Glass in energy

Glasses for solar energy II: solar thermal energy

MAT 498

Lehigh University

The use of glass in solar energy involves two general types of applications:

- bulk glass applications, requiring specific optical, thermal and chemical glass properties, such as glass tubing in solar thermal concentrators (in **concentrated solar power, CSP**);

- applications where glass is essentially a substrate for functional coatings (generally not glassy), which include again **CSP** (glass mirror substrates), but also low emissivity and solar control glass windows, solar panel glass windows, photovoltaic (PV) panels and photocatalytic (photochemical) self-cleaning glasses.

The scale of solar systems ranges from power plants to individual power units.

The four main applications which will be considered are, therefore:

- solar control glass (namely low emissivity) - today's **lecture 4**

→ - solar thermal: including **solar concentration** (parabolic trough and flat heliostat mirror technologies) and solar hot water panels; - lecture 5

- photovoltaic (glass containing) panels, including solar panel glass windows; - lecture 6

- photochemical (namely photocatalytic, self-cleaning glass windows) "

Solar concentration

Since the sun has a low energy density when it reaches the surface of the earth, **optical concentration** is a good way to increase the energy density of the solar radiation. This allows the use of absorbers with small surfaces, which have lower heat losses, since these are proportional to the absorber surface.

Also, higher temperatures can be achieved under *concentrated conditions*, as in **CSP** and thermodynamics suggests that the conversion of solar energy into work can be done more efficiently the higher the temperature.

The concentrated sunlight must be converted to a useful form of energy, usually heat (hence the designation *solar thermal*). If desired, heat can be converted to electricity by means of an engine and generator.

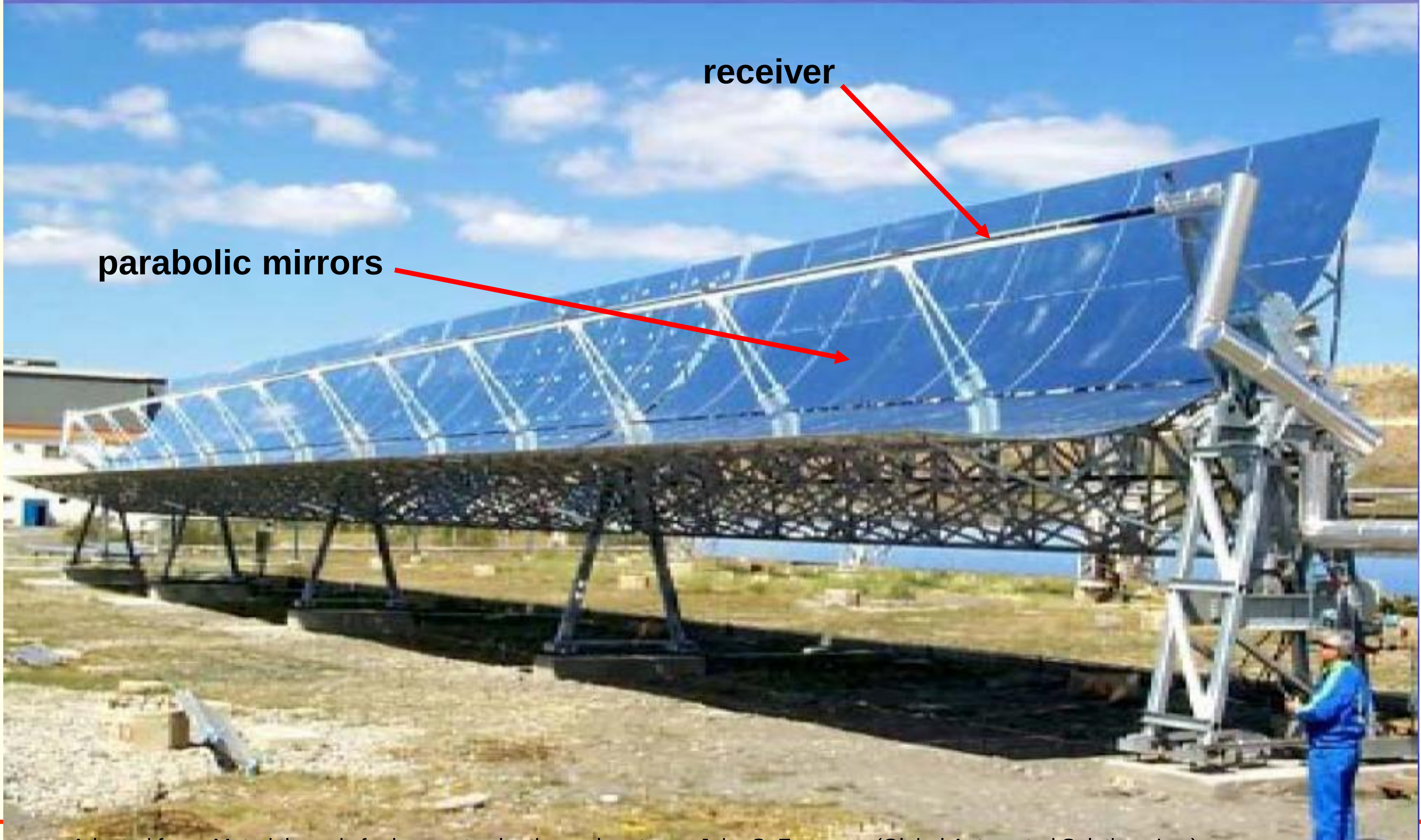
One example of a concentrated solar **power (CSP) plant** is the Solar Electric Generating Systems (SEGS) in the Mojave Desert of Southern California, in commercial operation for ~ 20 years. This plant uses the **Parabolic trough technology**, where large, long parabolic mirrors concentrate the solar radiation on a metal tube surrounded by glass, where a thermo-fluid (thermo-oil) is **heated** to generate steam at **400 ºC** to drive turbines for the production of electricity (350 MW, for half a million people). Parabolic trough collectors are *intermediate temperature solar concentrators.* Sometimes, a combination of photovoltaic solar cells with a solar thermal panel generates both electricity and heat energy.

