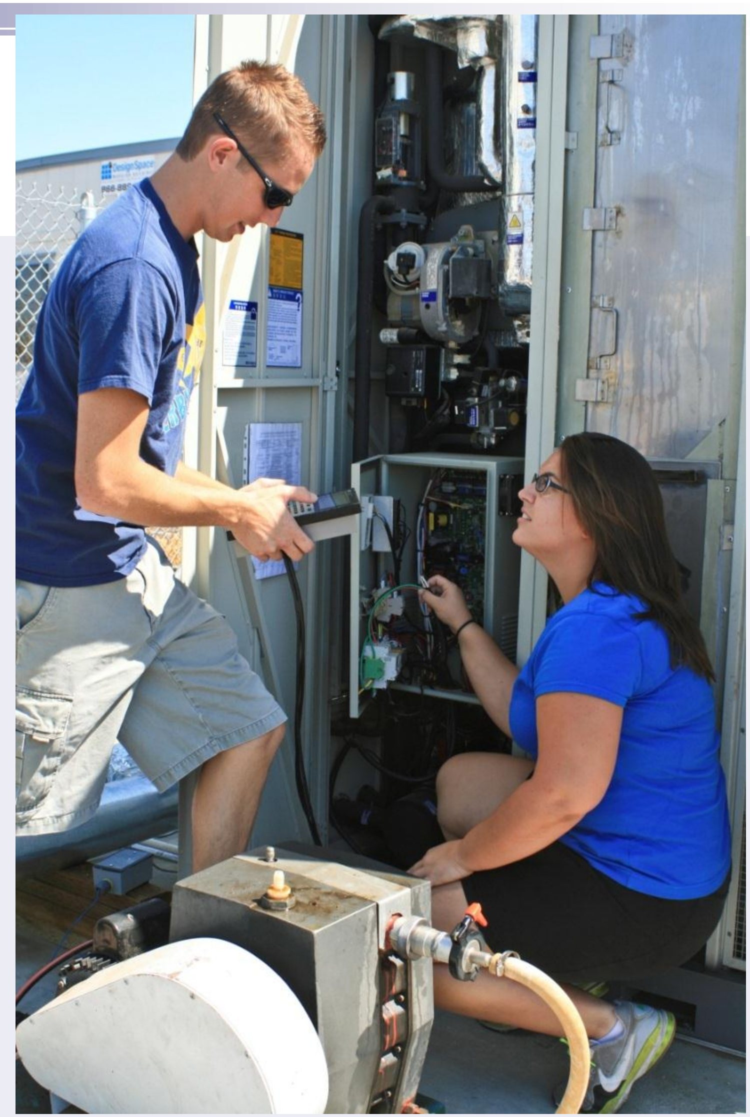
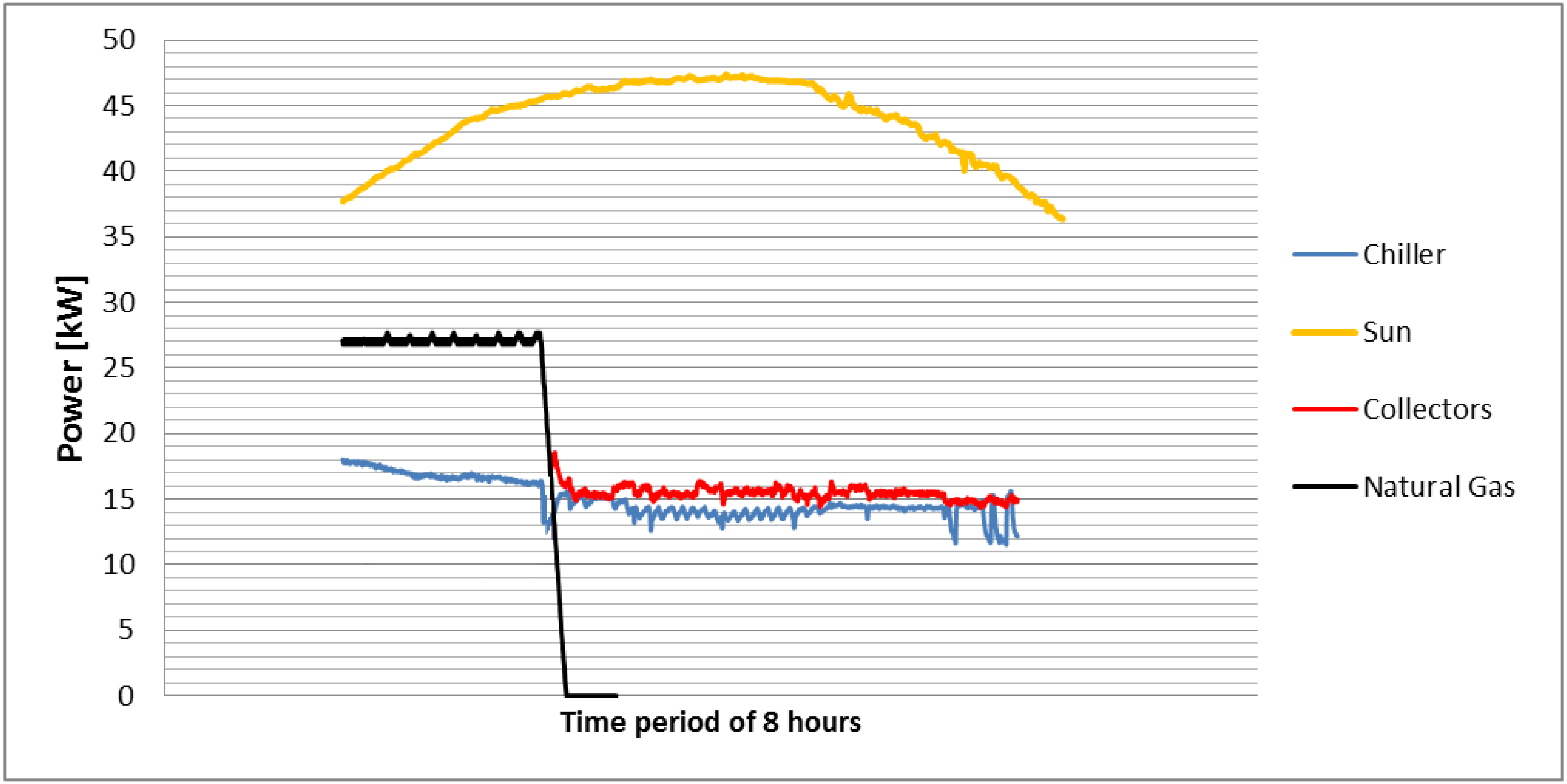
