Renewable Solar-thermal Production Of Fuels from Biomass

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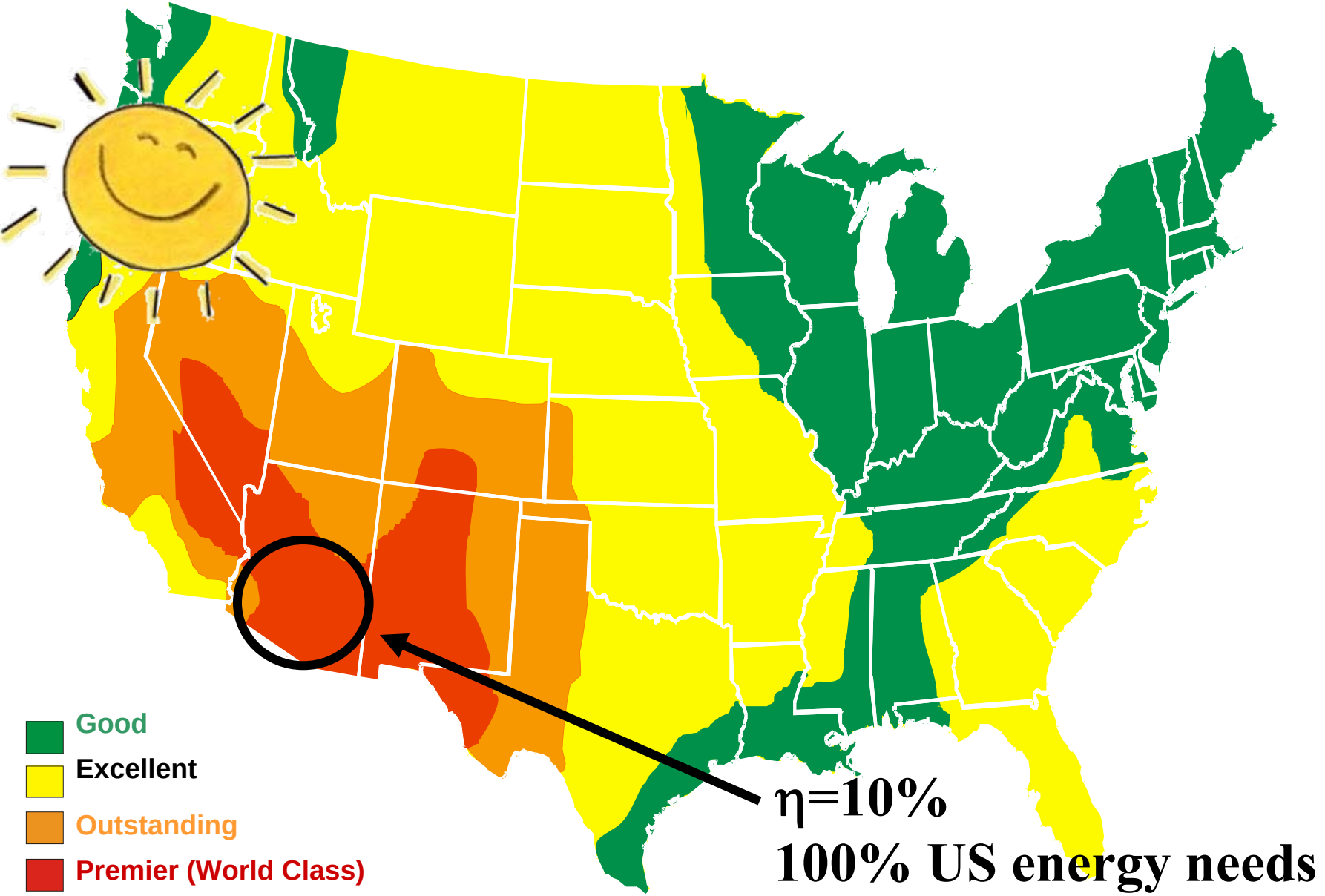
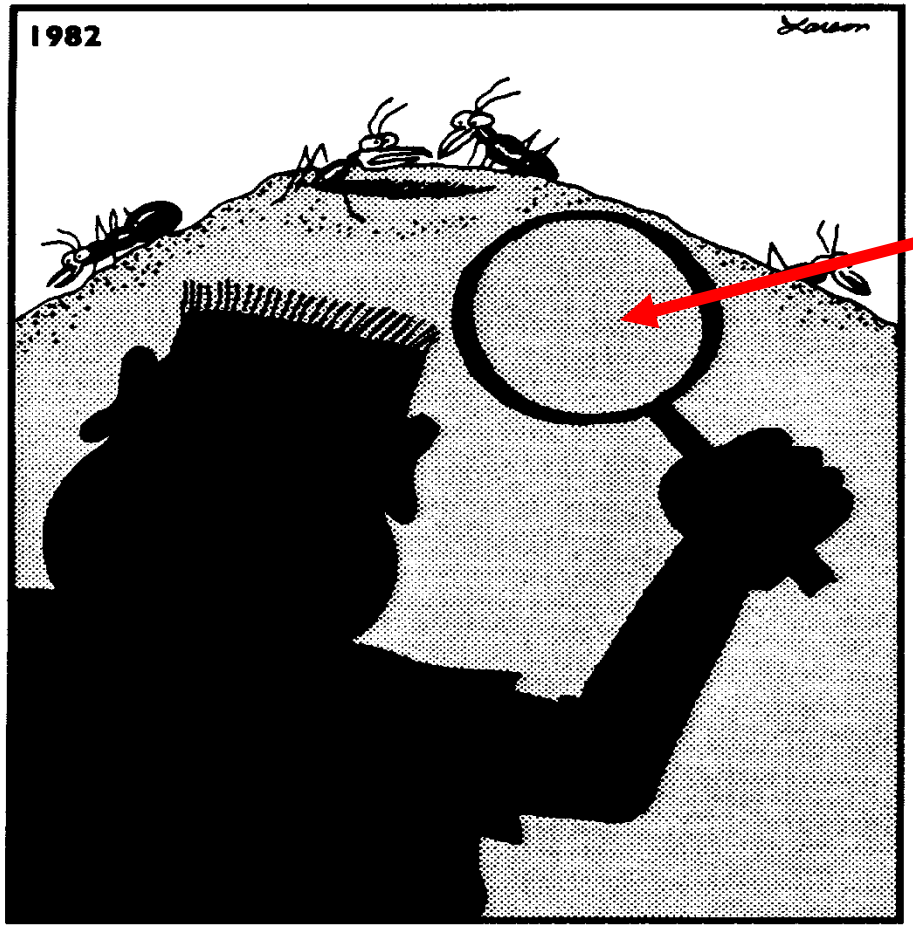
Carbon Recycling Meeting, Phoenix, AZ (June 18, 2008)

Simple Solar-thermal Thermodynamics

World Class Direct Resource in U.S.



Concentrated sunlight will **directly** drive chemical reactions at fast rates



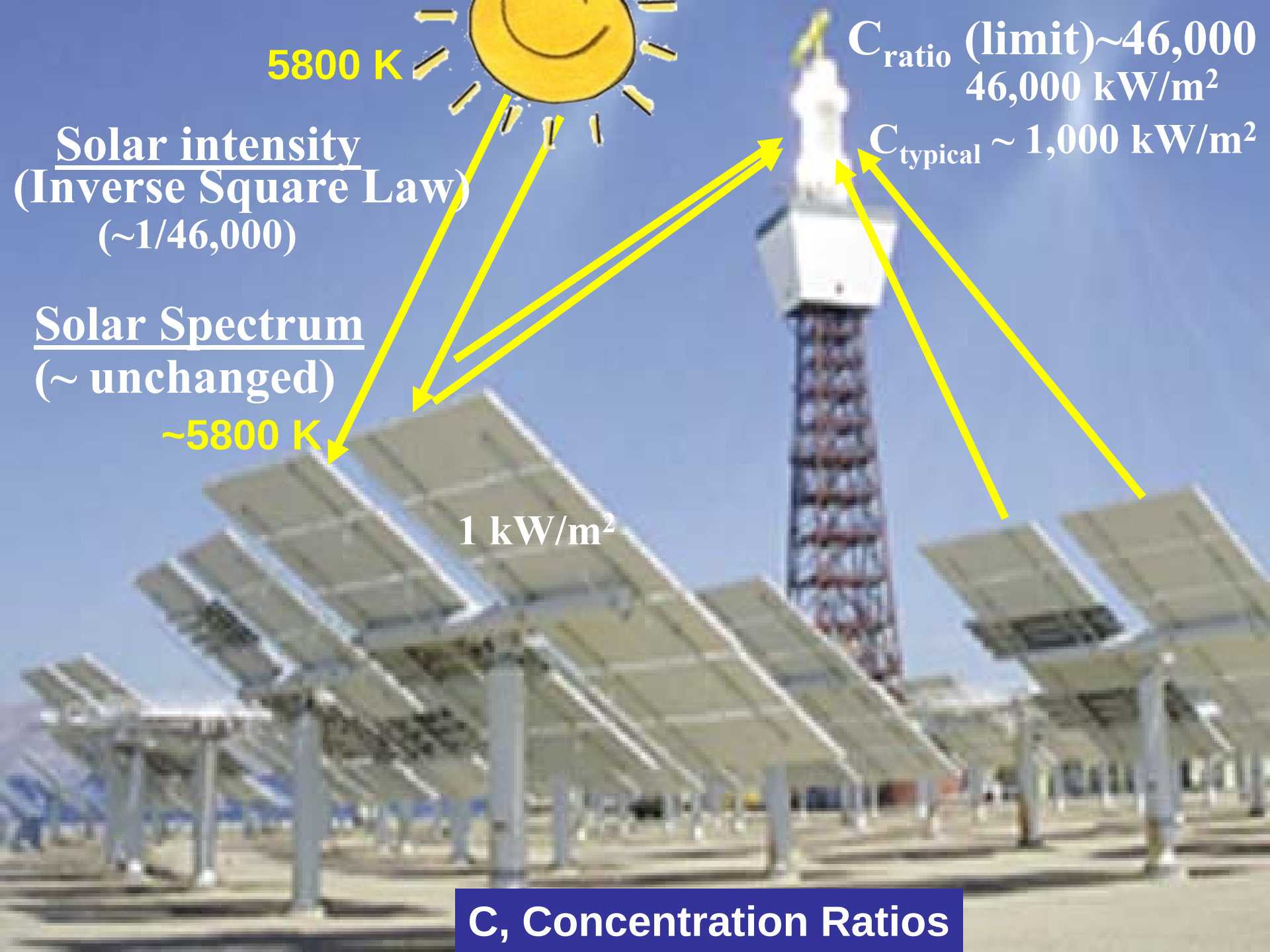
"Say … now *I'm* starting to feel kinda warm!"

