جامعة الملك سعود
King Saud University

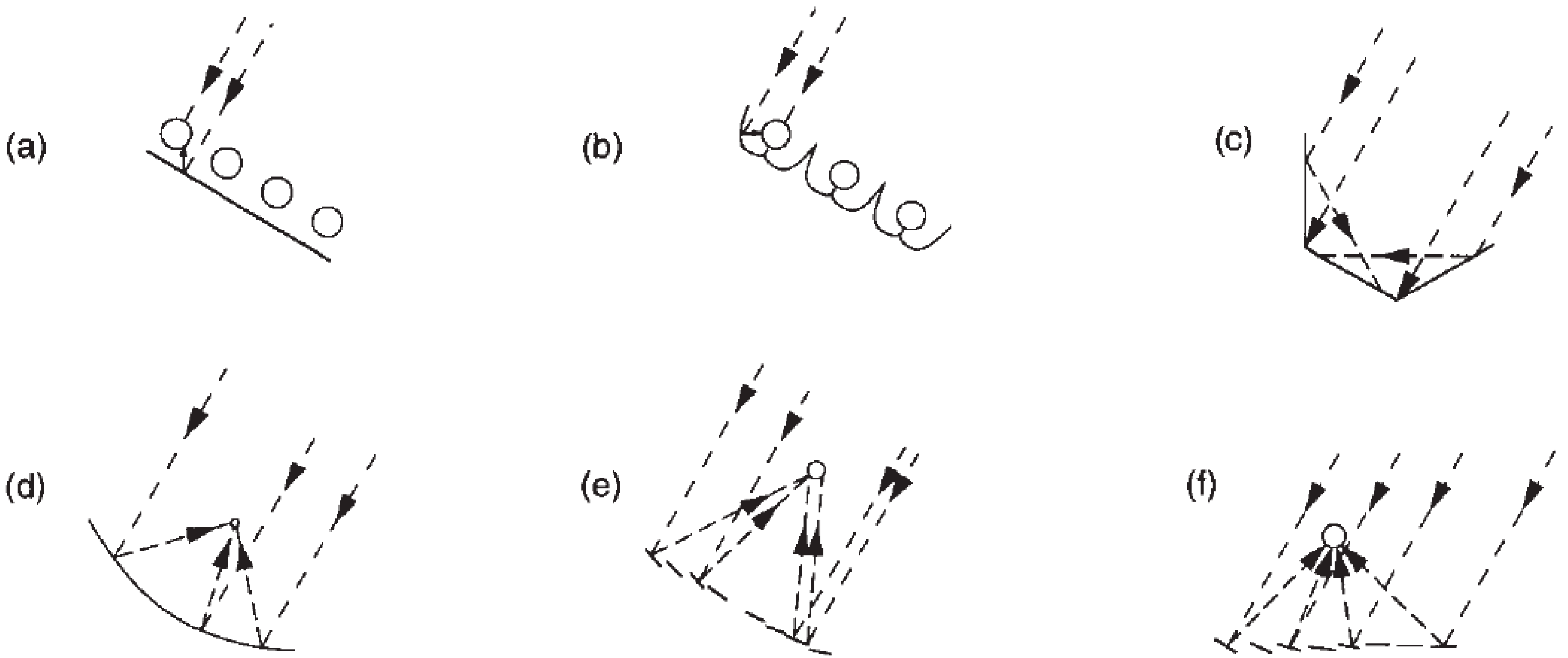
ME 476
Solar Energy

UNIT FOUR
SOLAR COLLECTORS
Concentrating Collectors

Concentrating Collectors

- For many applications it is desirable to deliver energy at temperatures higher than those possible with flat-plate collectors or evacuated tube collectors.
- Energy delivery temperatures can be increased by decreasing the area from which heat losses occur.
- This is done by concentrating solar radiation on a small absorber.
- The small absorber will have smaller heat losses compared to a flat plate collector or evacuated tube collector at the same absorber temperature.