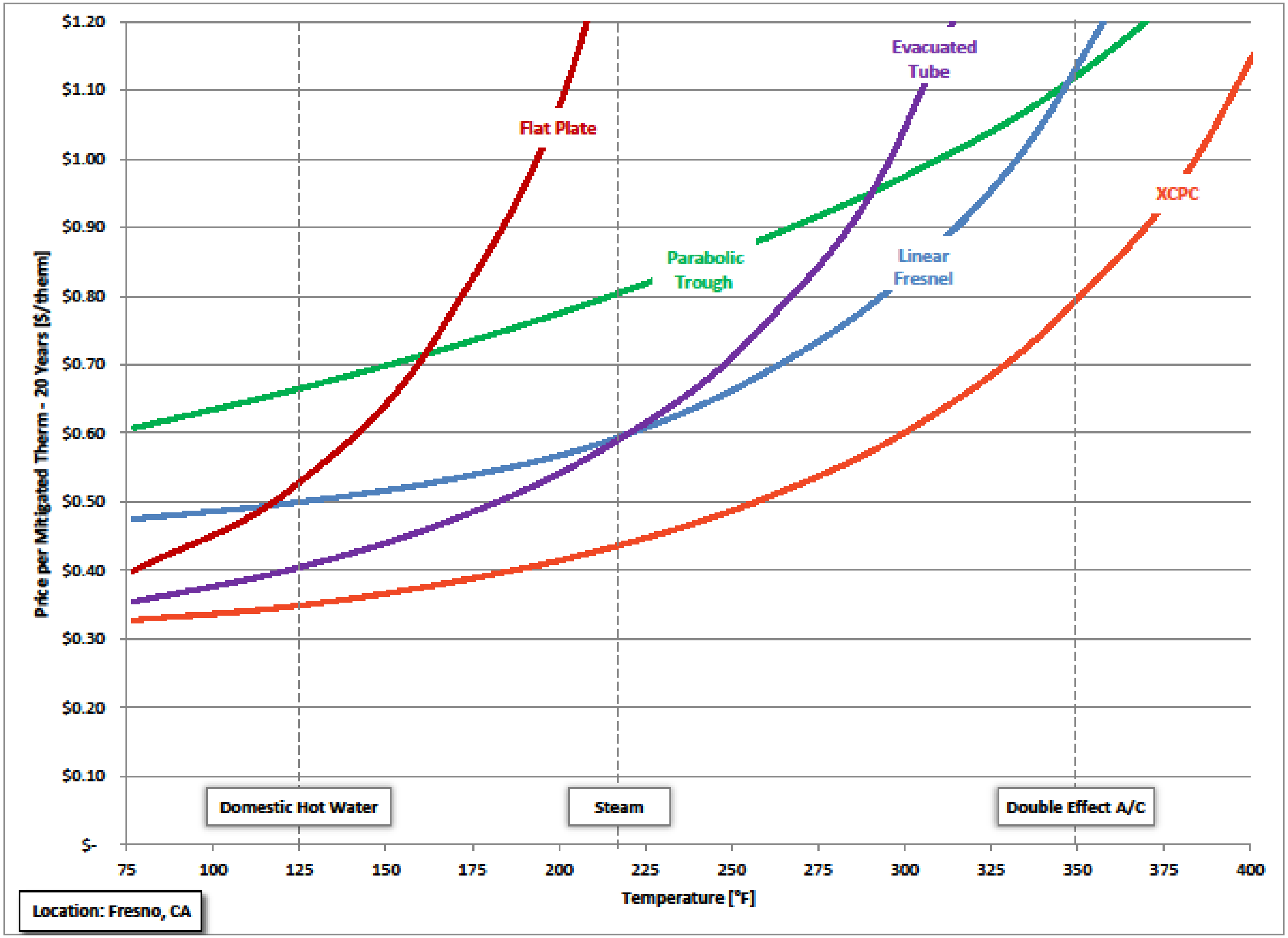