5800 K Black Body

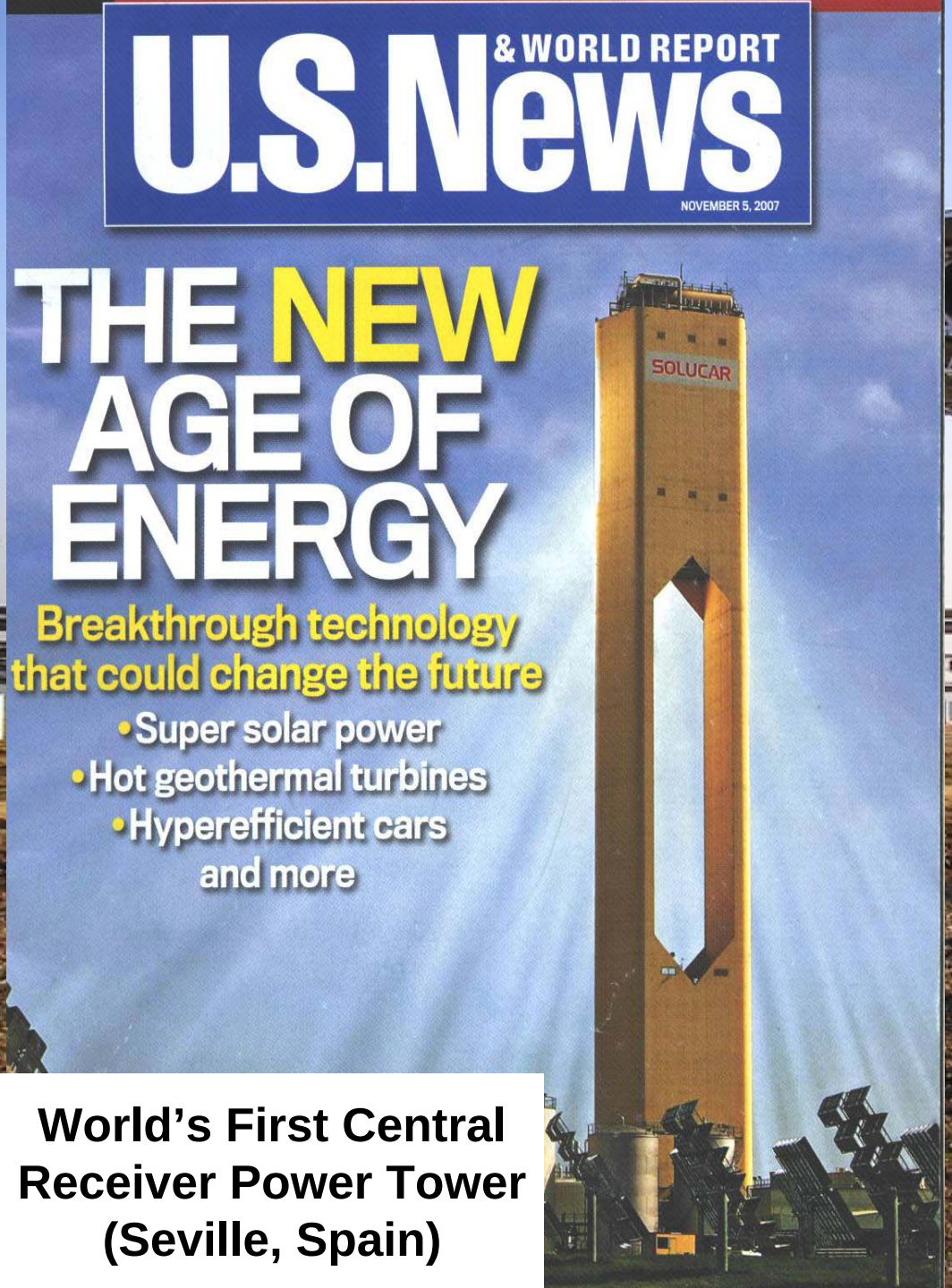
Fossil fuels + air ➔ 2300 K (max)
Nuclear fuels ➔ 1300 K (max)

30 to 50% efficiency loss

Electricity



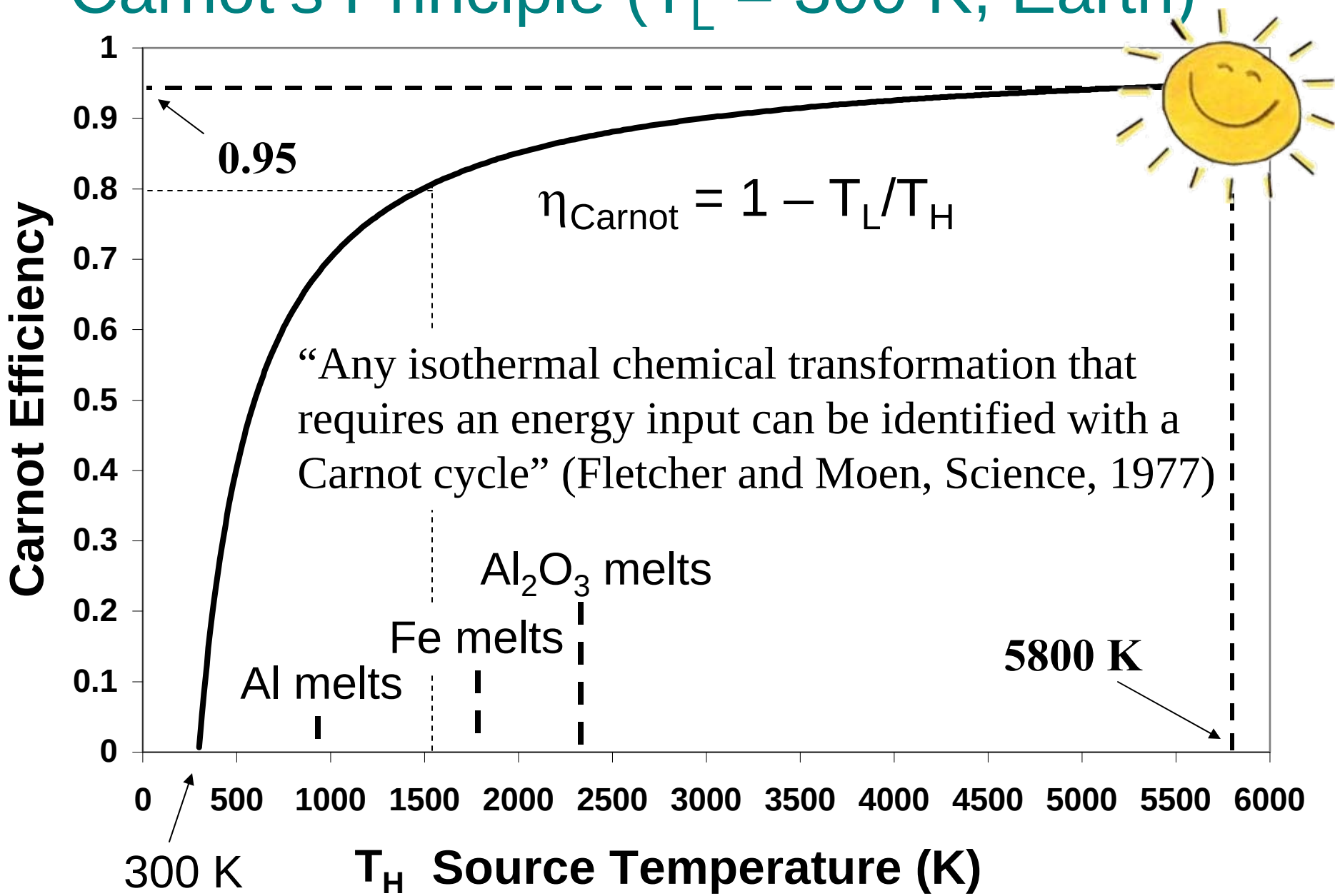
C, Concentration Ratios



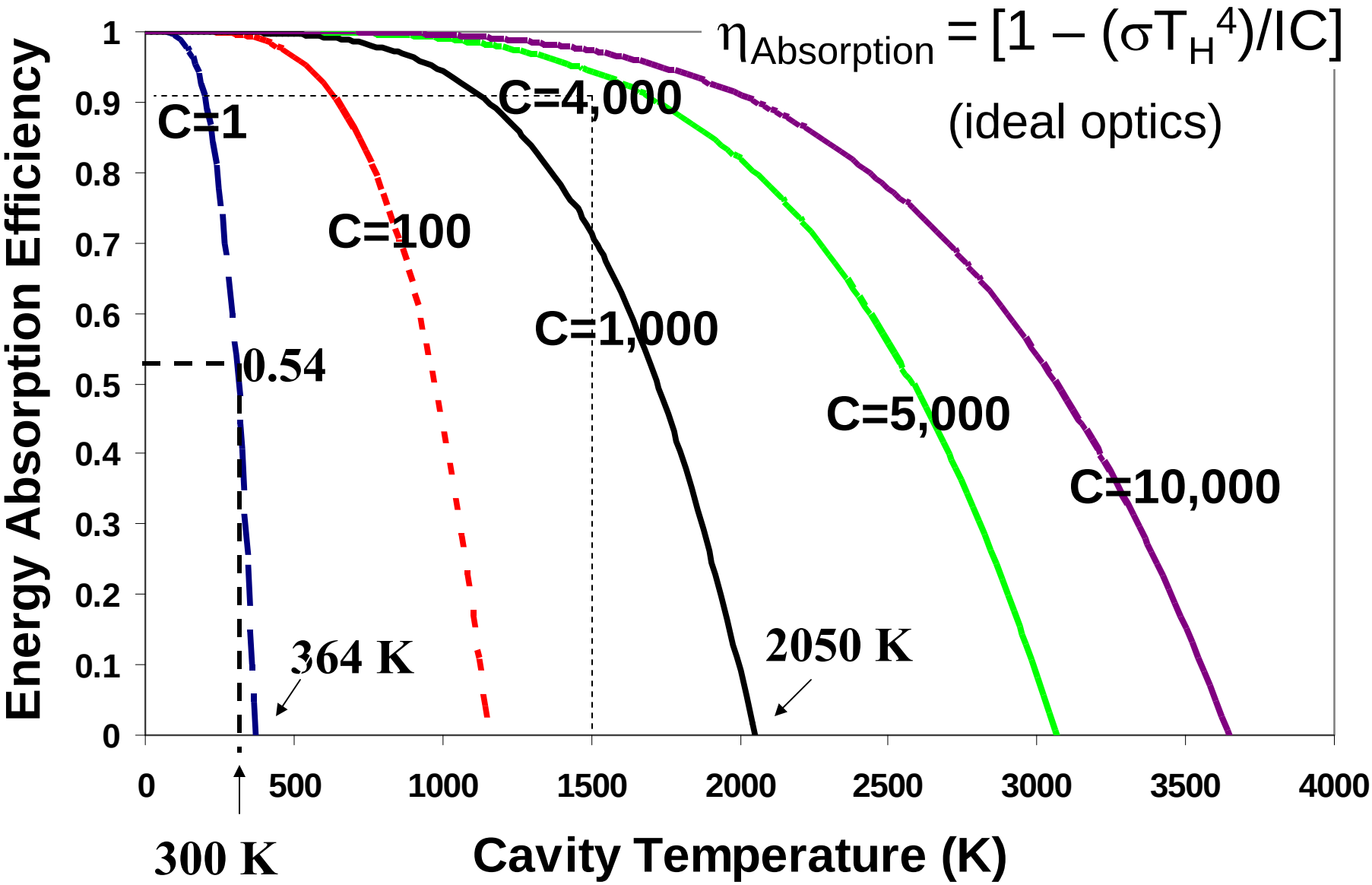
World's First Central Receiver Power Tower (Seville, Spain)

PS 10 Commercial Solar-thermal Facility (Seville, Spain)

Carnot's Principle (T_L = 300 K, Earth)



Energy Absorption Efficiency of a Black Body Cavity with its T at Various Solar Concentration Ratios



Ideal System Efficiency of a Process

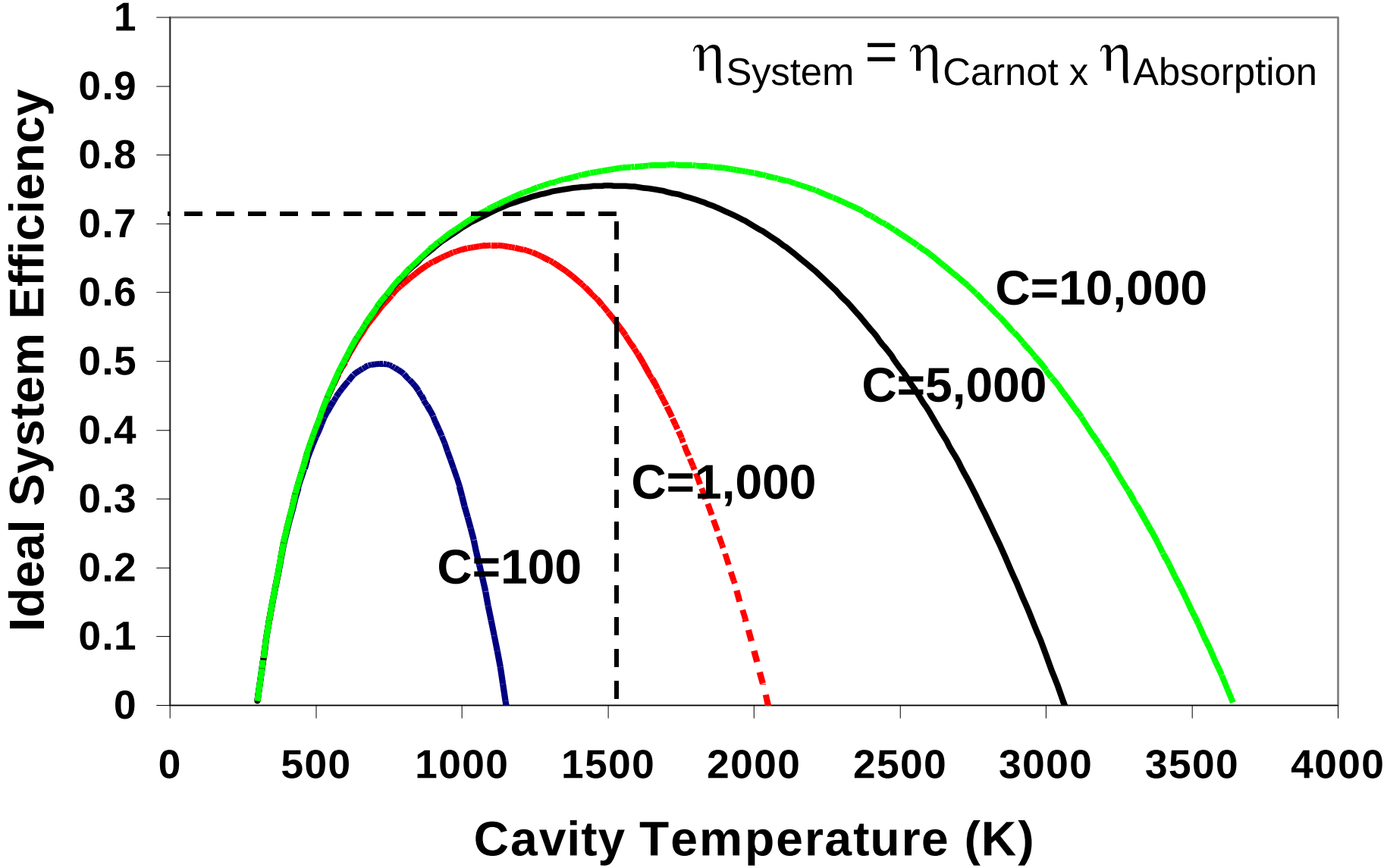
$$\eta_S = \eta_{Carnot} \bullet \eta_{Ideal\ Energy\ Absorption\ (Collection)}$$