Another example is the Solar Two power tower, also located in the Mojave desert, which uses the **Heliostat tower receiver** technology, employing flat mirrors. This kind of CSP plant reaches much higher operating temperatures, **above 1000 ºC**, for power generation or for the chemical production of fuels, e.g.. These solar power towers are *high temperature solar concentrators.*

Parabolic trough technology

Parabolic Trough

Euro Trough during construction in Granada Spain



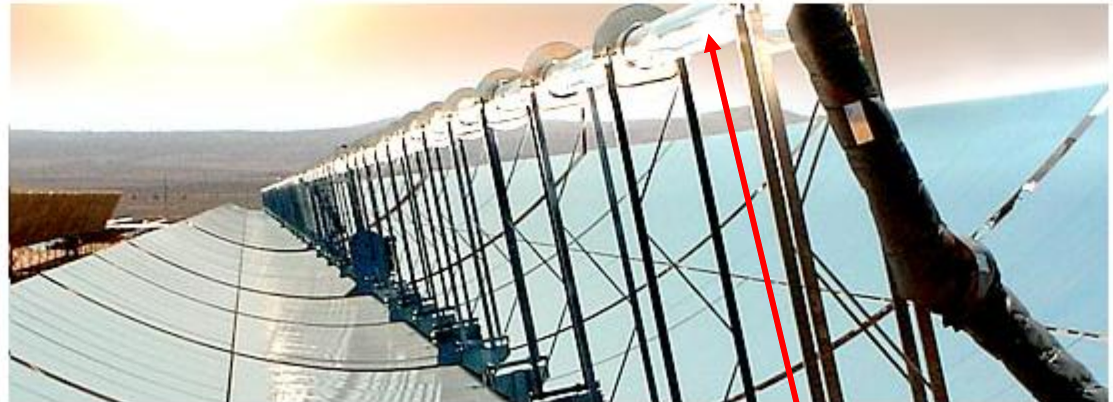
Adapted from: Material needs for low cost solar thermal systems, John S. Fangman (Global Automated Solutions Inc.), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

The receiver

Parabolic trough technology

for Concentrated Solar power (CSP)

The parabolic trough reflector concentrates the sunlight on an insulated tube (e.g. steel), the **receiver**, placed at the focal line and containing a coolant which transfers heat to the boilers in the power station.



Welcome to SCHOTT Solar Concentrated Solar Power!

Concerning solar power, photovoltaics is not the only available option. Concentrated Solar Power (CSP) technology provides for electricity generation as well, above all for large-scale applications. Amongst the various CSP processes, solar power plants with parabolic trough technology have proven their practical value for more than 20 years. SCHOTT Solar is one of the world's leading suppliers of a key component for this technology – the receiver.

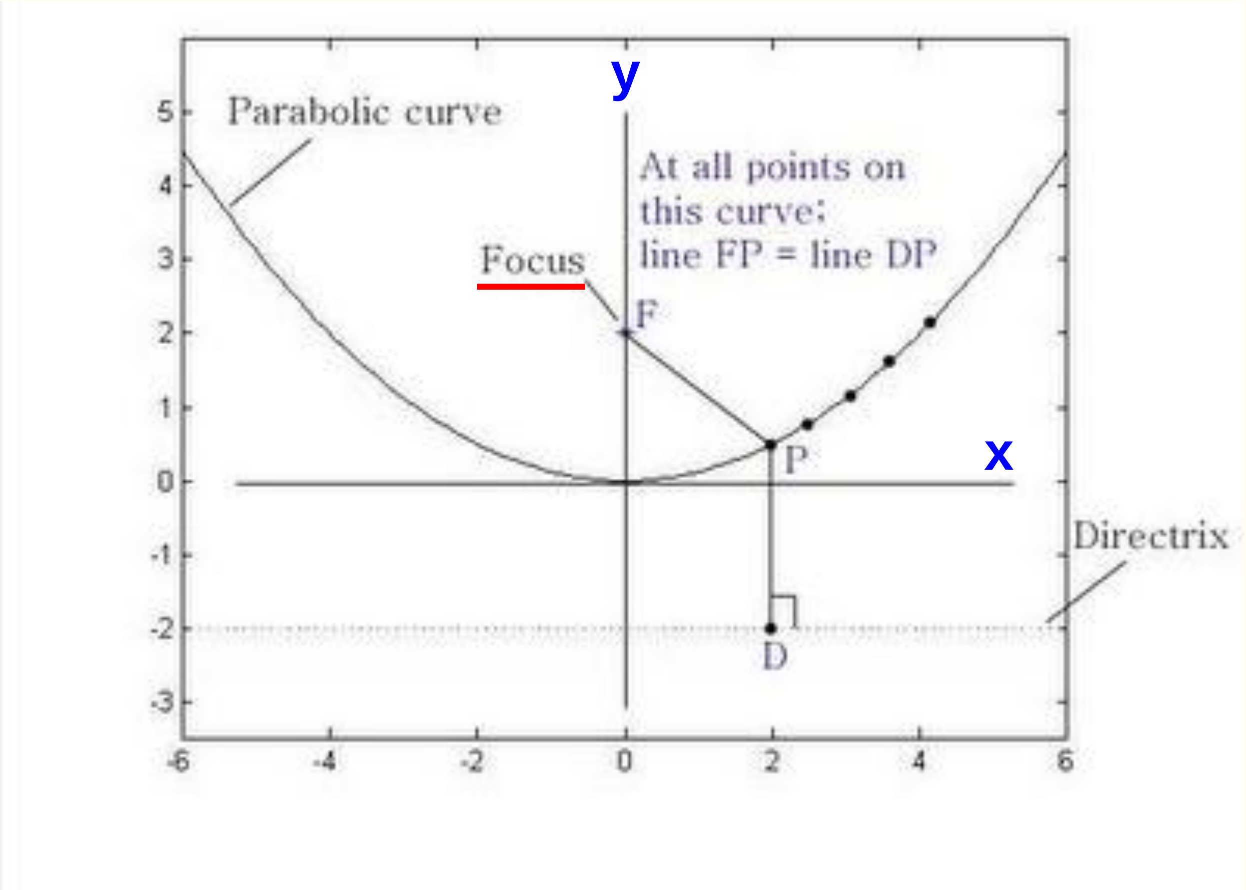
Visit us at us.schottsolar.com

The key component – SCHOTT PTR 70 Receiver
The key component in the solar field for Concentrated Solar Power plants that use parabolic trough technology. **[more...]**