Power Output of the Solar Cooling System





Price per Mitigated Therm - 20 Years [$/therm]
$1.20
$1.10
$1.00
$0.90
$0.80
$0.70
$0.60
$0.50
$0.40
$0.30
$0.20
$0.10
$-
75
100
125
150
175
200
225
250
275
300
325
350
375
400
Temperature [°F]
Flat Plate
Evacuated Tube
Parabolic Trough
Linear Fresnel
XCPC
Domestic Hot Water
Steam
Double Effect A/C
Location: Fresno, CA

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tammy.mcclure@b2usolar.c
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Demonstrated Performance

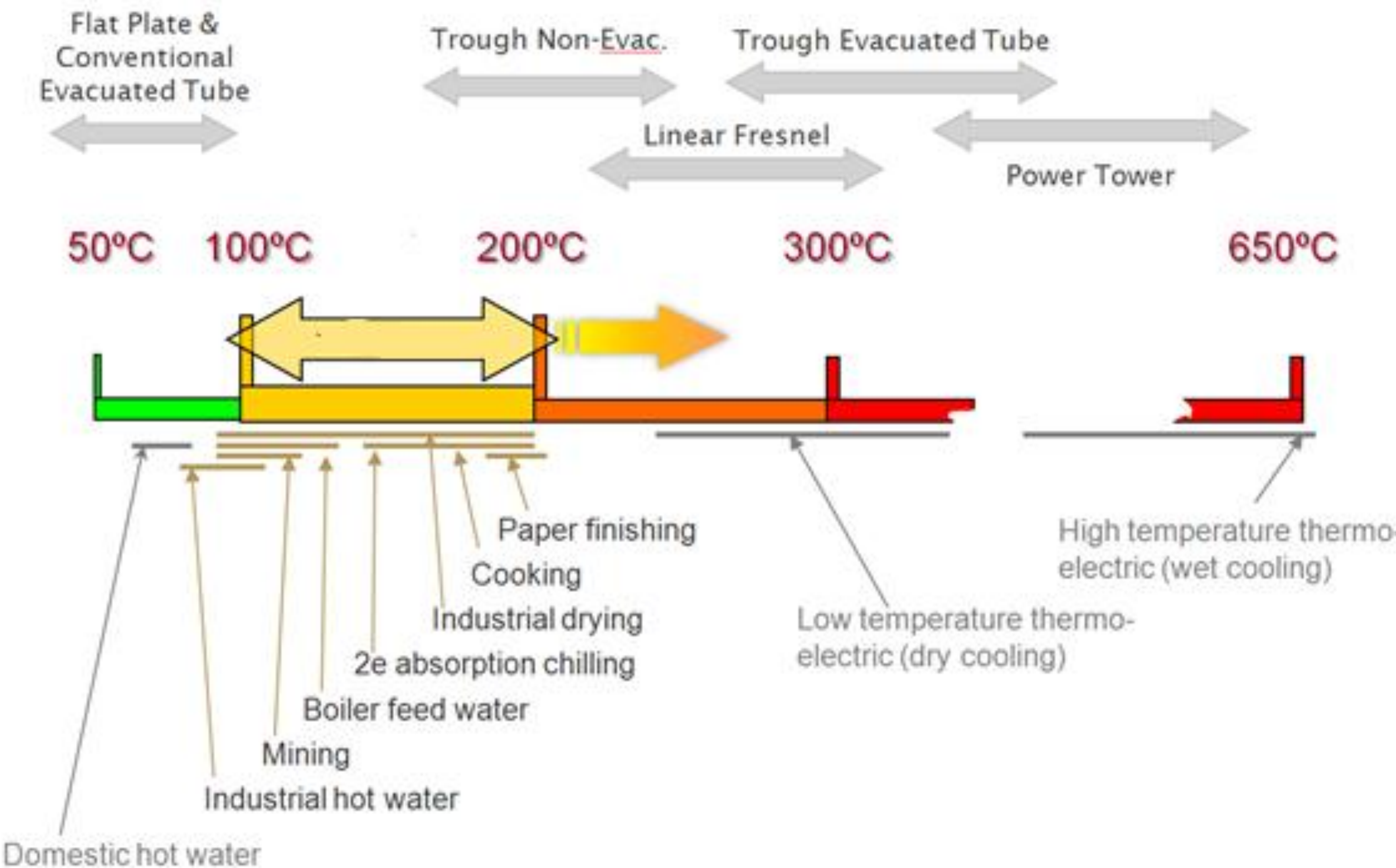
10kW Array Gas Technology Institute

Conceptual Testing
SolFocus & UC Merced

10kW test loop NASA/AMES

Hospital in India

Roland, I hope Shanghai went well Hit 200C yesterday with just 330W DNI. Gary D. Conley~*Ancora Imparo*
www.b2uSolar.com



Flat Plate &
Conventional
Evacuated Tube
Trough Non-Evac.
Trough Evacuated Tube
Linear Fresnel
Power Tower
50ºC
100ºC
200ºC
300ºC
650ºC
Paper finishing
Cooking
Industrial drying
2e absorption chilling
Boiler feed water
Mining
Industrial hot water
Domestic hot water
High temperature thermo-
electric (wet cooling)
Low temperature thermo-
electric (dry cooling)

I am frequently asked- Can this possibly work?

EPILOGUE

In case you have been wondering,
WHERE IS UC MERCED???

Where we are

TUOLUMNE
MARIPOSA
MERCED
STANISLAUS
SAN JOAQUIN
KINGS
TULARE
KERN
INYO
MONO
SAN BERNARDINO
LOS ANGELES
VENTURA
SANTA BARBARA
SAN LUIS OBISPO
RIVERSIDE
ORANGE
SAN DIEGO
IMPERIAL


UC Merced Campus
Under Construction January 2004
Photo By Hans Marsen

UCMERCED

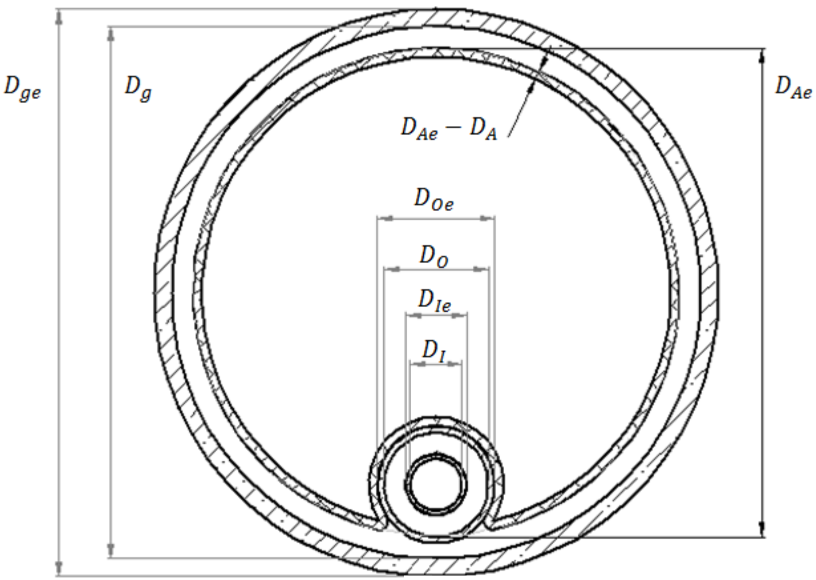
Thank you…

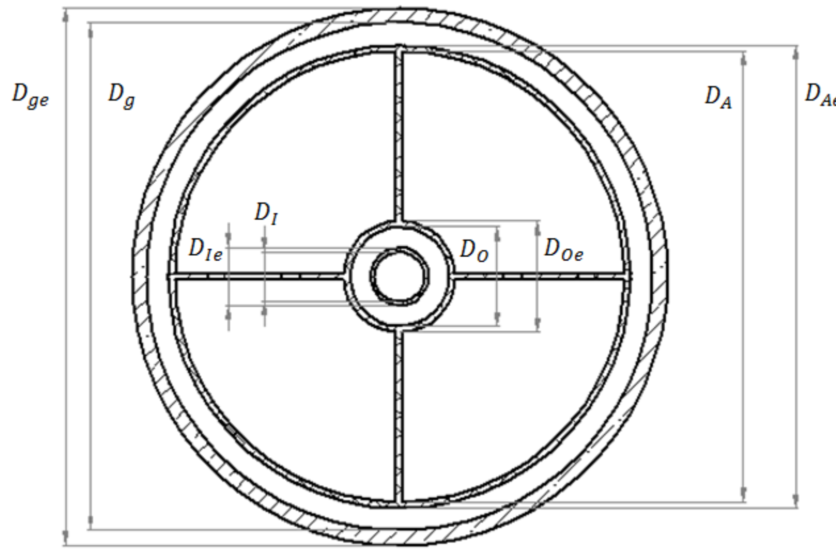
Highlight Project—Solar Thermal

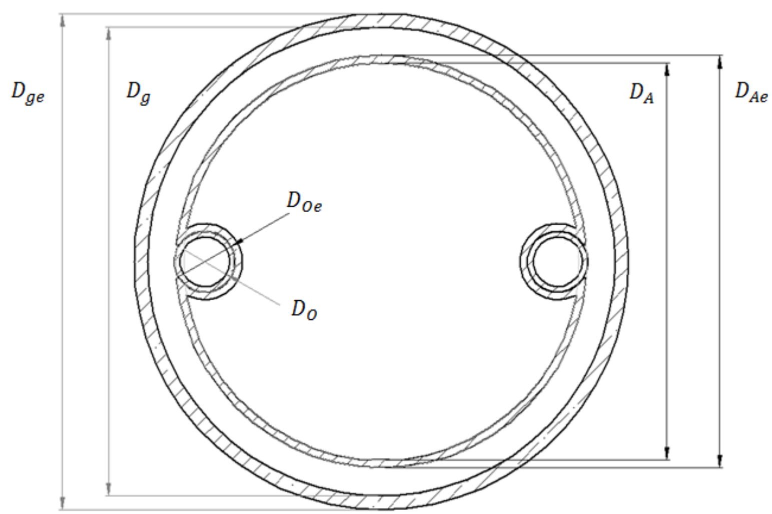
- UC Merced has developed the External Compound Parabolic Concentrator (XCPC)