Monotonically ↑ as T_H ↑

Monotonically ↓ as T_H ↑

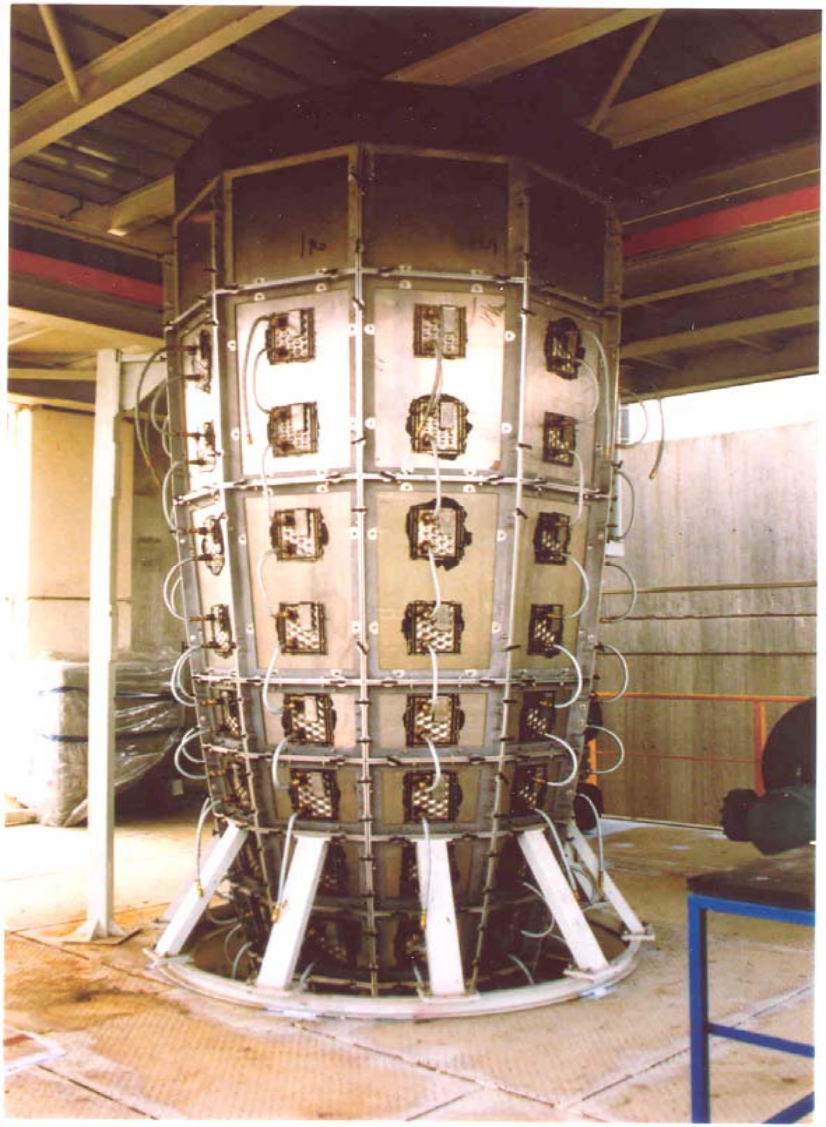
Fletcher and Moen, *Science* (1977)

Ideal System Efficiency of a Process with Cavity Temperature at Various Solar Concentration Ratios

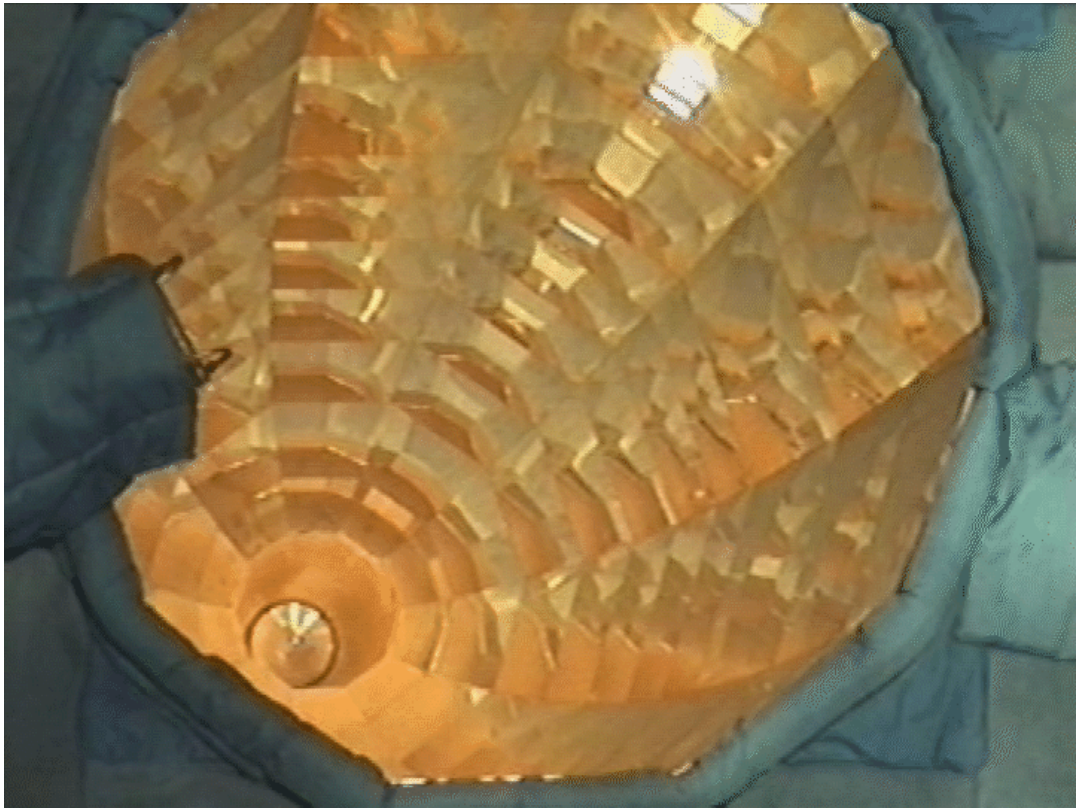


Heliostat/Dish-driven Solar Furnace-CNRS, Odeillo, France

Large Secondary Concentrator Technology for C=5,000 +



outside



inside

Weizmann Institute, Rehovot, Israel (beamdown secondary)

Solar-thermal/Biomass Conversion Interface

Significant Innovation is often Realized at the Interface of Technologies

Concentrated Solar Power

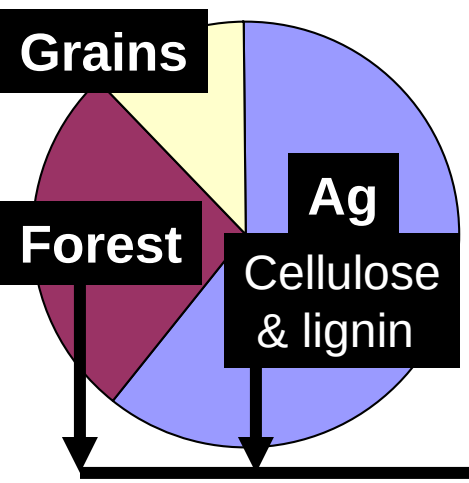
Biomass

<u>Near Zero Carbon Footprint</u> – 100% of the conversion energy comes from the sun

Solar-thermal Rationale (renewable thermochemical "sledgehammer")