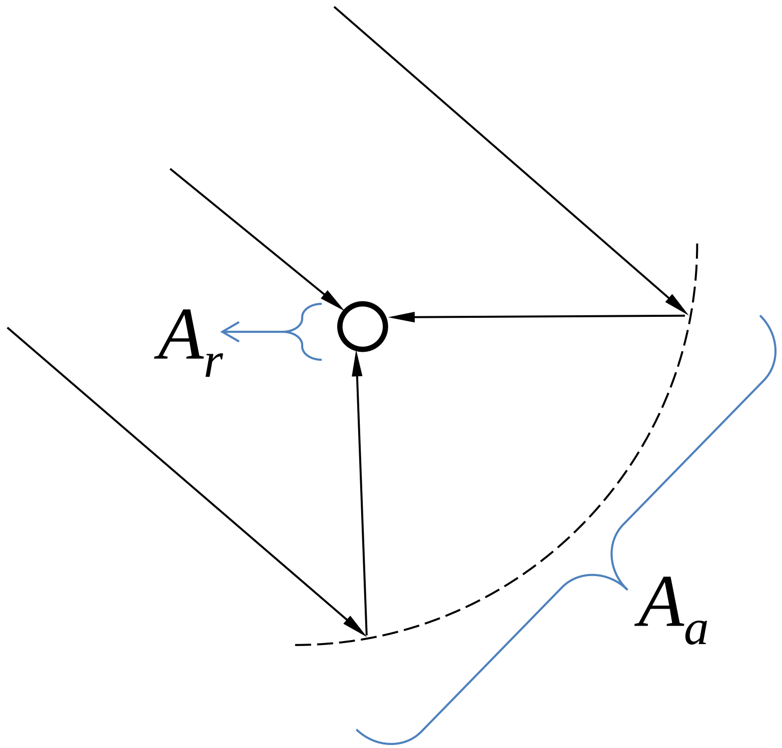
Types of Concentrating Collectors



(a) tubular absorbers with diffuse back reflector
(b) tubular absorbers with specular cusp reflectors
(c) plane receiver with plane reflectors
(d) parabolic concentrator
(e) Fresnel reflector
(f) array of heliostats with central receiver.