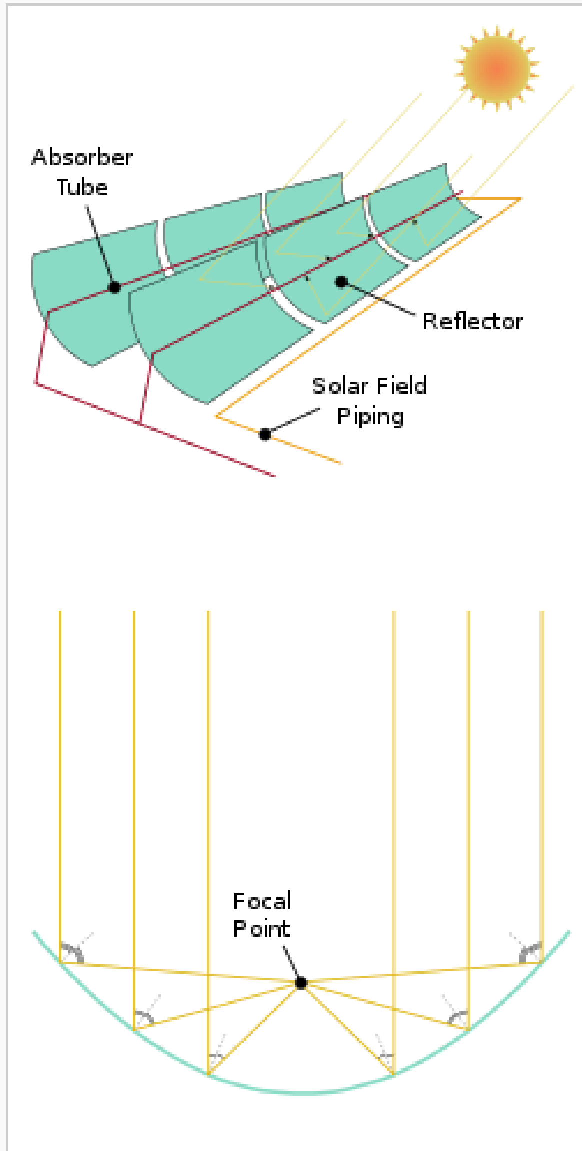
← **Glass receivers**

www.schott.com (Nov. 16, 2011)

Parabola: $y = x^2 / 4F$



Adapted from: http://sunenergyworld.blogspot.com/2006/03/knowing-parabolic-concentrators.html (26 Jan 2012)



Parabolic trough

Adapted from: http://en.wikipedia.org/wiki/Solar_thermal_collector#Parabolic_trough (28 Jan 2012)

The receiver of a trough concentrator is typically a metal (usually steel) absorber surrounded by a glass tube. The absorber pipe is low-E coated to allow incoming visible radiation and to decrease emittance (radiative loss) at IR wavelengths. The T at the absorber pipe can reach up to 400 ^{o}C. **Borosilicate glass** is used due to its low thermal expansion and excellent environmental resistance.

The evacuated gap between the metal tube and the glass is designed to minimize heat transfer losses by conduction and convection. Glass reflection losses at the two glass/air surfaces require the glass tube to be coated with a quarter-wave AR coating (~ 100 nm). Good adhesion AR coatings on borosilicate glass have been developed by *sol-gel*, in the form of nano-porous (~ 35%) silica (with index ~ $1.458^{1/2}$ = 1.2). Phosphoric acid has been found to enhance adhesion to the borosilicate glass when added to the sol-gel dip-coating solution.

Adapted from: Concentrating Solar Power-Trough Technology, Alex Marker (Schott North America), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

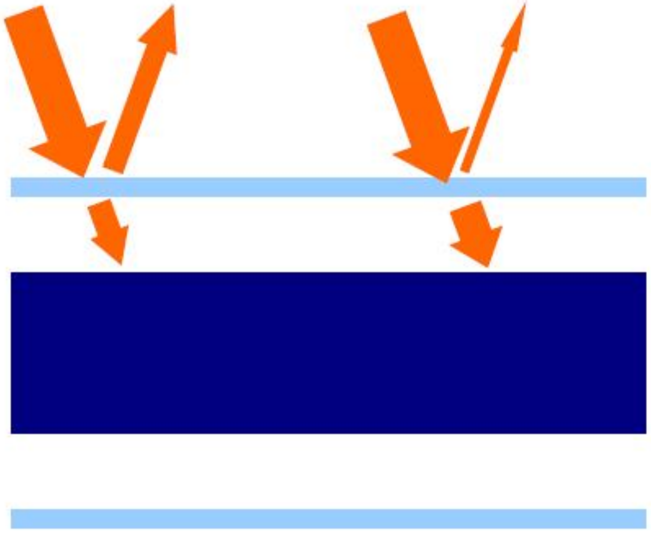
AR Coating with High Solar Transmittance

- Sol-Gel coating for borosilicate glass based on alcoholic dilutions with SiO_2 nano-particles for improved abrasion resistance
- Solar transmittance of > 0,96 achieved
- Challenges in production:
  - homogenous and stable coating of long glass tubes (✓)
  - automated high precision solar transmittance test for long glass tubes (✓)

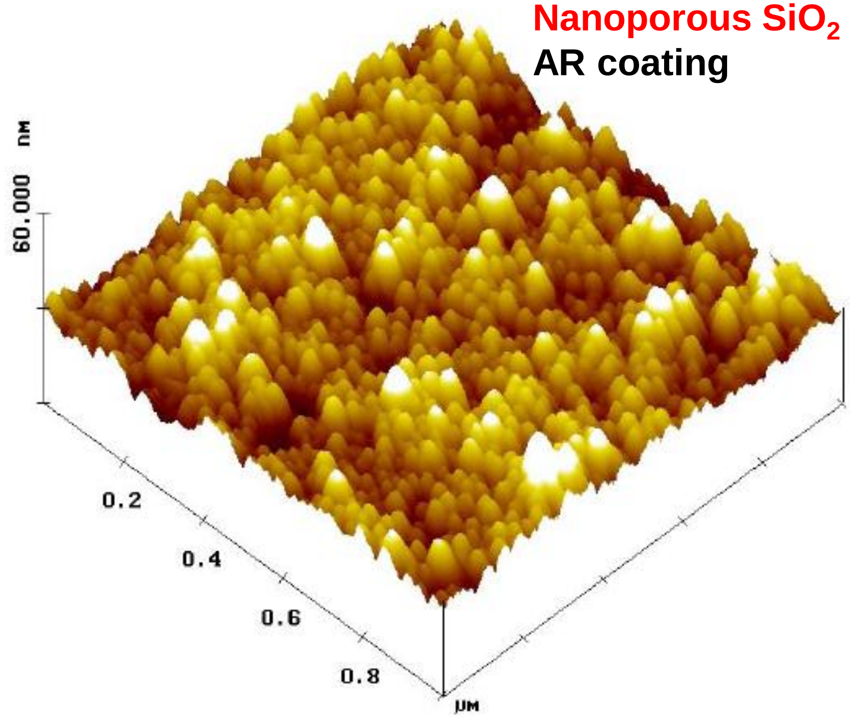
$$n_{eff}^{porous} \sim (1 - v_p)\, 1.458 + v_p\ (\times 1)$$