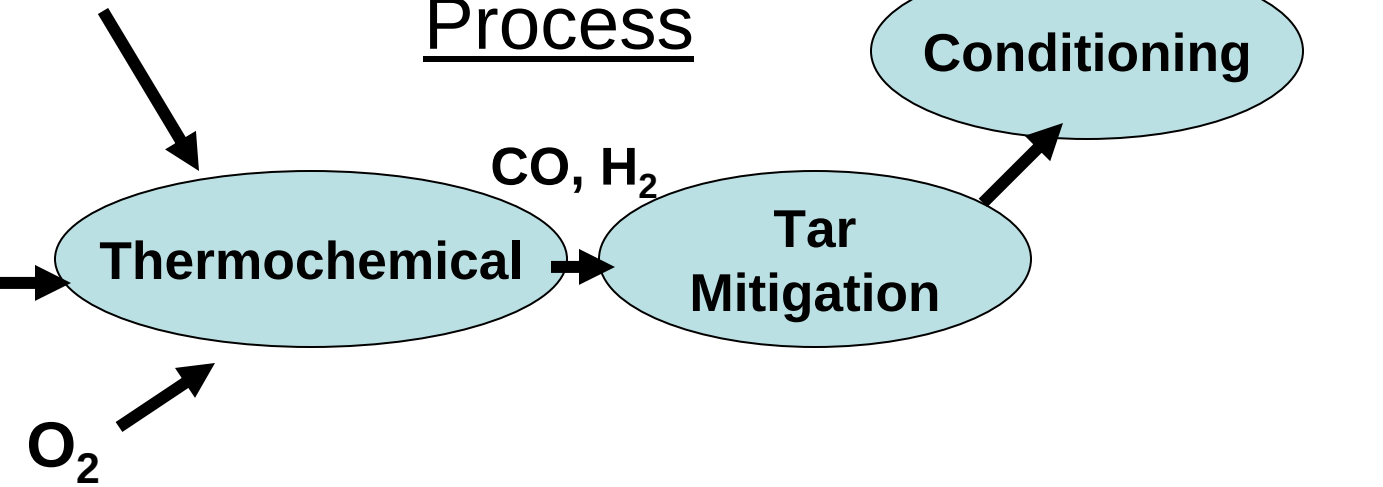
Solar option

- > 90% yield to products
- No oxygen plant
- No tars, reduced gas cleanup



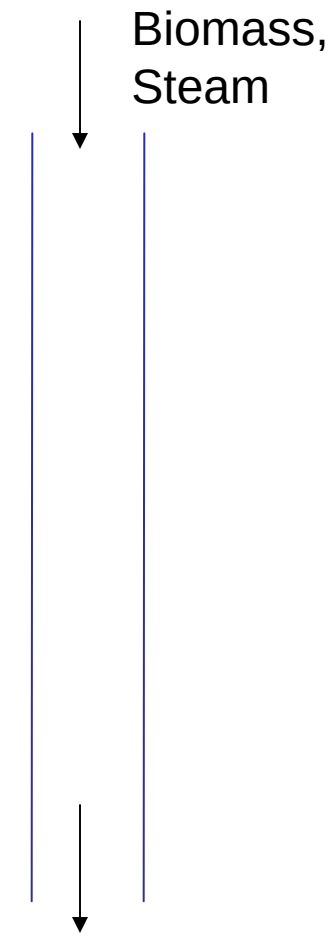
Low Carbohydrates

Conventional Thermochemical Process



Off-sun Preliminary Experiments

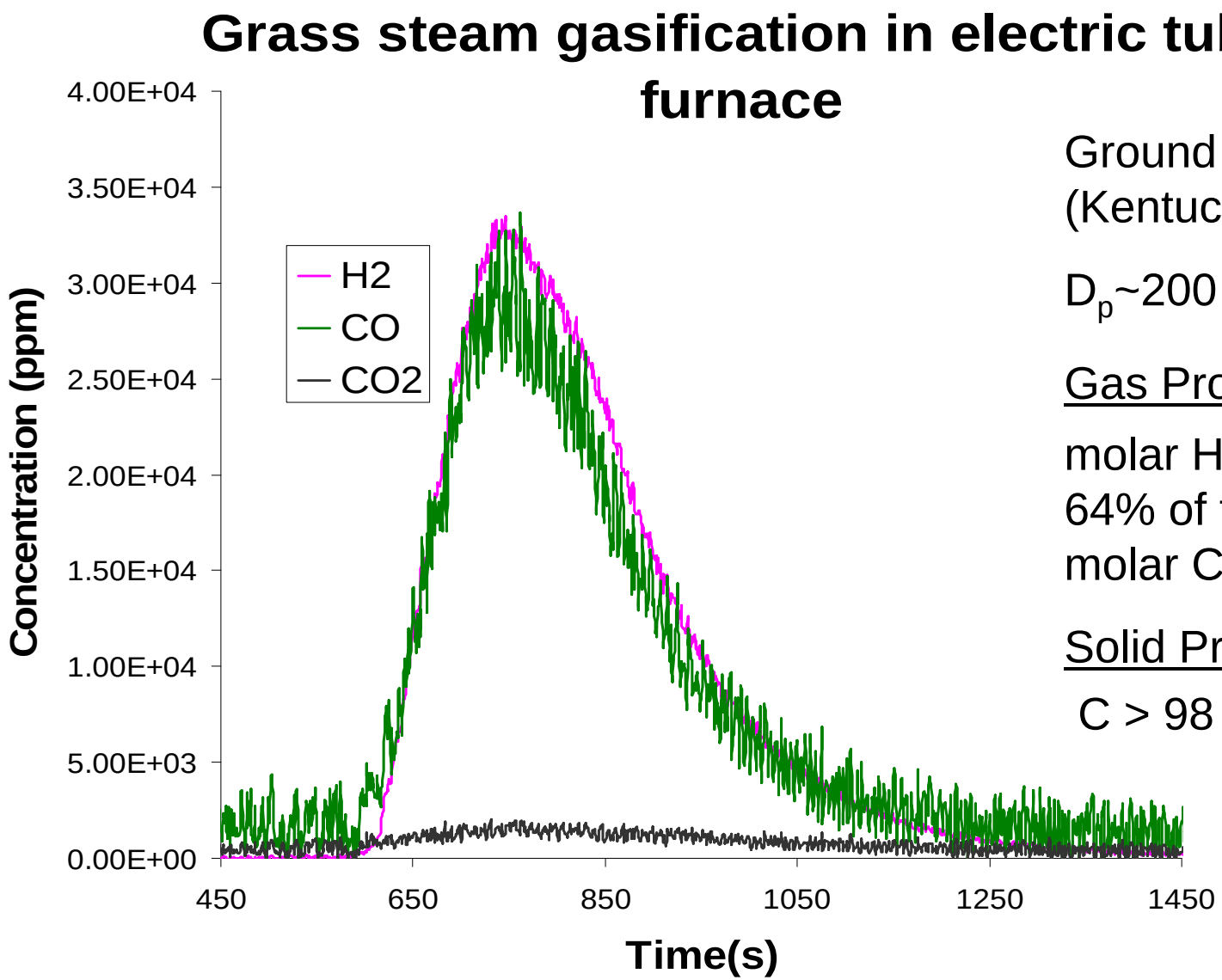
Transport Tube Reactor (alumina)



Transport Tube Reactor (quartz)

Mass Spectrometer Trace (1177°C; t_r~1 s)

98% conversion to products



Ground *Poa pratensis* (Kentucky Bluegrass)

D_p~200 μm

<u>Gas Product</u>

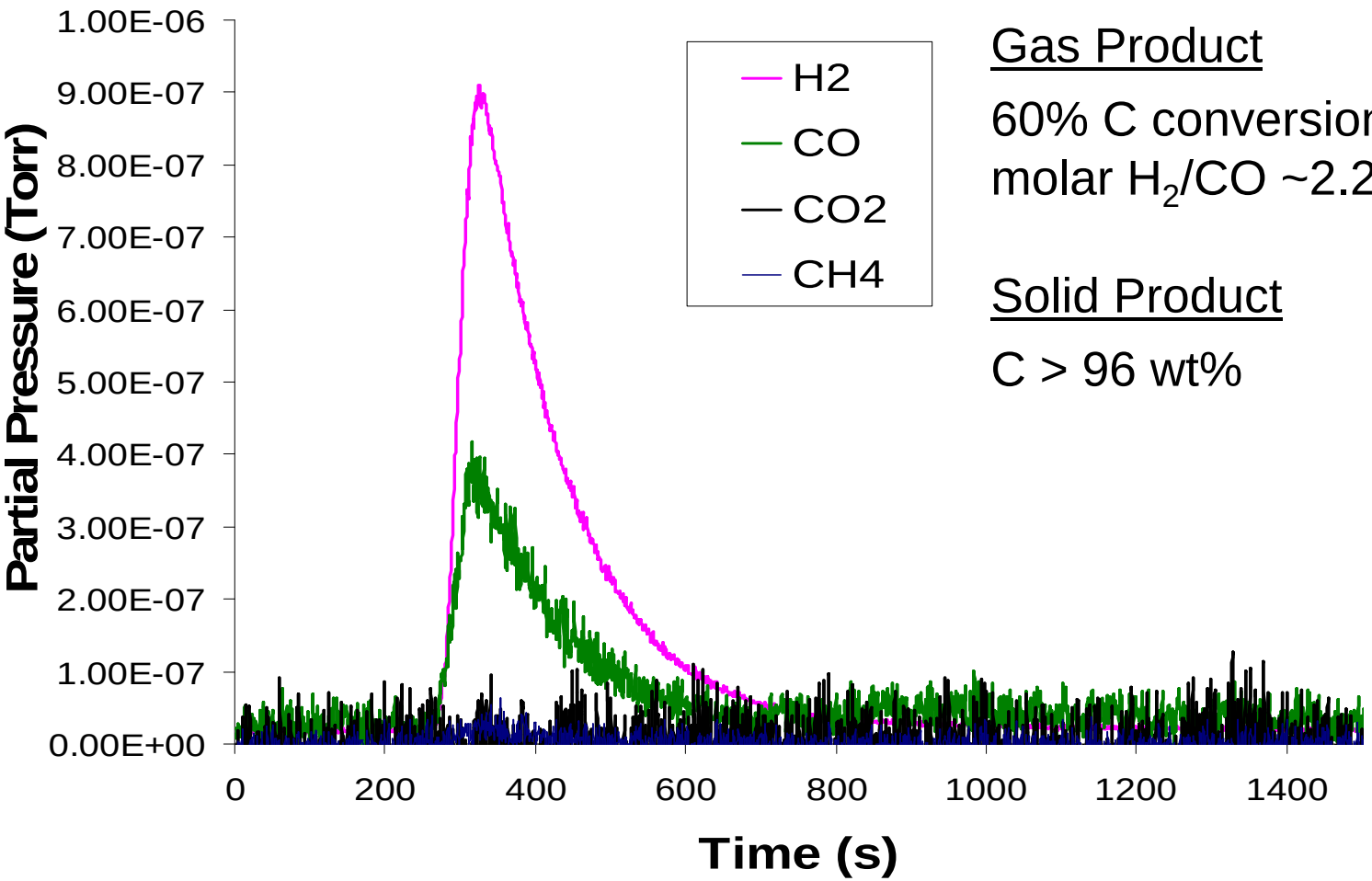
molar H_2/CO ~ 1:1
64% of feed C to CO
molar CO/CO2 ~ 10:1

<u>Solid Product</u>

C > 98 wt%

Mass Spectrometer Trace (1177°C; t_r~2 s)

Lignin pyrolysis in electric tube furnace



Gas Product

60% C conversion to CO/CO_2

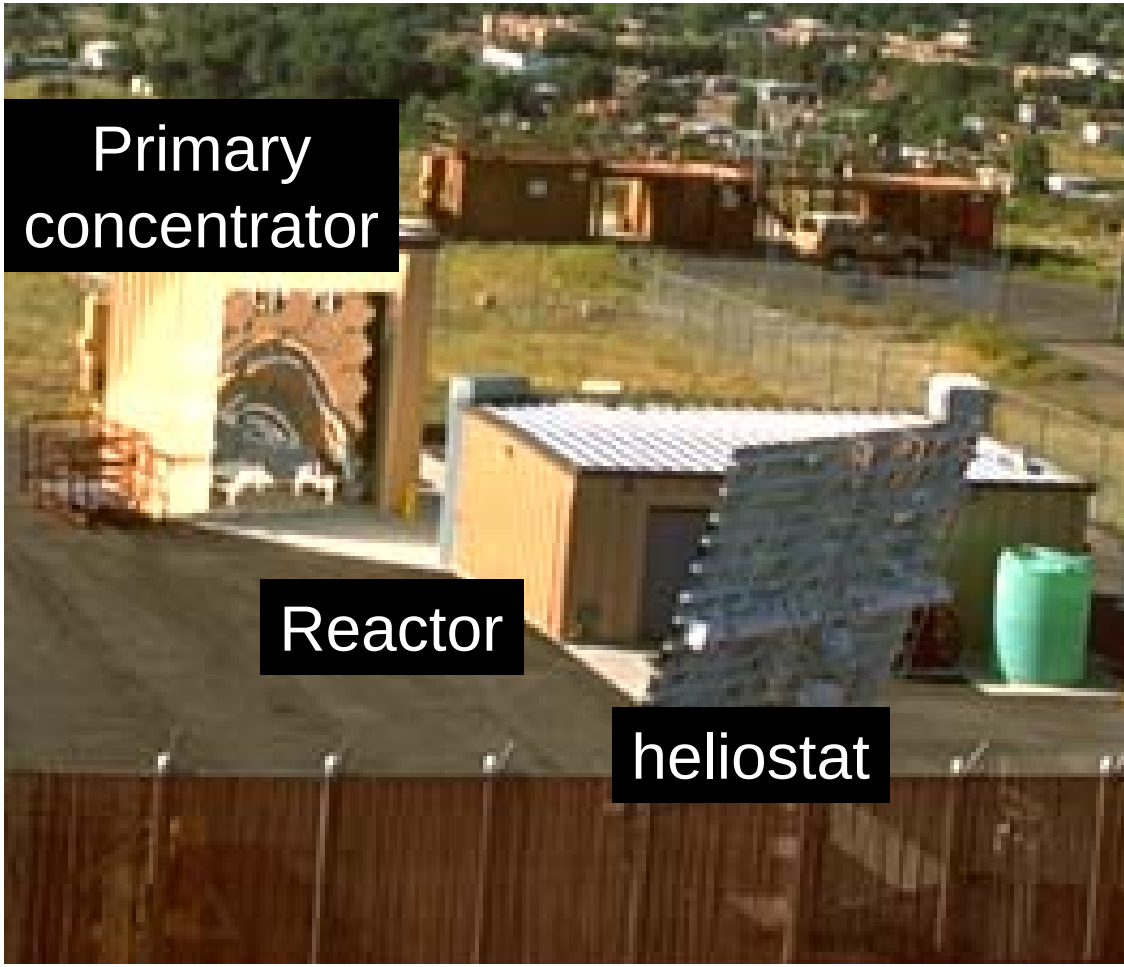
molar H_2/CO ~2.2:1

Solid Product

C > 96 wt%

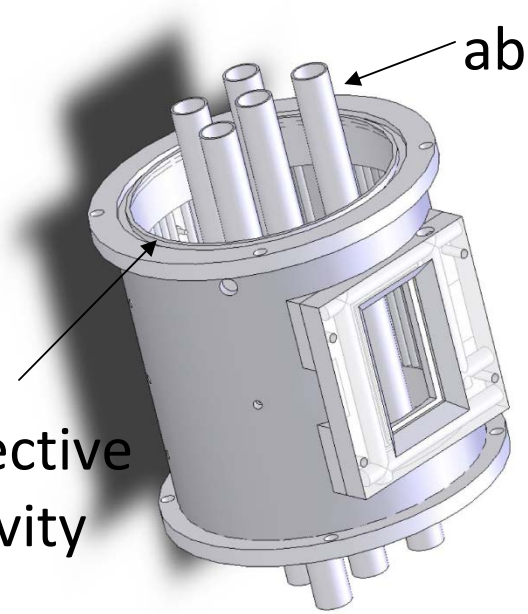
Reduction to Practice
(10 kW Solar Furnace at NREL)