- XCPC features include:
  - Non-tracking design
  - 50% thermal efficiency at 200
  - Installation flexibility
  - Performs well in hazy conditions
- Displaces natural gas consumption and reduces emissions
- Targets commercial applications such as double-effect absorption cooling, boiler preheating, dehydration, sterilization, desalination and steam extraction

UC Merced 250°C Thermal Test Loop

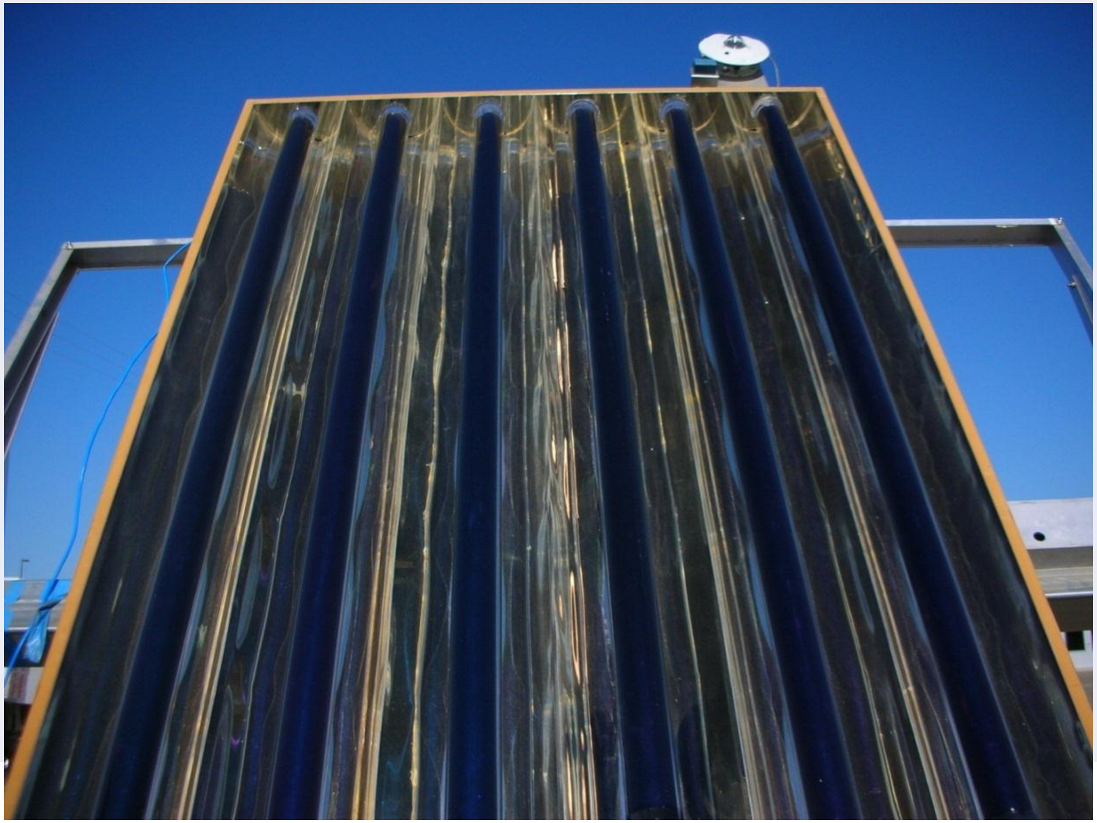

D_{ge}
D_g
D_{Ae}
$D_{Ae} - D_A$
D_{Oe}
D_O
D_{Ie}
D_I


D_{ge}
D_g
D_A
D_{Ae}
D_I
D_{Ie}
D_O
D_{Oe}

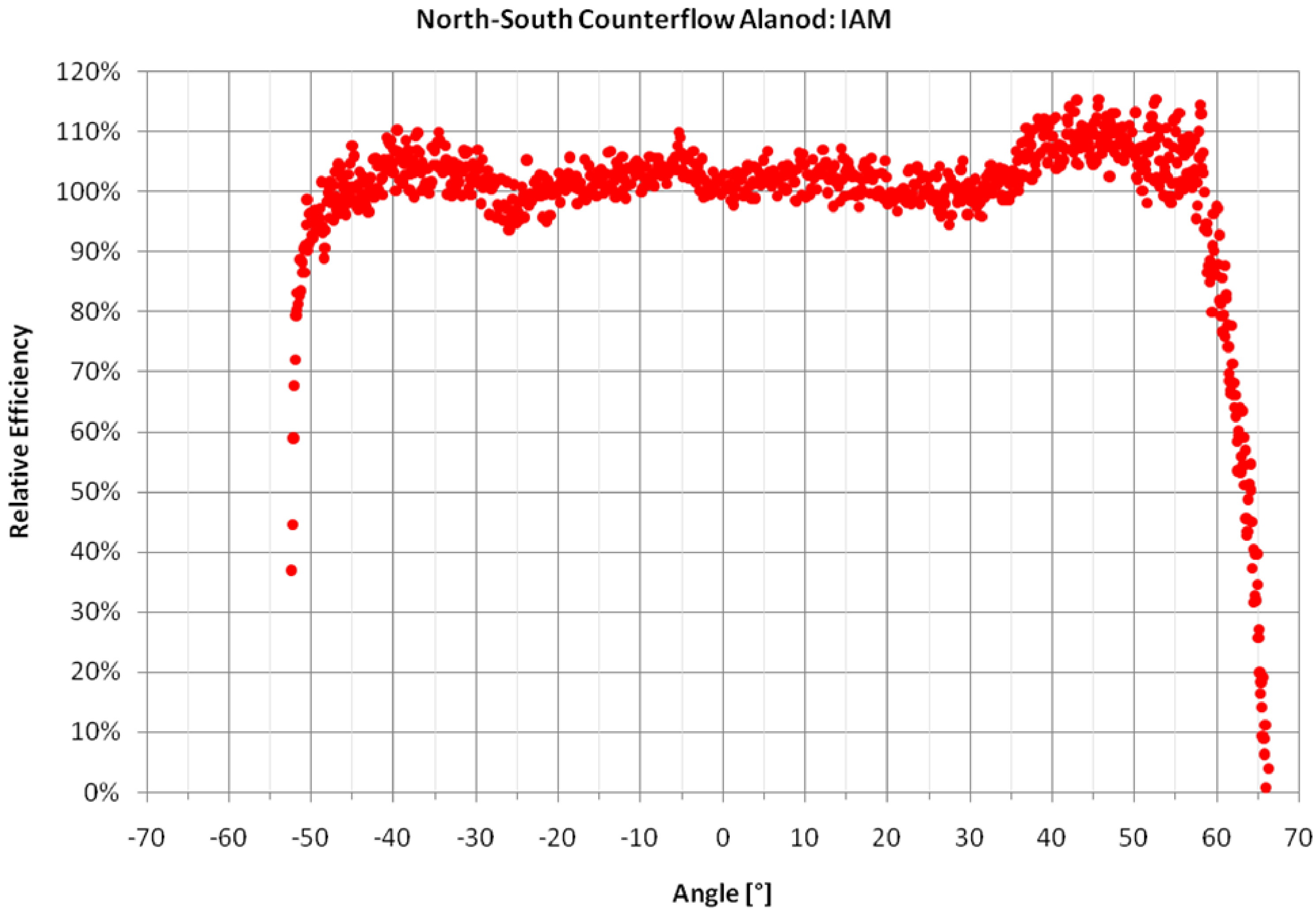

D_{ge}
D_g
D_A
D_{Ae}
D_{Oe}
D_O

Testing

- Efficiency (80 to 200 °C)
- Optical Efficiency (Ambient temperature)
- Acceptance Angle
- Time Constant
- Stagnation Test