Only glass: τ = 92%

With AR-coating: τ > 96%



Nanoporous SiO_2
AR coating



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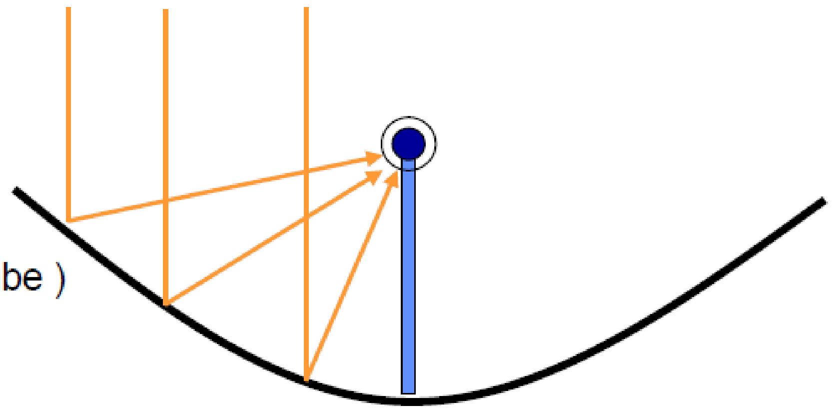
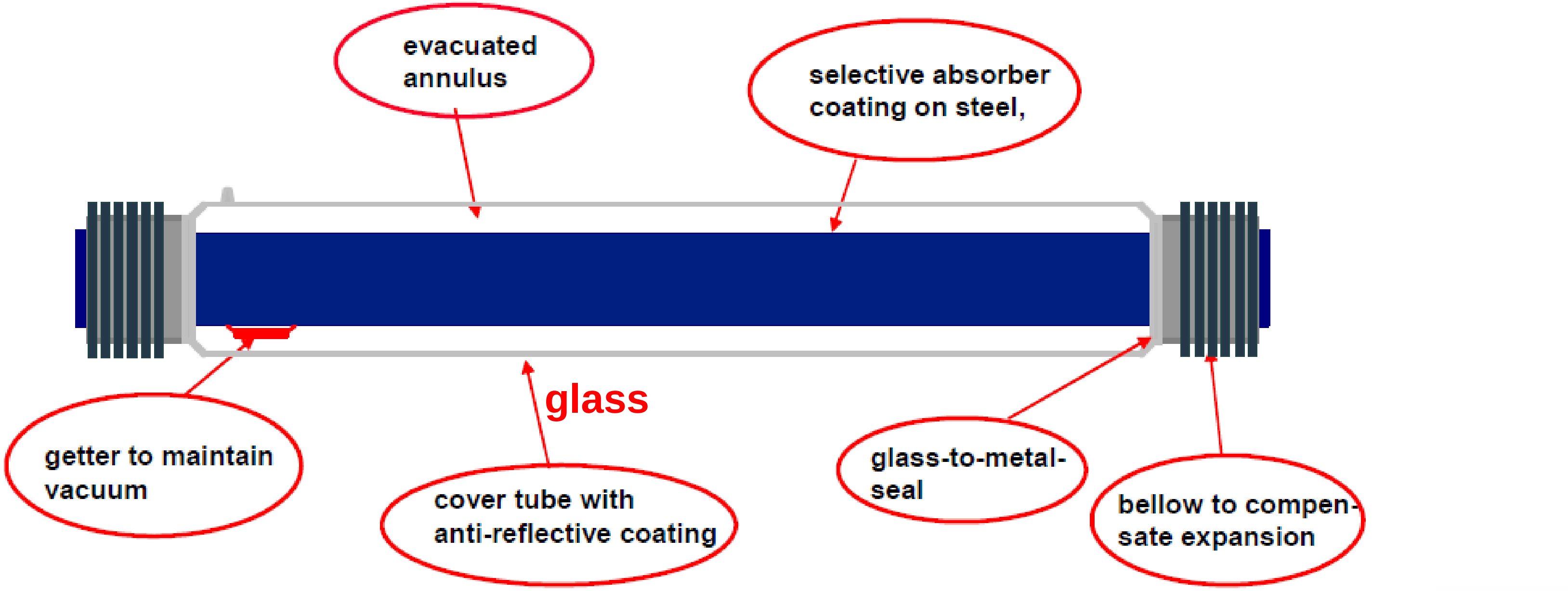
Receiver is the Key Component in Parabolic Trough Collectors

The receiver achieves high efficiency with

- Low thermal losses
  (→ vacuum, absorber with low thermal emittance)
- High solar absorptance
  (→ efficient absorber, highly transmitting outer glass tube)
- Minimum of shading
  (→ short bellows)





The metal receiver should be designed to minimize heat loss. Heat retention by the receiver is enhanced by covering the metal receiver with a selective (low-E) coating which will absorb virtually all the concentrated radiation, but will reradiate little energy back.

The glass window introduces heat loss and heat gain effects. Some energy will be reflected from the front surface and rear surface of the window and never reach the receiver. The inner surface of the window may be coated with a heat mirror like tin oxide, which reduces the radiation loss by reflecting radiated energy back to the metal receiver. An AR coating or etching of the outer surface of the glass window reduces the reflection from the surface, increasing transmission.