Reactor on-sun



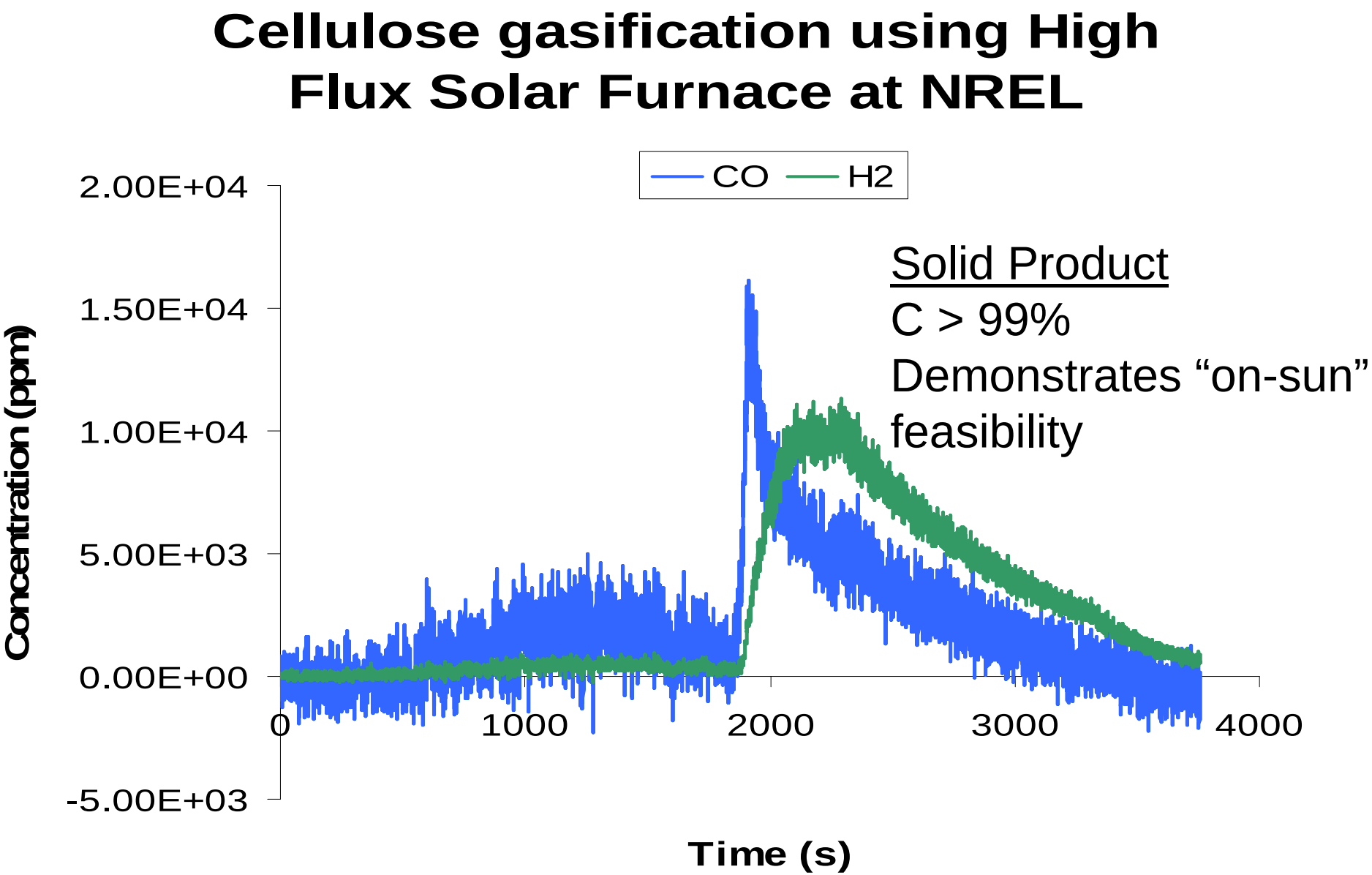
Pilot Solar Reactor to Syngas

Technology Innovation: SurroundSun Receiver – 10 kW

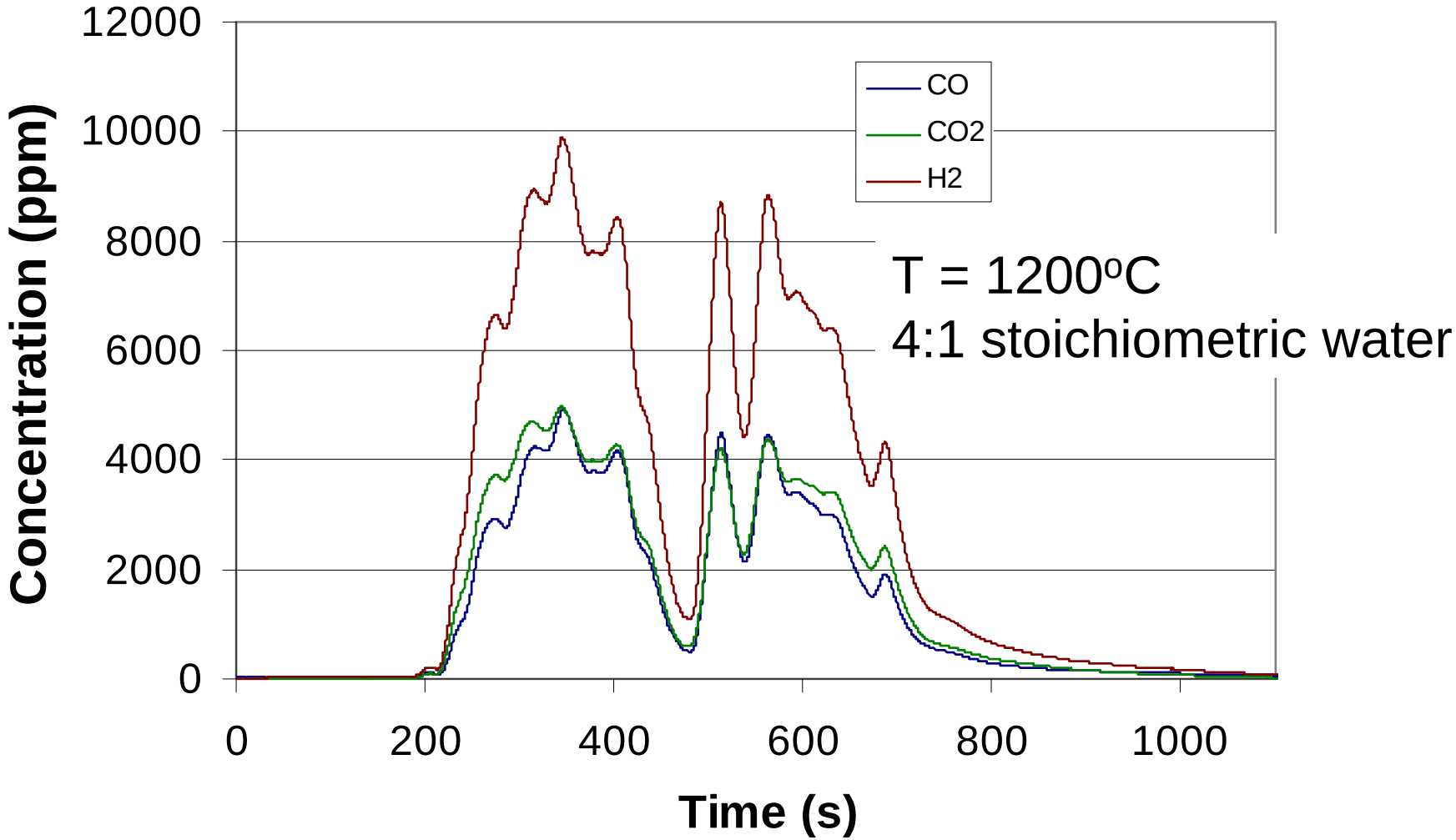


Enables high efficiency operation with standard materials and scalable systems

Mass Spectrometer Trace (1200°C; t_r ~ 0.5s)