Acceptance Angle



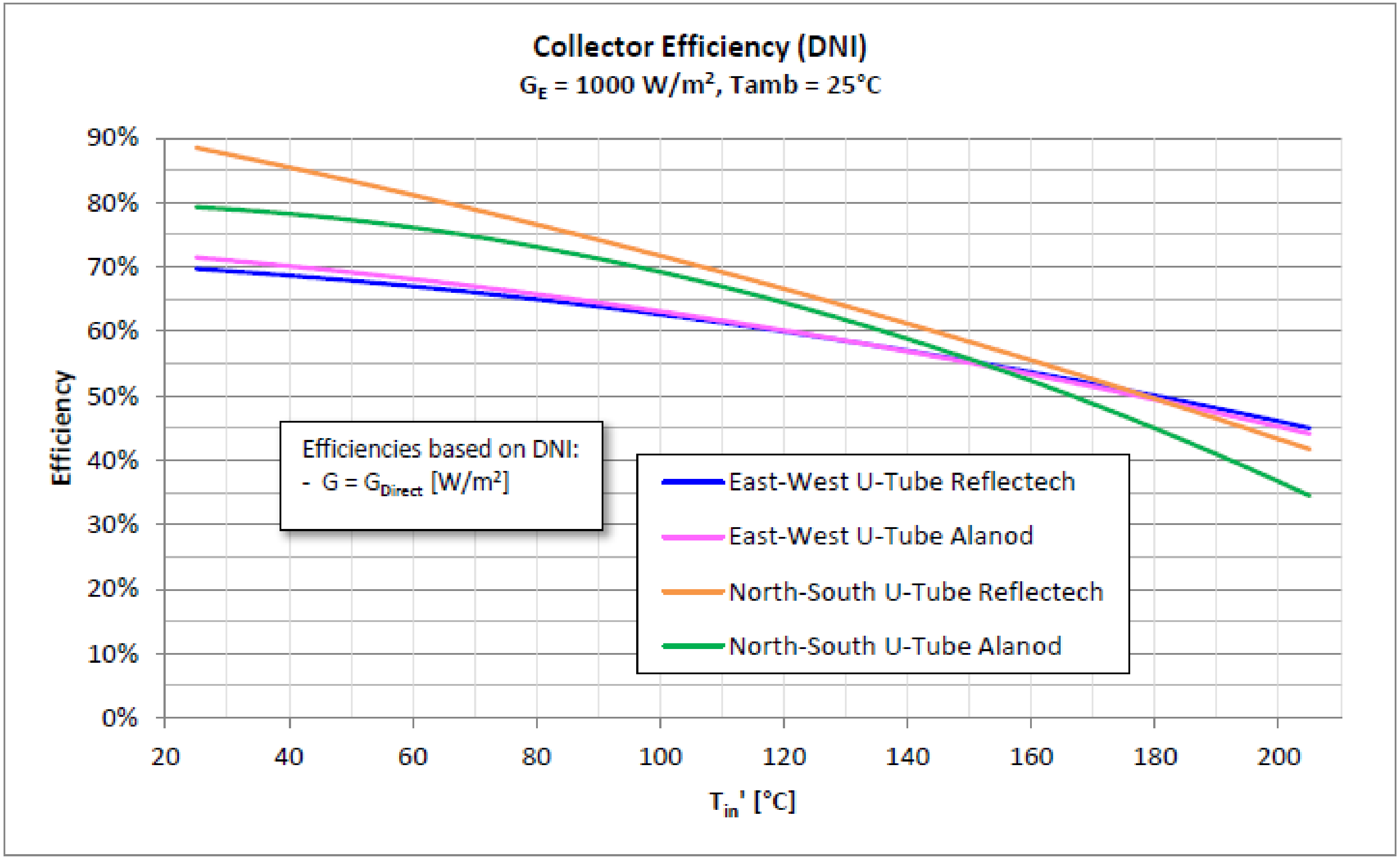
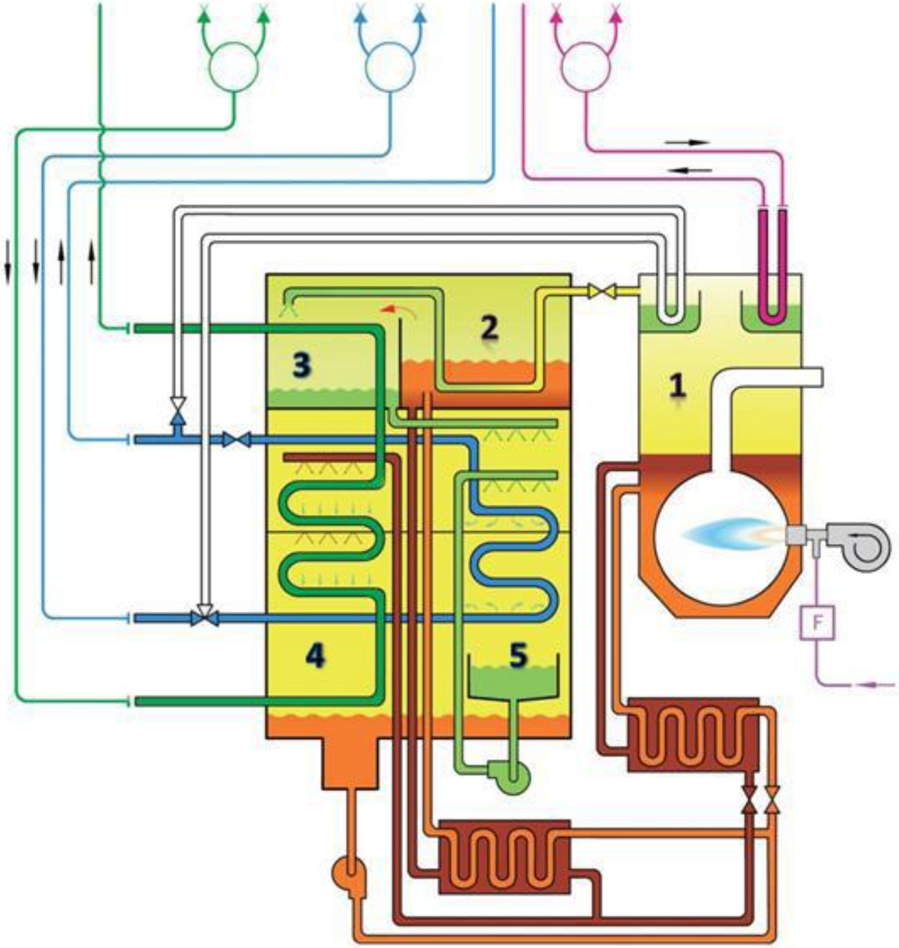