Conduction loss is reduced by decreasing the cross-section of structures in direct contact with the receiver, and using poor thermal conductors for these structures. A vacuum between the window and the receiver further reduces convection and conduction losses (somewhat similar to a Dewar tube).

The **receiver** is a glass to **metal-**sealed **borosilicate glass covered metal tube**, which has a thermo-oil inside the metal absorber tube.

The surrounding glass insulates the coated pipe from wind and reduces convective and conductive heat loss.

Three critical issues with the receiver are:

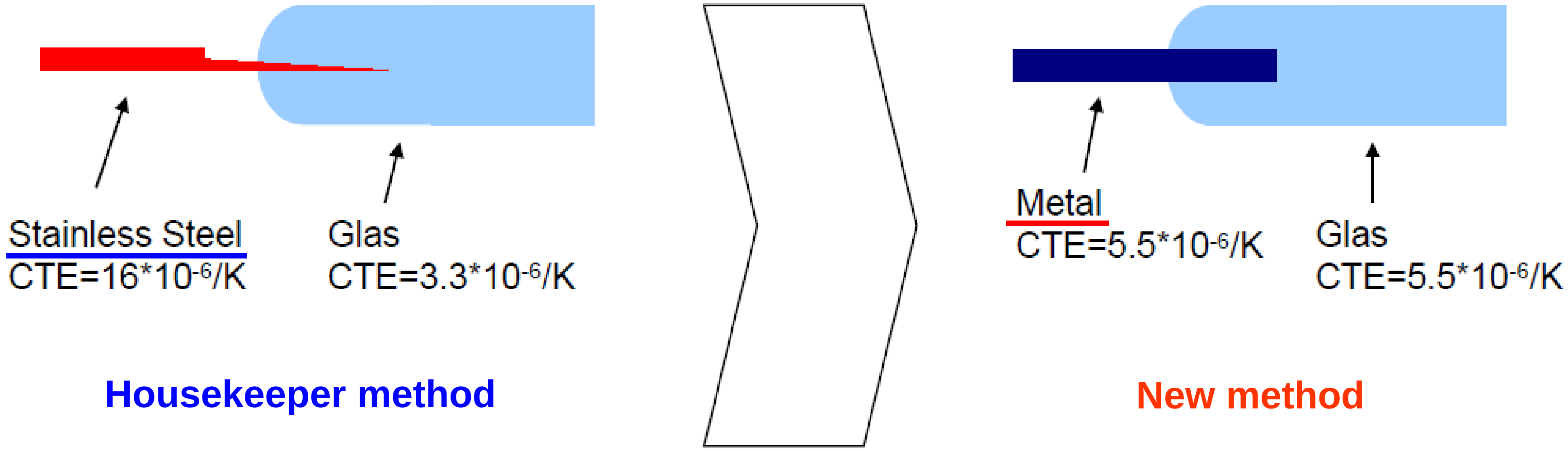
- breakage of the glass-to-metal seal

- thermo-oil decomposition

- weather resistance of the glass tube

New Glass-to-Metal Seal Improves Strength Properties

- Breakage of glass-to-metal sealing (Housekeeper) is the main cause for damages of receivers in existing power plants
- Automated production process required to reduce cost and to ensure quality
- New approach with matched CTE values yields a glass-to-metal seal with low stress
- Only one glass type necessary



Coefficient of (linear) thermal expansion α_{th} for selected materials. $\alpha_T \times 10^{-6}\ ^oC^{-1}$

Material	$\alpha_{th}(\times 10^{-6}\ °C^{-1})$	Material	$\alpha_{th}(\times 10^{-6}\ °C^{-1})$
Metals		**Ceramics**	
Al	25	Al_2O_3	6.5–8.8
Cr	6	BeO	9
Co	12	MgO	13.5
Cu	17	SiC	4.8
Au	14	Si	2.6
Fe	12	Si_3N_4 (α phase)	2.9
Pb	29	Si_3N_4 (β phase)	2.3
Mg	25	Spinel ($MgAl_2O_4$)	7.6
Mo	5	Soda-lime-silicate glass	9.2 (used in light bulbs)
Ni	13	Borosilicate glass	4.6 (used with Kovar)
Pt	9	Silica (96% pure)	0.8
K	83	Silica (99.9% pure)	0.55
Ag	19	**Polymers (unoriented)**	
Na	70	Polyethylene	100–200
Ta	7	Polypropylene	58–100
Sn	20	Polystyrene	60–80
Ti	9	Polytetrafluoroethylene	100
W	5	Polycarbonate	66
Zn	35	Nylon (6/6)	80
1020 steel	12	Cellulose acetate	80–160
Stainless steel	17	Polymethylmethacrylate	50–90
3003 aluminum alloy	23.2	Epoxy	45–90
2017 aluminum alloy	22.9	Phenolformaldehyde	60–80
ASTM B 152 copper alloy	17	Silicones	20–40
Brass	18		
Pb-Sn solder (50-50)	24		
AZ31B magnesium alloy	26		
ASTM B160 nickel alloy	12		
Commercial titanium	8.8		
Kovar (Fe-Ni-Co)	5		

(Adapted from: *The science and design of engineering materials*, J.P. Schaffer et al., McGraw-Hill, 1999)

Adapted from: Concentrating Solar Power-Trough Technology, Alex Marker (Schott North America), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