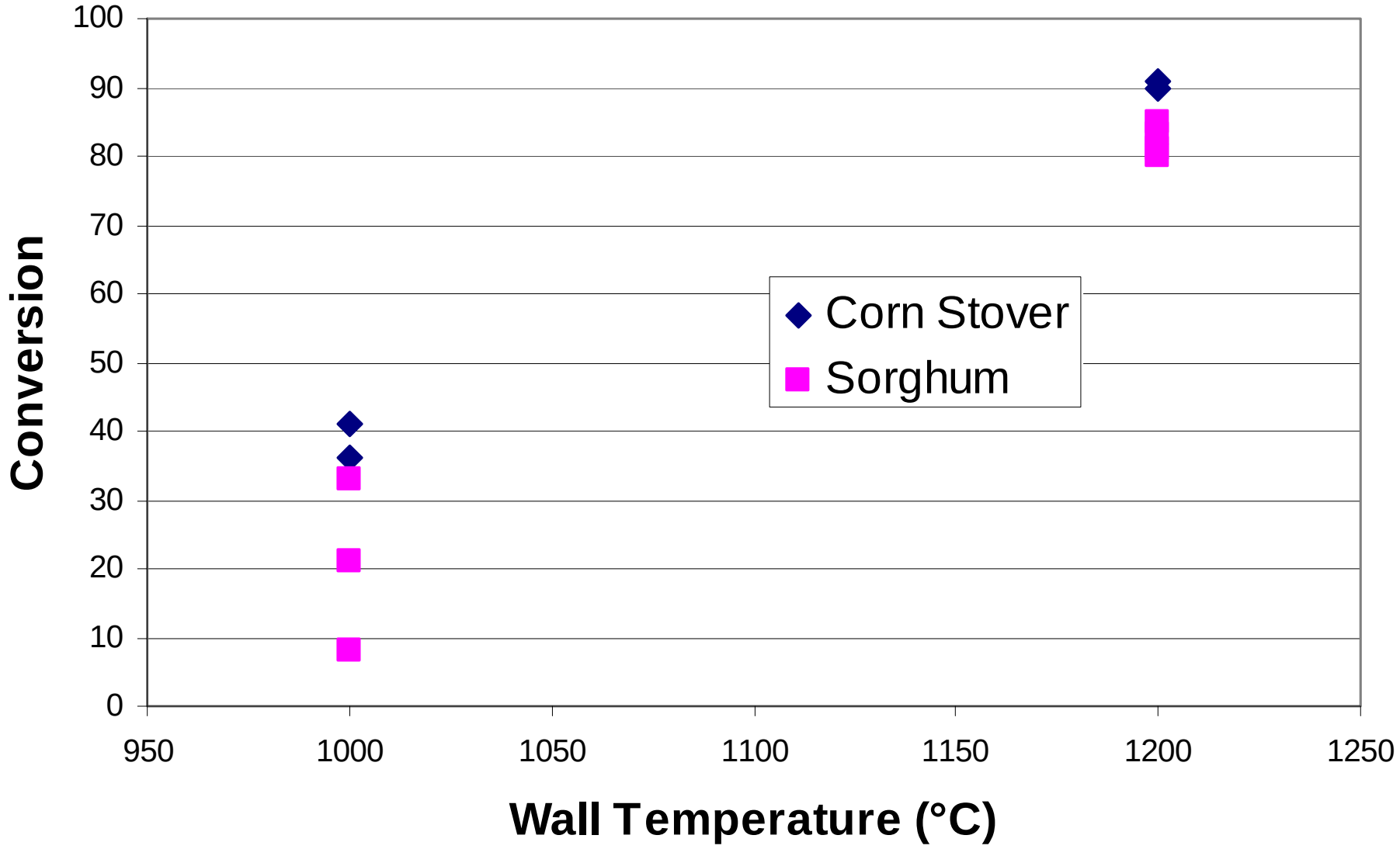


Representative Gas Trace

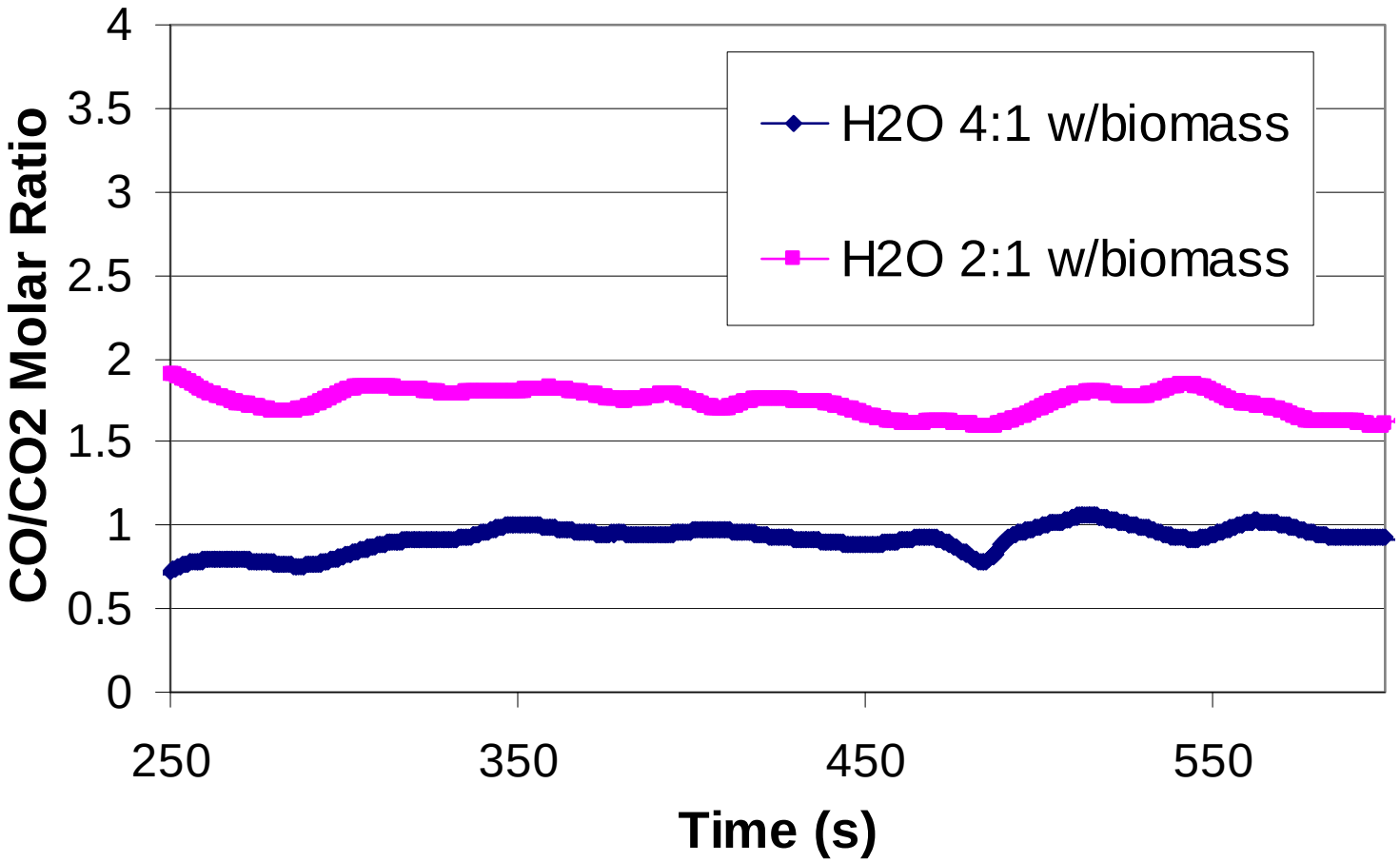


No significant amounts of higher hydrocarbons seen

Initial results – conversion (t < 1 s)

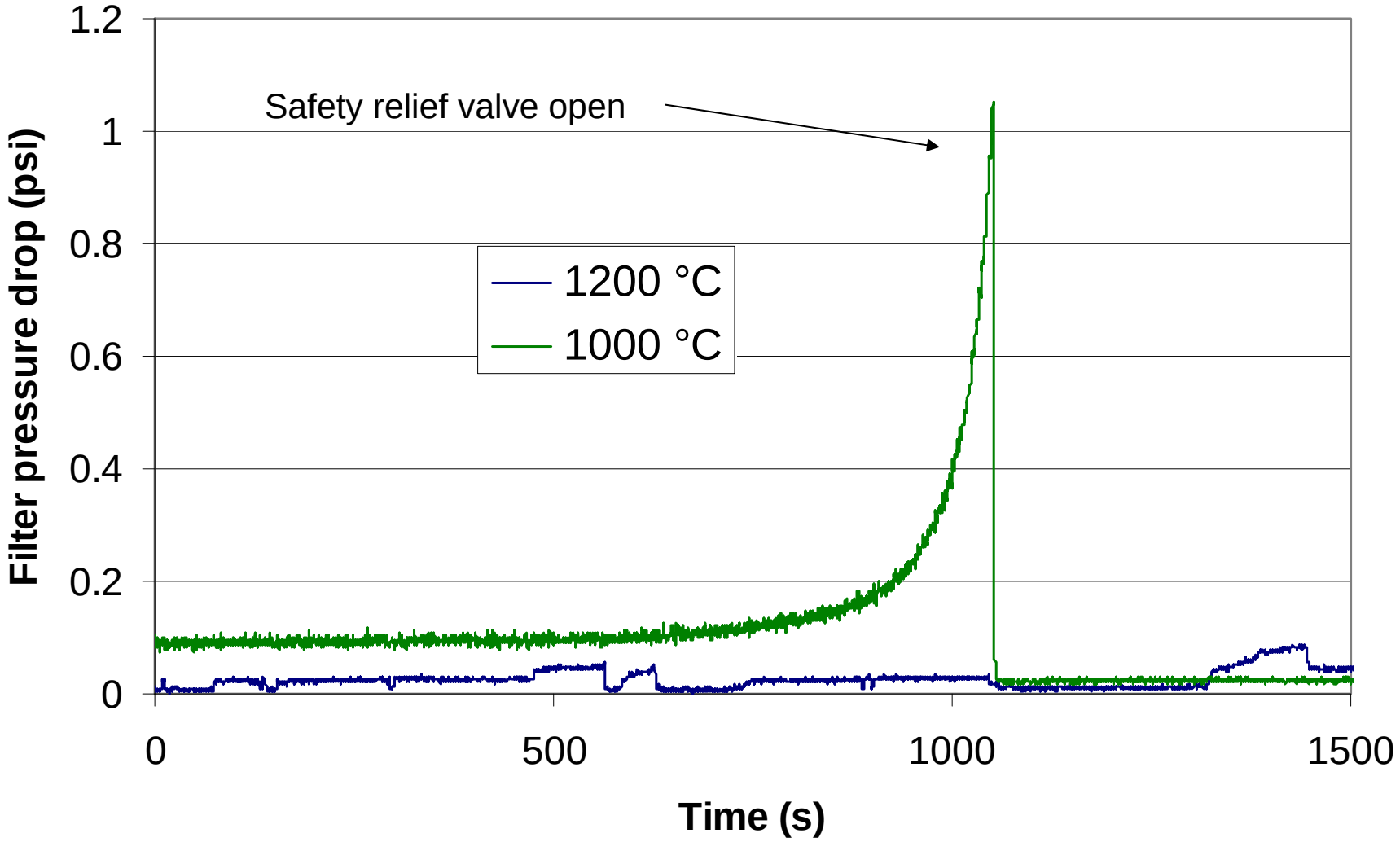


Excellent CO/CO_2 tunability ($t < 1$ s)



(Feedstock Flexible)

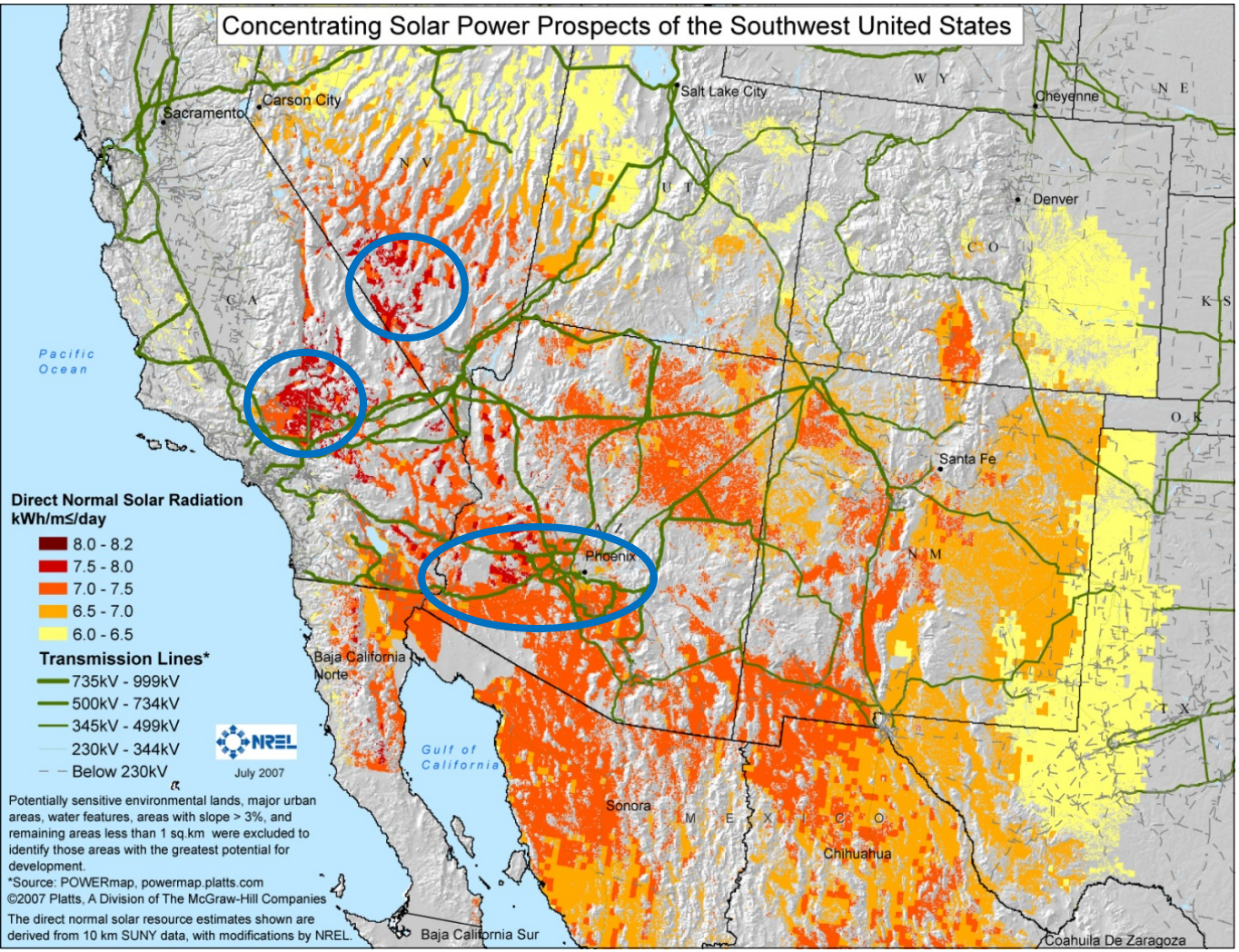
Better selectivity at high T (no tars)



Corn stover – Low temperatures lead to tar deposition and pressure rise

Biomass/Water Availability in High Sun Regions

Locations of operation near biomass production



- Good solar resources
- Accessible biomass ?
- Proximity to distribution pipelines
- Likely candidates:
  - -Hawaii
  - -Barstow, CA
  - -Las Vegas, NV
  - -Phoenix, AZ

Arizona Public Service Algae Farm

35.8 kg dry, ash free algae/m^2/yr (2-4% CO_2; 24-35^oC)