Figure 84. U-Tube Collector Efficiency (DNI)


1
2
3
4
5
F

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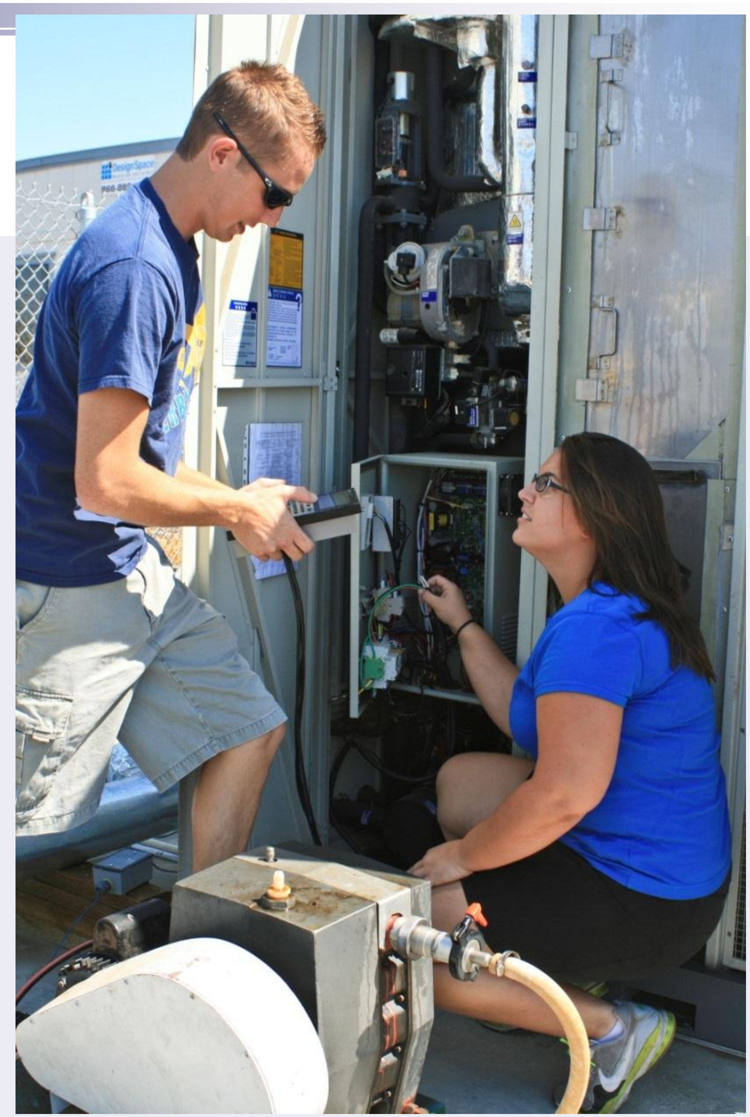