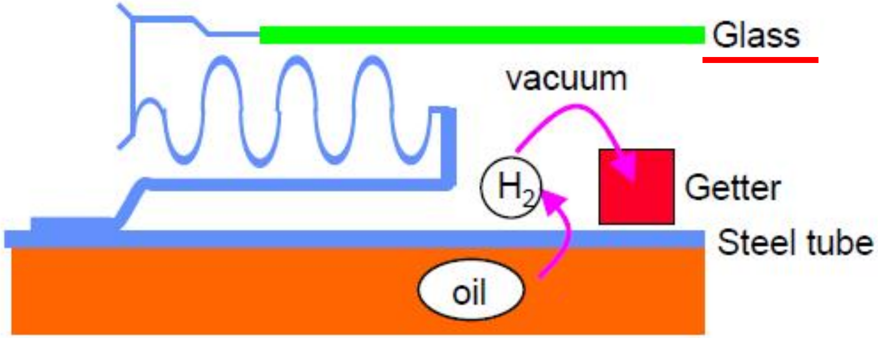
Solutions for Hydrogen Problem

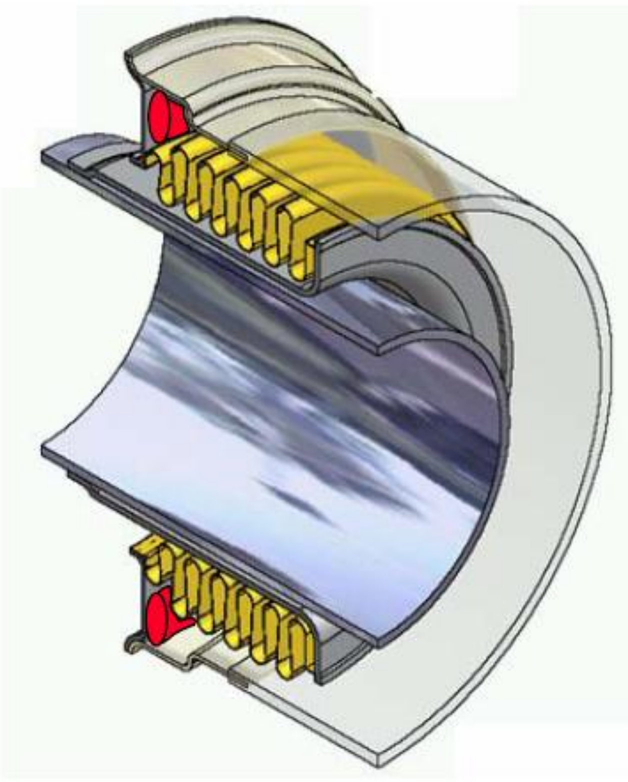
Problem:

- Thermo-oil decomposes during operation, hydrogen is generated.
- Hydrogen permeation through steel absorber tube leads to vacuum loss and increased heat loss (factor 2-3)

Solution:

- Barrier coating to reduce permeation rate
- Well designed getter quantity mounted in „cool" place





The **third issue** is the improvement of the borosilicate glass receiver resistance to acid rain. In fact, the degradation of functional materials and consequent loss of performance is a crucial factor for the economic viability of solar systems, which are severely exposed to the unpredictable outdoor weather.

Q.

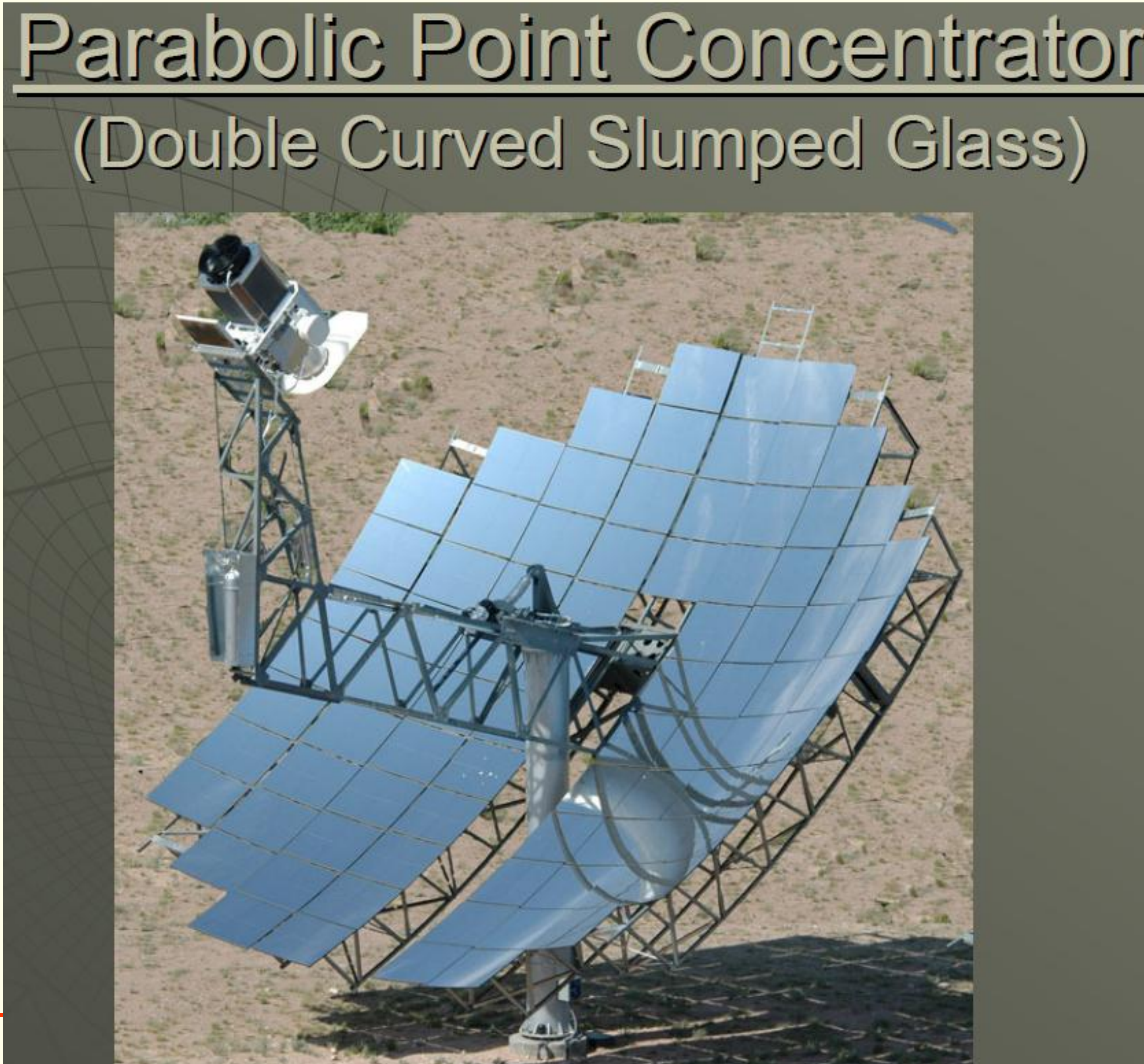
The mirrors

Parabolic trough technology for CSP

One of nine solar electric energy generating systems at Kramer Junction, California, with a total output of 354 MWe.