Composition of Dry Micro Algae

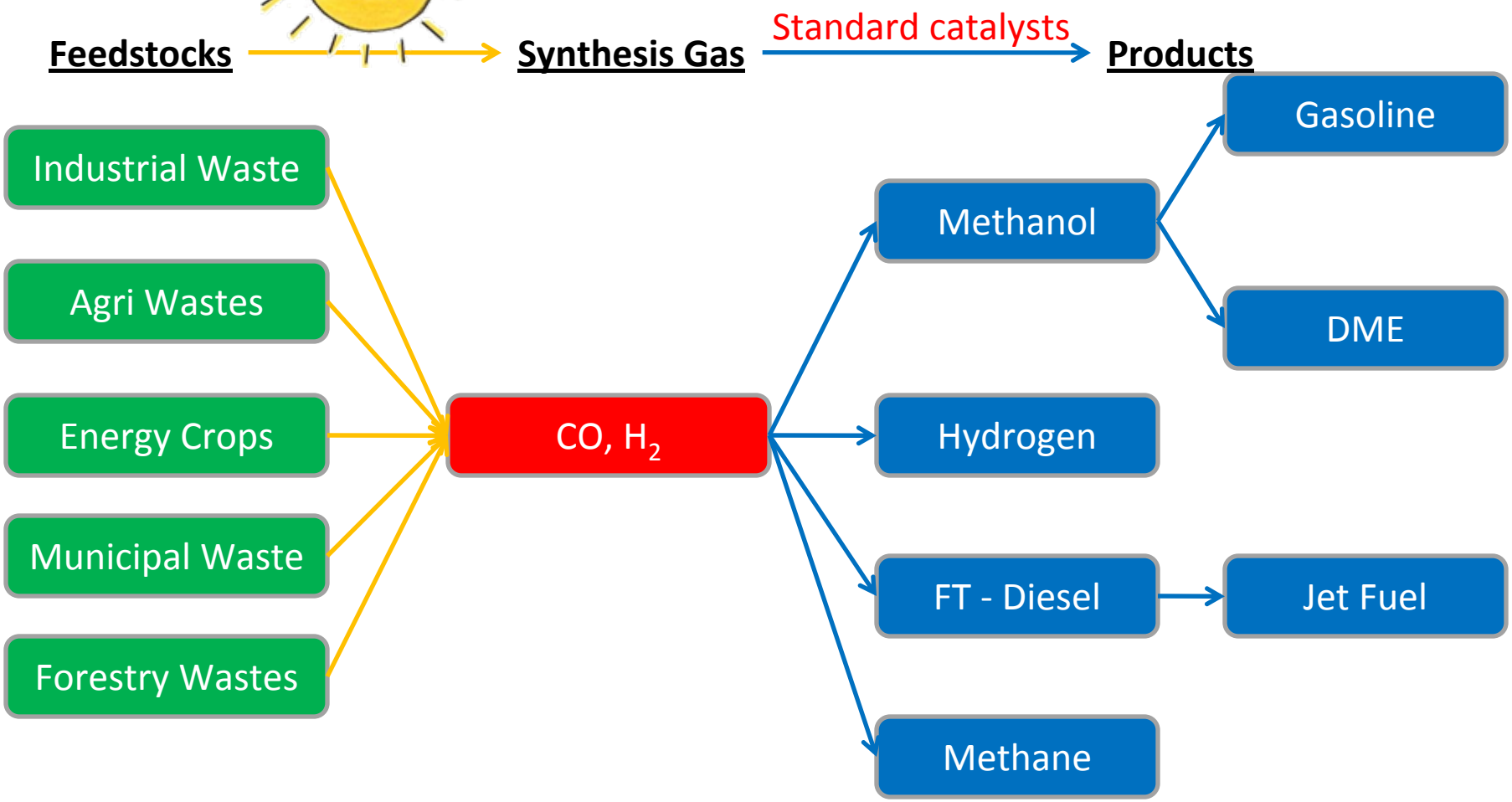
	Micro Algae			Coal
	Spirulina	Chlorella	Littorale	Illininois No. 6
C:	46.1	47.3	35.5	79.7
H:	7.4	7.2	5.4	5.4
O:	41.4	37.6	53.1	10.3
N:	4.8	8.2	6.0	1.4
S:	0.4	0.7	~0	3.3

Ikenaga, N. et al., Energy & Fuels, 15, 350-355 (2001)

Solar-thermal need is for fast growing carbon, lipids not needed; can process before, or post- lipids extraction remains; need not be totally dried

Gateway to Renewable Gasoline is through Methanol

Synthesis gas – an ideal intermediate



Flexible syngas can respond quickly to market opportunities

Biomass to Gasoline ➔ Net Water Producer (100 kg Methanol Basis)

133 kg Corn Stover (C.S) [61.2% cellulose, 28.8% lignin, 10% ash]
21 kg Water
(MW C.S ~ 322 g/mol, incl. ash)

CO_2, ash

Syngas
(H_2/CO=2/1)

100 kg Methanol

56 kg H_2O
44 kg Hydrocarbons
(i.e. gasoline)

<u>Assumptions</u>

95% biomass conversion
4 kg C.S. / gal CH_3OH
0.189 gal H_2O/gal CH_3OH (via C.S)
1 mol C.S ➔ 7.9 mol syngas (H_2/CO=2/1)
1399 kJ/mol (rxn) + 546 kJ/mol enthalpy

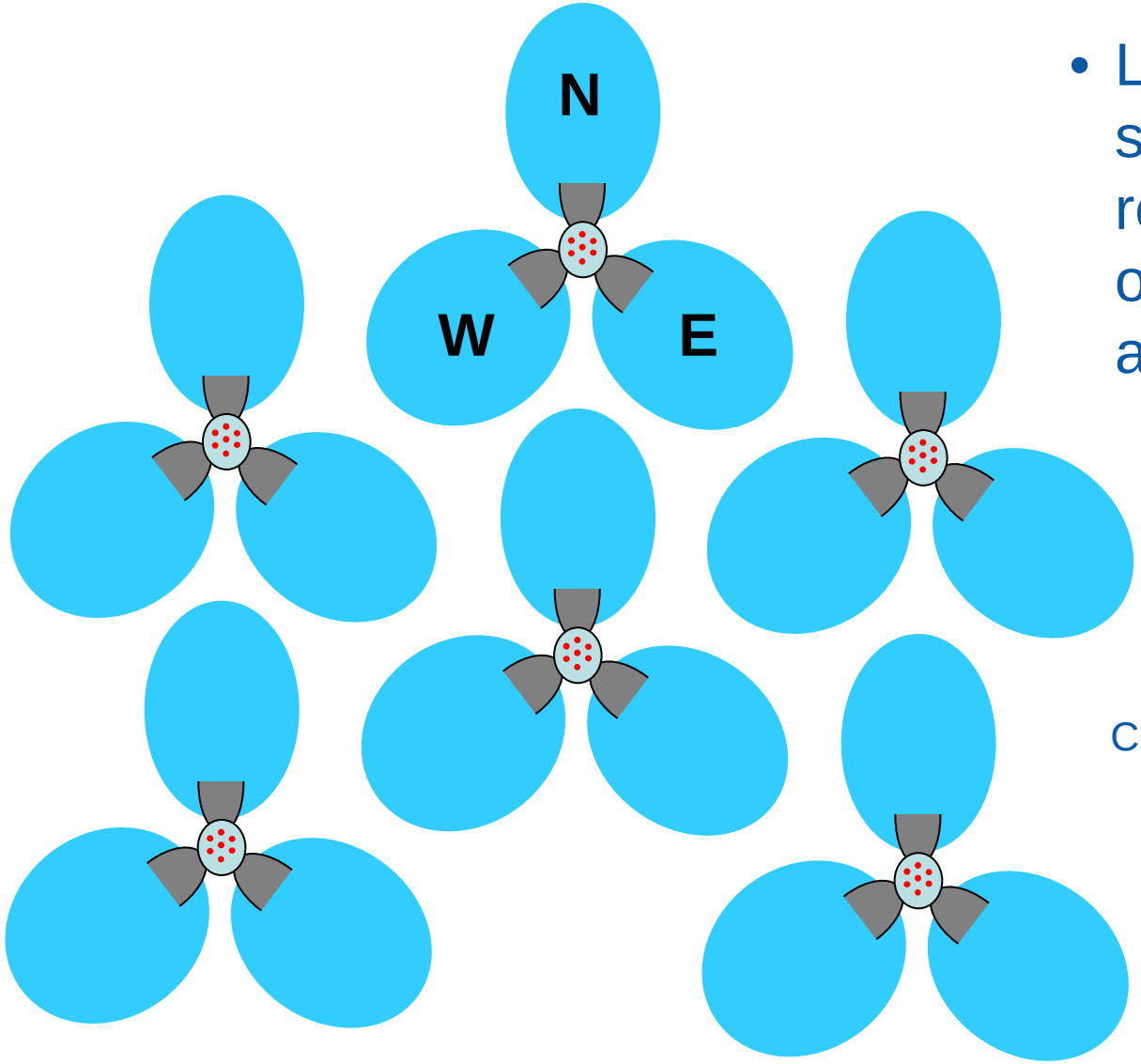
Gasoline from Solar-thermal Conversion of Micro Algae

Greenfuel Technologies/APS: 35.8 kg algae/m^2-yr (dry, ash free)

(35.8 kg algae/m^2-yr)(0.473 kg C/kg algae)
x(1 kg methanol/0.375 kg C)
x (1 gal methanol/3.0136 kg methanol)
x (gal gasoline equiv./1.74 gal methanol)
= 8.61 gge/m^2-yr

= 34,851 gge/acre-yr
(= 25,049 actual gallons gasoline/acre-yr)

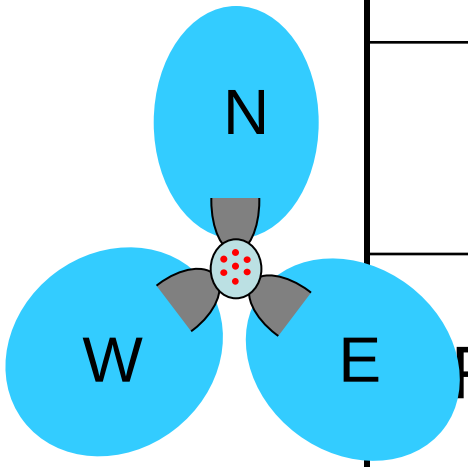
Multiple Field, Single Reactor Concept Mid Concentration



- Larger ellipse and smaller lookout angle requires different orientation of fields around receiver

Components not show to scale

Solar Field Design @1300°C, Daggett, CA
200 m Tower Central Receiver System



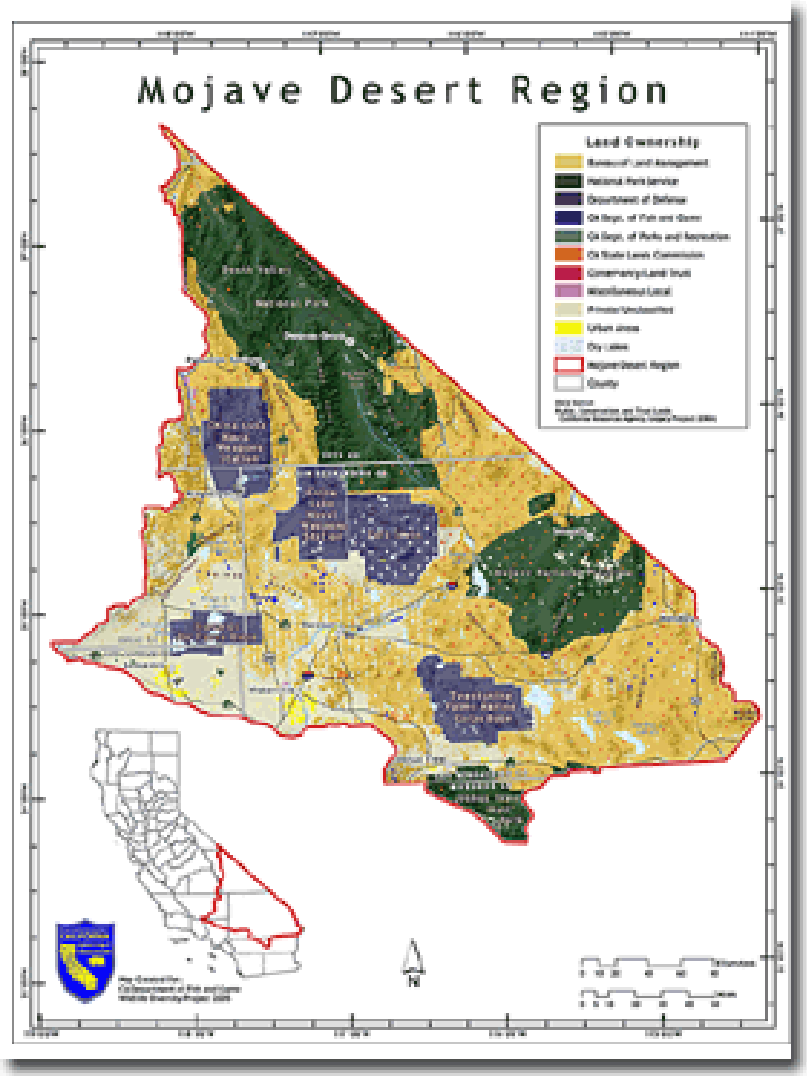
Field>	West	North	East
Field η	.494	.540	.494
Receiver η	.880	.892	.880
Net η	.440	.487	.440