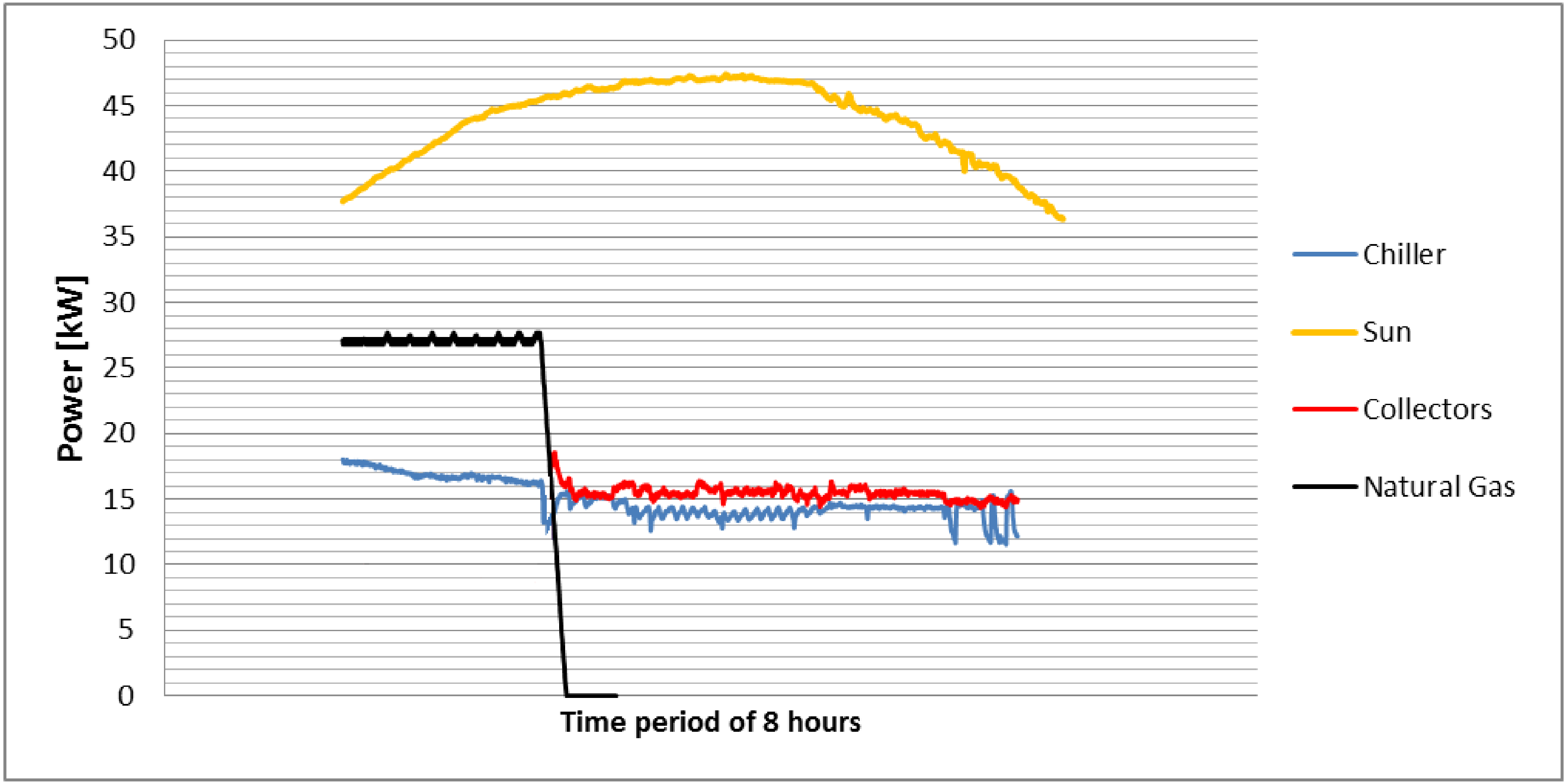
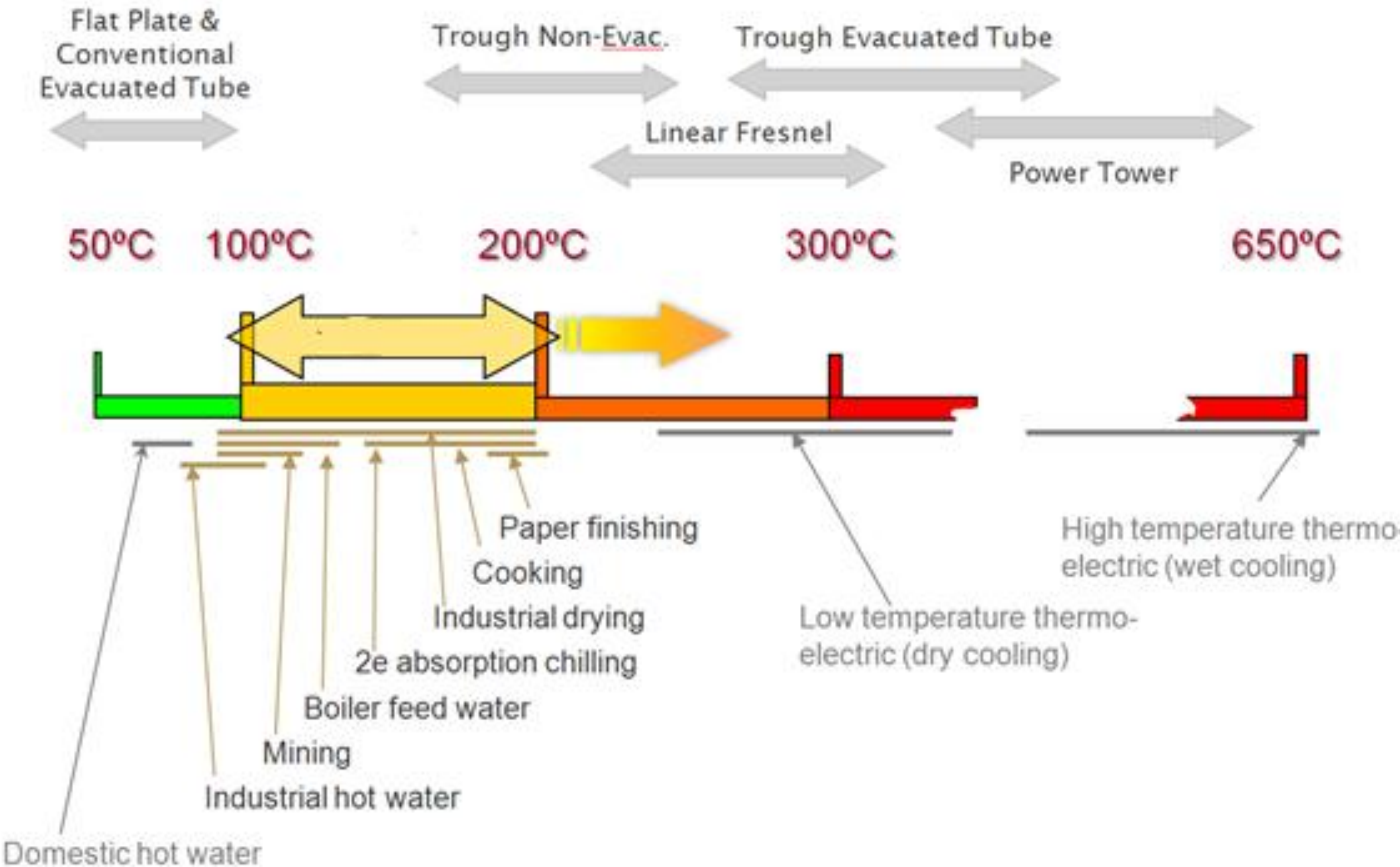
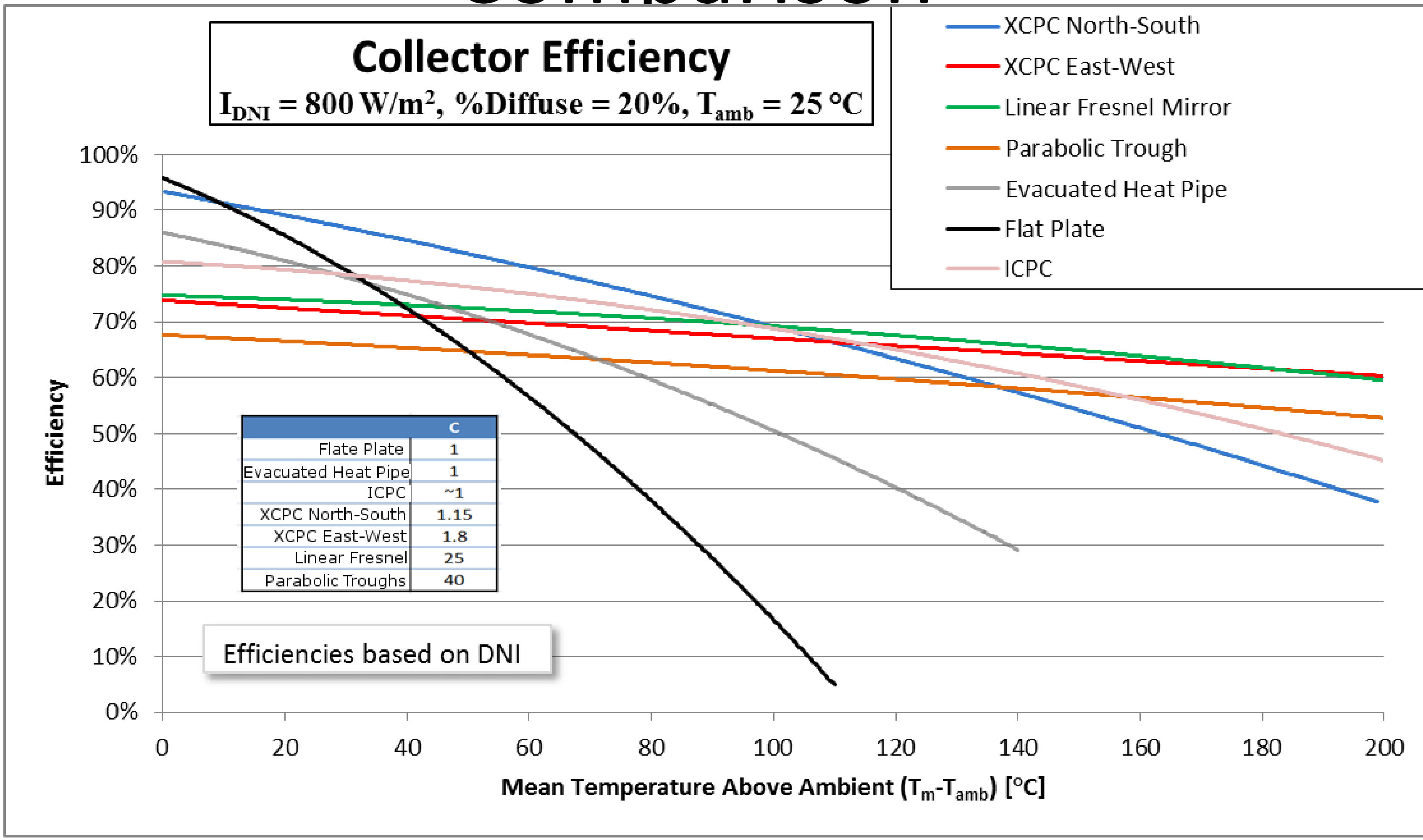