Adapted from: http://www.powerfromthesun.net/Book/chapter01/chapter01.html

Adapted from: Material needs for low cost solar thermal systems, John S. Fangman (Global Automated Solutions Inc.), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA



Parabolic dish

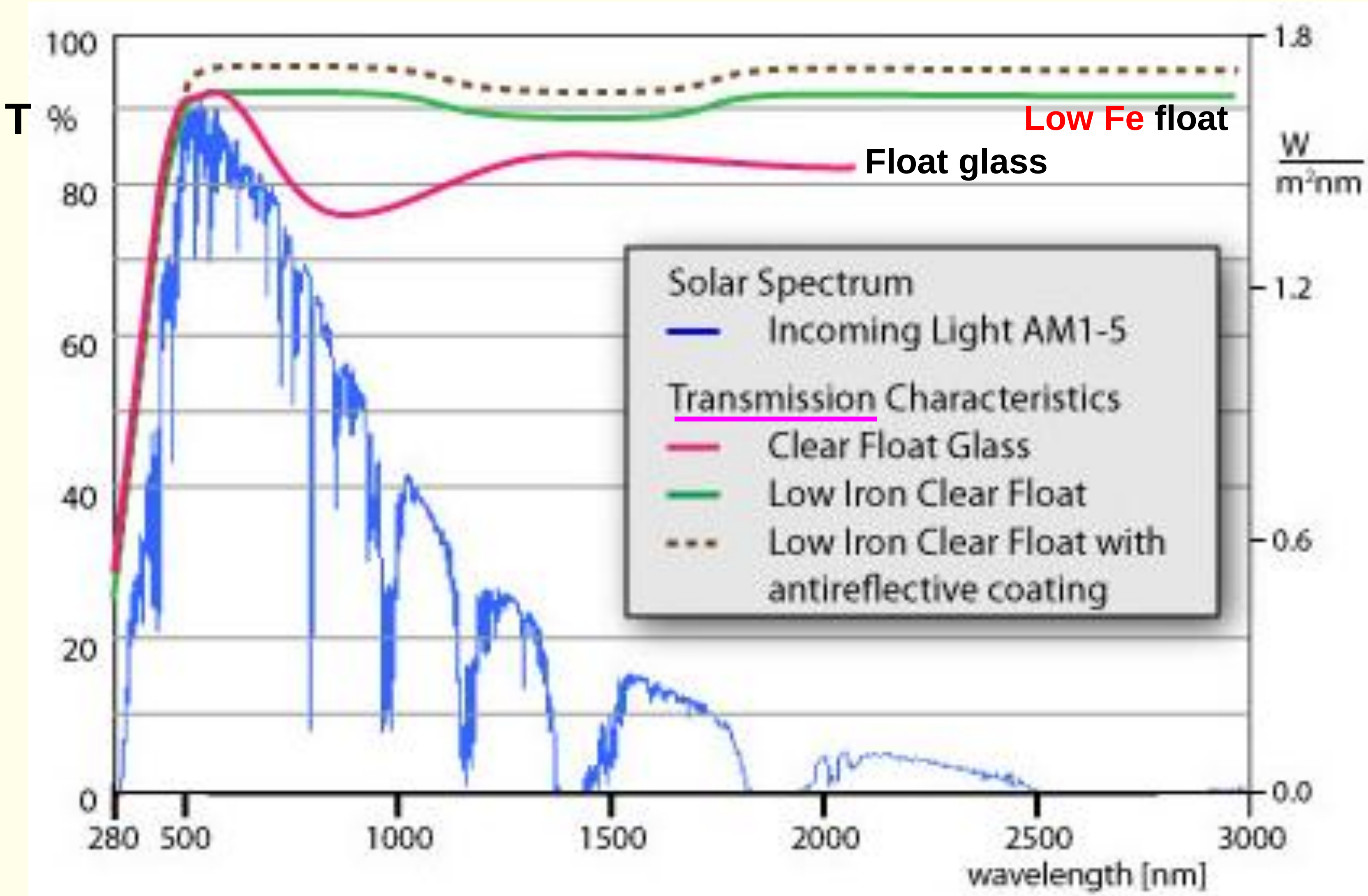
The sun is continuously tracked by the mirrors.

Disk-shaped parabolic reflectors, together with a positioning system, track the sunlight.

Glass mirrors have the best durability and lowest degradation of reflectance over time. The mirror substrates are mostly bended (parabolic), or flat (heliostats) float glass sheets, Ag-metallized at the back surface.

The mirror glass substrate is usually 3 – 4 mm thick soda-lime float glass (not borosilicate) of rather low Fe content (*white* glass) compared to normal float glass and thus with high transparency in UV-Vis-NIR range. A durable, low cost reflector is highly needed.

Need for low Fe glass



Adapted from: Solar Glass & Mirrors, Gree Rhino Energy Ltd. Website (7 Dec. 2011)

The Ag layer of solar mirrors, located on the back of the glass substrate, is also covered with a protective coating containing Cu and varnish in a multilayer stack, to protect Ag from its poor mechanical and chemical environmental resistance.

The use of glass mirror substrates ensures a service life > 20 years for the CSP plant, even under extreme weather conditions.

A trough shaped mirror can be expected to deliver at least 60% of the incident solar radiation on the metal collector. At present, the efficiency of CSP is higher than that of PV, for example.

Q.

Heliostat tower receiver technology

High temperature solar concentrators

The high temperature solar concentration concept has been known since the ancient Greeks used a *burning mirror* to enlighten the Olympic flame.

Later on in the 15th century, Leonardo da Vinci proposed a technique to weld copper using concentrated solar radiation and in the 18th century appeared the first prototypes of parabolic dish concentrators to generate steam to drive steam engines.

Then oil and natural gas became available as fuels and only in the early 1970s, at the time of the first oil crisis, solar concentration research started in several industrialized countries. And the first high temperature commercial solar power tower systems started to operate around ~ 10 years ago.

Adapted from: Material needs for low cost solar thermal systems, John S. Fangman (Global Automated Solutions Inc.), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

Power Towers

Solar Two located in the Mojave Desert of California.