- Yearly Direct Daggett: 2787 kWhr/m^2
- Yearly Delivered (@ annual avg efficiency): 1255 kWhr/m^2
- Annual Energy Delivered (to drive process): 352 GWhr; C=3800

Preliminary Process Design for Solar-thermal biomass ➔ syngas ➔ methanol ➔ gasoline

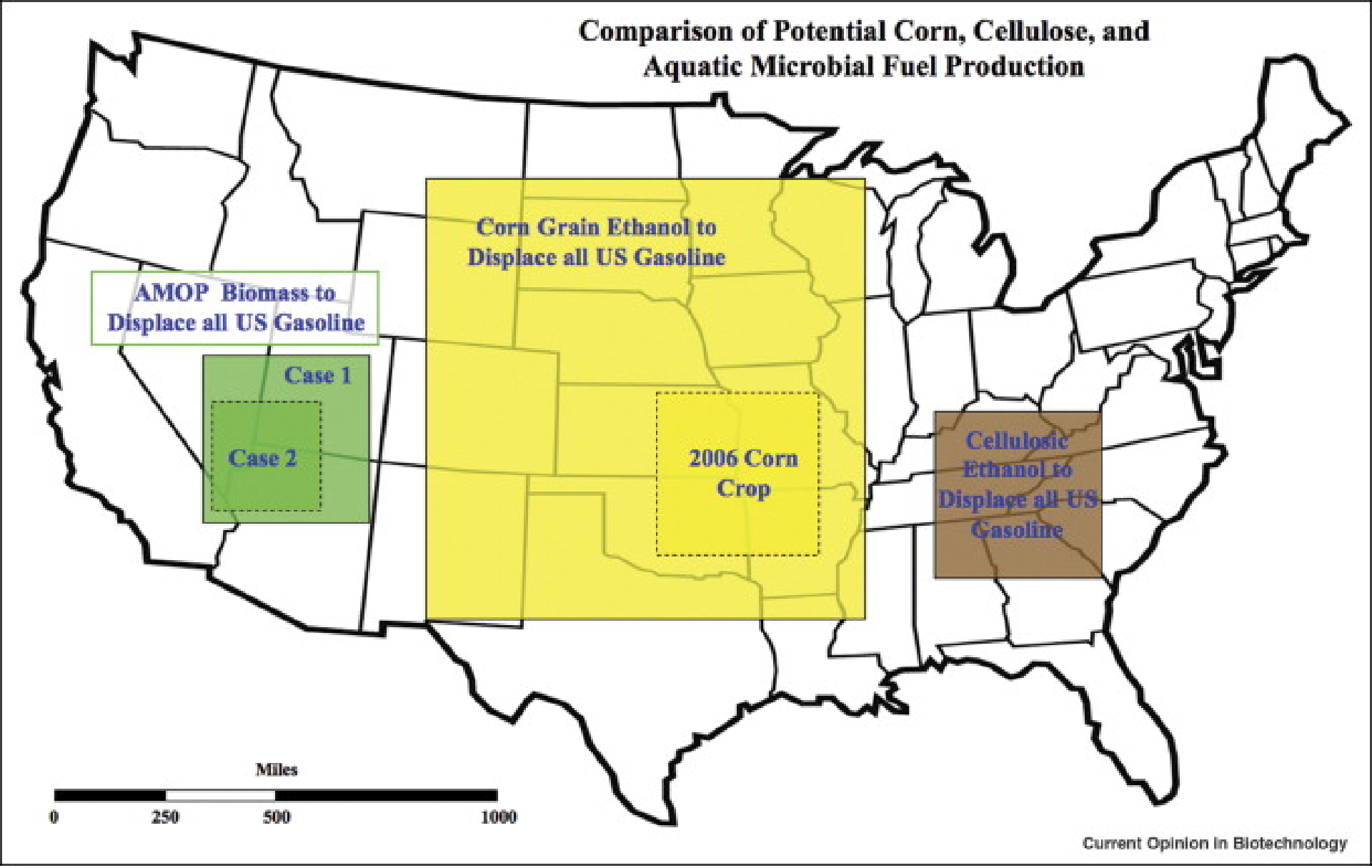
- End Product ~ 23 million gallon/yr renewable gasoline plant
- Requires 360 GWhr/yr Delivered Solar Energy
- ~ 280,000 m^2 heliostats (151 acres of land)
- One 200 m tall power tower

Mohave Desert



32 million acres
(CA, NV, AZ, UT)
2,787 kWhr/m^2-yr

<u>Solar-thermochemical plant</u>
~280,000 m^2 heliostat
~151 acres
C = 3,800 suns
360 GWhr annually
~ 56 M gal methanol/yr
or 32 M gge/yr (1.74/1)
(23 M gal gasoline/yr)



Dismukes, G.C. et al, Current Opinion in Biotechnology, 19, 235 (2008)

Common Feedstocks

Feedstock	Cost	Energy Density (GJ/mt)	Energy Cost ($/GJ)
Fossil Fuels			
Crude oil	$100/bbl	44.9	16.3
Shale oil (new capacity)	$ 85/bbl	44.9	13.9
Tar sand oil (new capacity)	$ 50/bbl	44.9	8.2
Natural Gas	$10/1000 scf	53.3	9.5
Coal	$55/ton	27.1	2.2
Renewables			
Sugar (US)	$ 0.21/lb	16.5	28.0
Corn	$ 6/bushel	19.1	16.0
Switchgrass	$ 80/dry mt	18.4	4.3
Pine Sawdust	$ 50/ton	19.9	2.8
Sorted municipal solid waste	-$ 50/dry mt	13.0	-3.8

Sierra, R. et al, CEP, S10, August (2008)

Mohave Desert Land Use

-32 million gge/yr
-25,049 gal gasoline/acre-yr
requires ~ 918 acres of land for algae
+ 151 acres for solar field

1,069 acres total

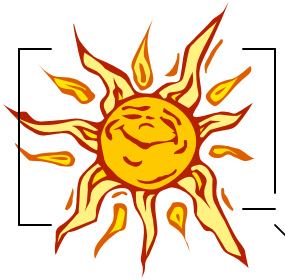
Hence,

Using 18% of the Mohave Desert land for algae
(32 million acres)(0.25)(25,049 gal gas/acre-yr)
= 2×10^{11} gal/yr (~1.44×10^{11} gal gasoline/yr)

U.S. Gasoline Supply

Daily Consumption: 400,000,000 gallons gasoline/day
= 1.46×10^{11} gallons/yr

Hence, using 25% of the Mohave Desert for growing algae, the entire U.S. fuel supply can be achieved from

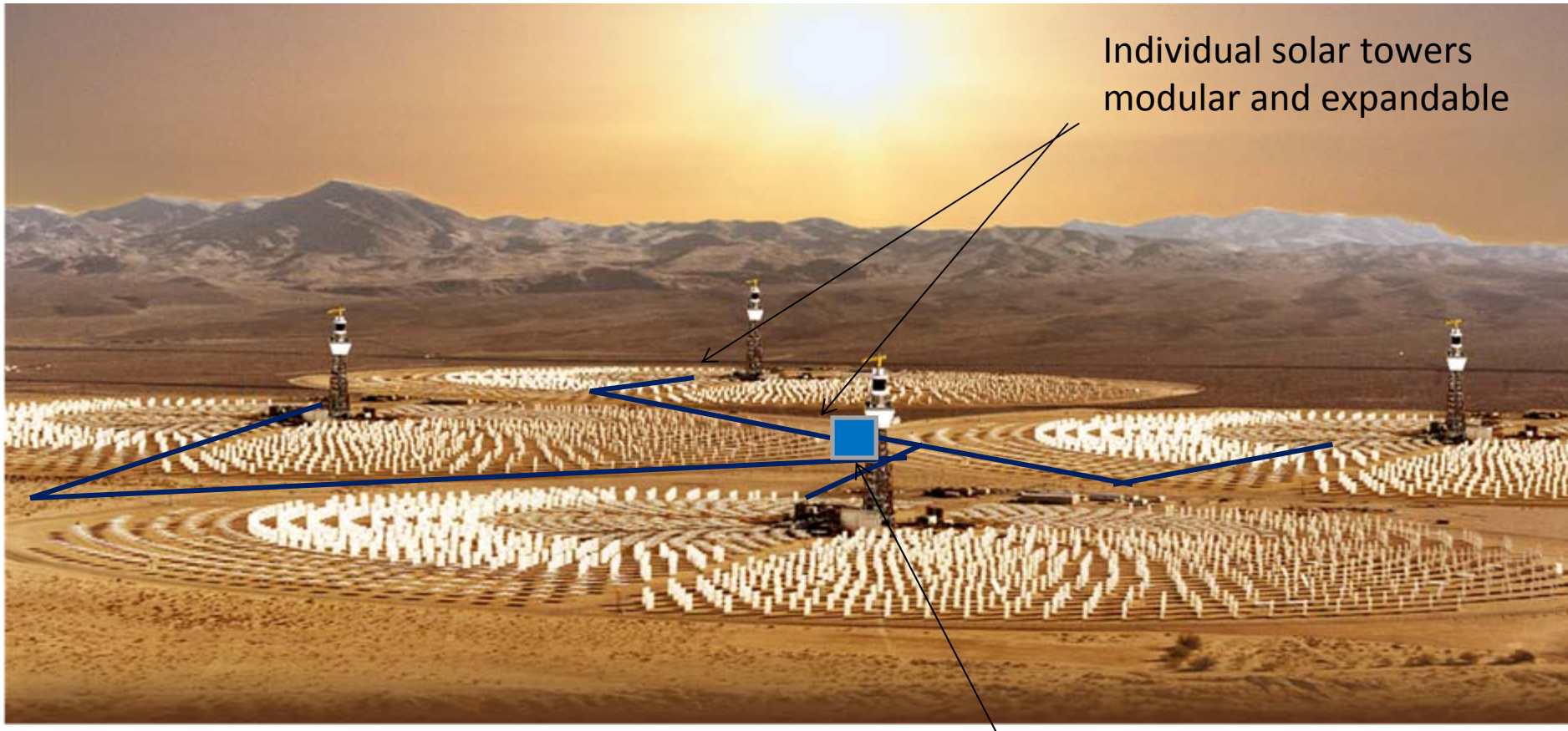


Algae → CO/H_2 → Methanol → Gasoline

$H_2O + CO_2$

The U.S. could fuel all of its vehicles with renewable gasoline !

Vision for modular plant layout



"Template" design reduces engineering/design fees for future plants

Each tower feeds to central processing plant to produce desired product

Conclusions/Future Work

Conclusions

- A solar thermal approach to biomass gasification accentuates the benefits of both renewable resources (100% renewable solution to large volume liquid fuels)
- Optimal conditions for gasification are only efficiently achievable through solar thermal energy, i.e. 1200°C
- Early process work shows excellent conversion, selectivity, repeatability and feedstock flexibility
- Early economic estimates look extremely promising (massive additional profitability in markets with favorable carbon policy);

Algae Connection

- Solar-thermal is a great fit with desert sun for growing algae
- Solar-thermal is a great fit with marginal land
- Methanol to Gasoline produces ~2.7 X amount of H2O needed to convert biomass (based on corn stover)
- Need to figure out how to economically concentrate algae up to about 80 wt% solids

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(a 56 M gal/yr methanol plant requires about 224 M kg biomass/yr or 614 mt biomass/day): 23 M gallons gasoline/yr
57 M gallons water/yr

Acknowledgements

- STTR Subcontracts from Sundrop Fuels
- C2B2 funded seed project for solar-thermal algae in progress (not presented here)
- Algae supplied by APS
- USDA/DOE grant to start (CSU, NREL, APS, Abengoa, Sundrop Fuels, ETH-Zurich)
- NREL
  - Allan Lewandowski (retired)
  - Carl Bingham

(Al Weimer has a financial interest in Sundrop Fuels)

Acknowledgements

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Blue Sun Biodiesel
Catchlight
Ceres
Chevron
Cobalt Biofuels
ConocoPhillips
Dow Chemical
DuPont
EcoPetrol
Flad Architects
General Motors
Kimberly-Clark
Korth O'Neil Engineering
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LS9
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