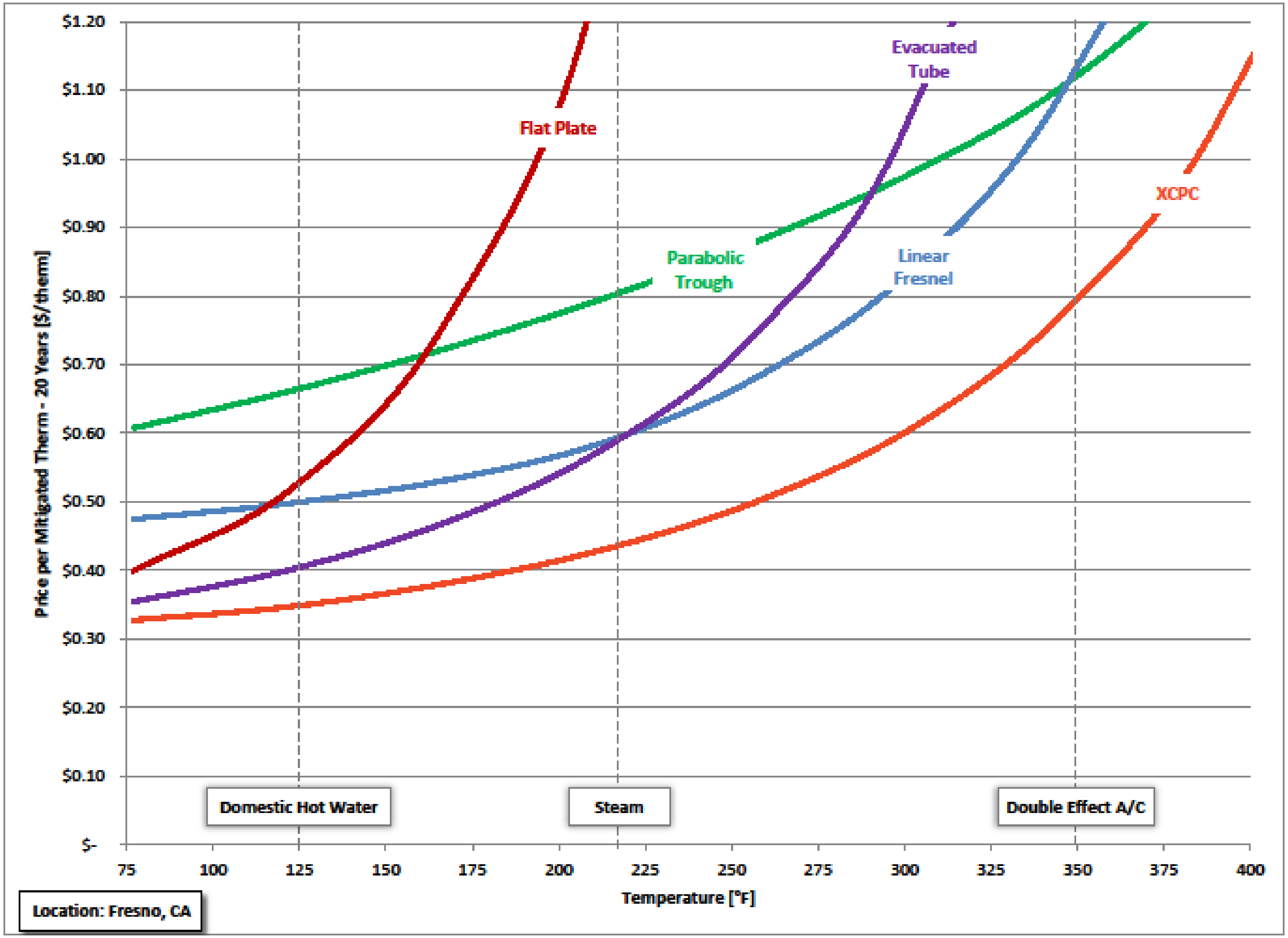
Power Output of the Solar Cooling System




Flat Plate & Conventional Evacuated Tube
Trough Non-Evac.
Trough Evacuated Tube
Linear Fresnel
Power Tower
50ºC
100ºC
200ºC
300ºC
650ºC
Paper finishing
Cooking
Industrial drying
2e absorption chilling
Boiler feed water
Mining
Industrial hot water
Domestic hot water
High temperature thermo-electric (wet cooling)
Low temperature thermo-electric (dry cooling)

Comparison


Collector Efficiency
I_{DNI} = 800 W/m², %Diffuse = 20%, T_{amb} = 25 °C
XCPC North-South
XCPC East-West
Linear Fresnel Mirror
Parabolic Trough
Evacuated Heat Pipe
Flat Plate
ICPC
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Efficiency
C
Flate Plate 1
Evacuated Heat Pipe 1
ICPC ~1
XCPC North-South 1.15
XCPC East-West 1.8
Linear Fresnel 25
Parabolic Troughs 40
Efficiencies based on DNI
0
20
40
60
80
100
120
140
160
180
200
Mean Temperature Above Ambient (T_m-T_{amb}) [°C]



$1.20
$1.10
$1.00
$0.90
$0.80
$0.70
$0.60
$0.50
$0.40
$0.30
$0.20
$0.10
$-
Price per Mitigated Therm - 20 Years [$/therm]
75
100
125
150
175
200
225
250
275
300
325
350
375
400
Temperature [°F]
Flat Plate
Evacuated Tube
Parabolic Trough
Linear Fresnel
XCPC
Domestic Hot Water
Steam
Double Effect A/C
Location: Fresno, CA

XCPC Applications

- **Absorption Chillers**
- Adsorption Chillers
- Desiccant Cooling
- Heat Driven Electrical Power Generation
- Steam Cycle Based Products
- Stirling Cycle Based Products
- Heat Driven Water
- Membrane Distillation
- Heat Driven Industrial Process

- Technology feasibility
- Economic Competitiveness
- Market Potential
- Time to

The *Best Use* of our Sun

b2u Solar

Delivering BTUs from the Sun

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Demonstrated Performance

Conceptual Testing
SolFocus & UC Merced

10kW Array Gas Technology Institute

10kW test loop NASA/AMES

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