In **tower** (**heliostat**) receivers, the temperature can reach more than 1000 ^{o}C, allowing in principle higher efficiency rates of energy conversion. The high temperature (metal or ceramic) receivers are covered by a cooled silica glass window in this case, where porous silica **quarter wave AR coatings** are also used.

The solar power tower (in the heliostat power plants, or power towers) is a type of solar furnace, using a tower to receive the focused sunlight. It uses an array of flat, movable mirrors (called heliostats) to focus the sun's rays upon a collector tower (the target). The collected heat is then transferred, by means of hot air or molten salt, from the absorber to a steam generator, which drives a turbine and electrical generator.

Early designs used the focused sun rays to heat water, and used the resulting steam to power a turbine. Newer designs using liquid sodium have been demonstrated, and systems using molten salts (40% KNO_3, 60% $NaNO_3$) as the working fluids have been in operation (namely at Solar Two). These fluids have high heat capacity, which can be used to store the energy before using it to boil water to drive turbines. Such designs allow power to be generated when the sun is not shining.

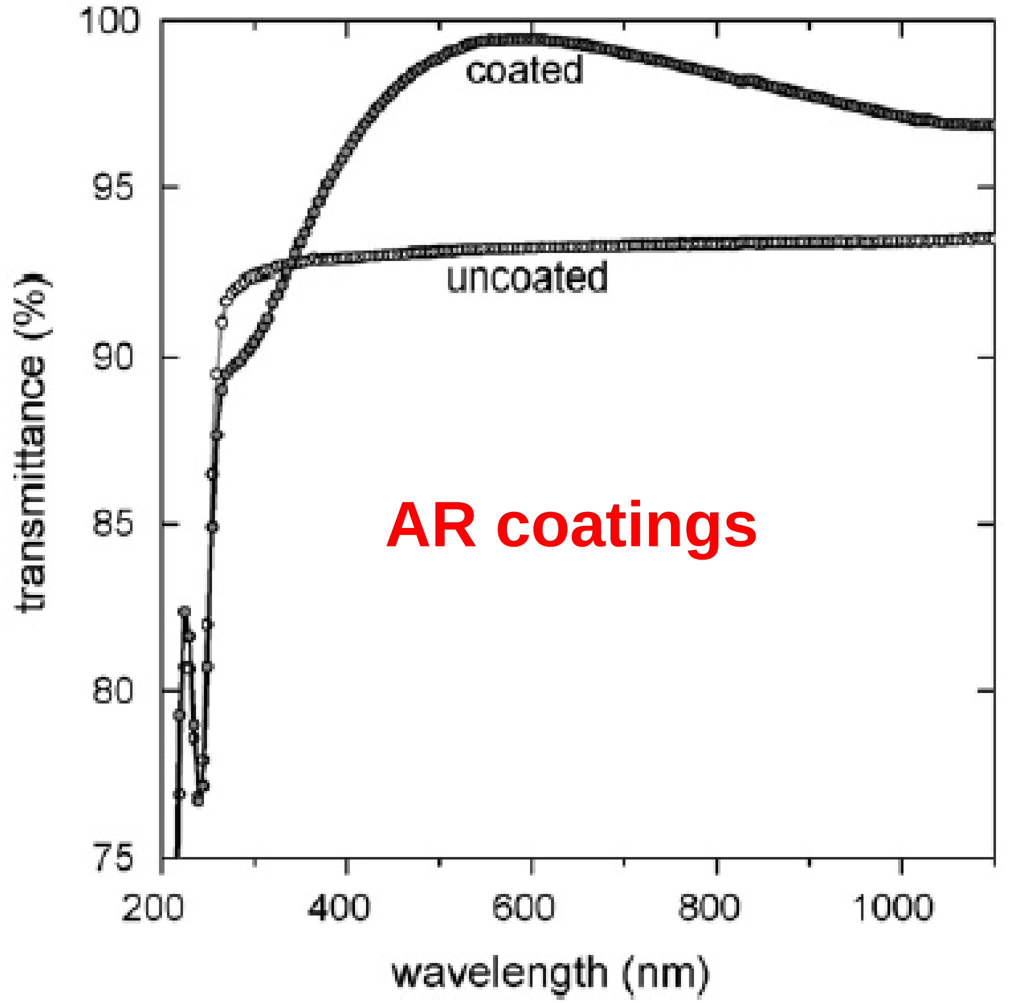


Fig. 3. Spectral transmittance of a cover glass for a high-temperature cavity receiver of solar tower plants: silica glass (4 mm) and coated with porous SiO_2-bearing sol–gel layer.

Adapted from: J. Deubener et al., J. Eur. Ceram. Soc. 29 (2009) 1203.

Concentrated solar thermal is seen as one viable solution for renewable, pollution free energy production with currently available technology.

For example, the efficiency of CSP is higher than PV.

So the generation of power in solar thermal plants is a fast growing market where glass plays a key role (tubes and mirrors).

Q.

Solar hot water panels

In order to heat water using solar energy in **solar hot water panels,** mostly for domestic application, a collector, often fastened to a roof or a wall facing the sun, heats working fluid that is either pumped (active system) or driven by natural convection (passive system) through it. The collector could be made of a simple glass-topped insulated box with a flat solar absorber made of sheet metal attached to copper pipes and painted black, or a set of metal tubes surrounded by an evacuated **borosilicate** **glass** cylinder. In industrial cases, a parabolic mirror can concentrate sunlight on the tubes. Heat is stored in a hot water storage tank.

Solar hot water panel

Combinations of different technologies

Solar chimney technology is also being proposed, where air is heated under a large scale circular **glass** roof (collector roof) and passes up a chimney through a wind turbine near the base of the chimney, as it rises. The turbine is used to generate electricity.

Yet another type are the luminescent solar concentrators (aka solar panel glass windows), consisting of a thin fluorescent film on **glass** substrates: organic dyes and quantum dots can be used as fluorescent materials and the emitted light is guided to PV cells by mirrors or by TIR.

Q.

References:

Richard K. Brow and Melodie L. Schmitt, J. Eur. Cer. Soc. 29 (2009) 1193.

J. Deubener et al., J. Eur. Cer. Soc. 29 (2009) 1203.

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Robert Pitz-Paal, **High temperature solar concentrators,** Solar energy conversion and photoenergy systems – Vol. 1, Encyclopedia of Life Support Systems.