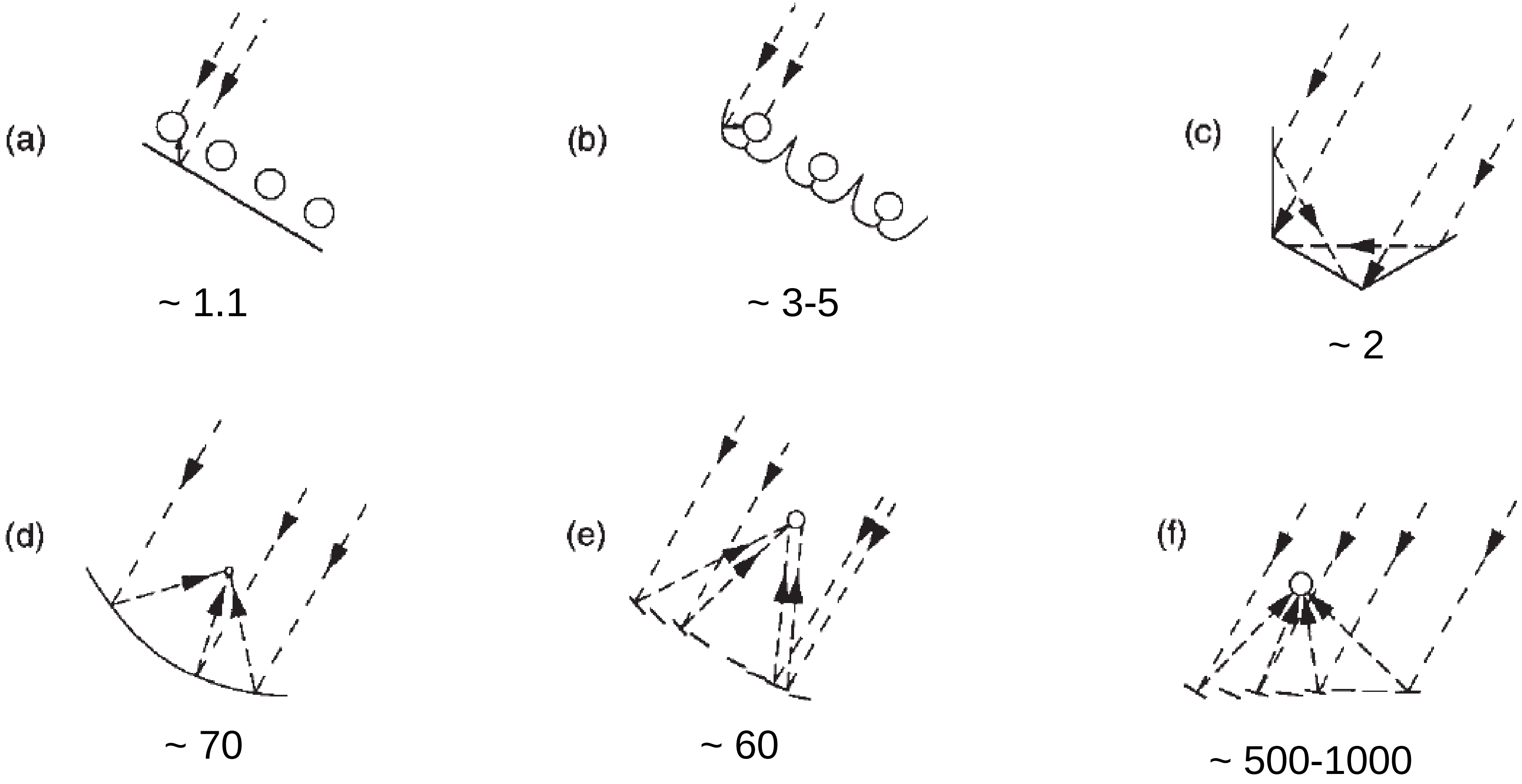
Concentration Ratio

- One of the most important factors in concentrating collectors is the concentration ratio.
- The most common definition of concentration ratio is the **area concentration ratio**
- It is defined as *the ratio of the area of aperture to the area of the receiver.*



$$C = \frac{A_a}{A_r}$$

Typical Concentration Ratios



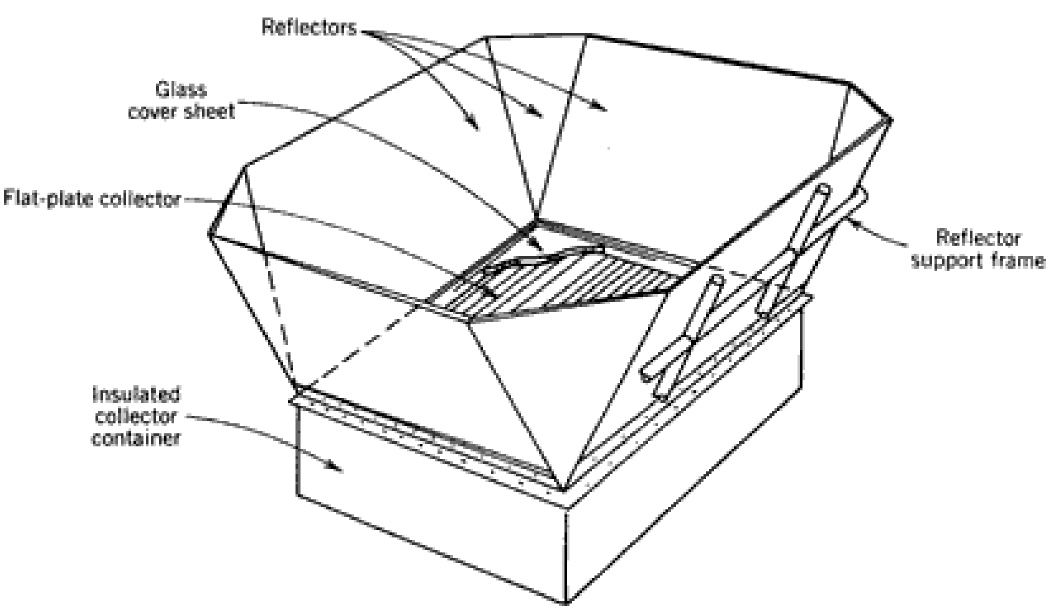
- The higher the concentration ratio, the smaller the area of the receiver → the smaller the heat loss by convection or radiation.

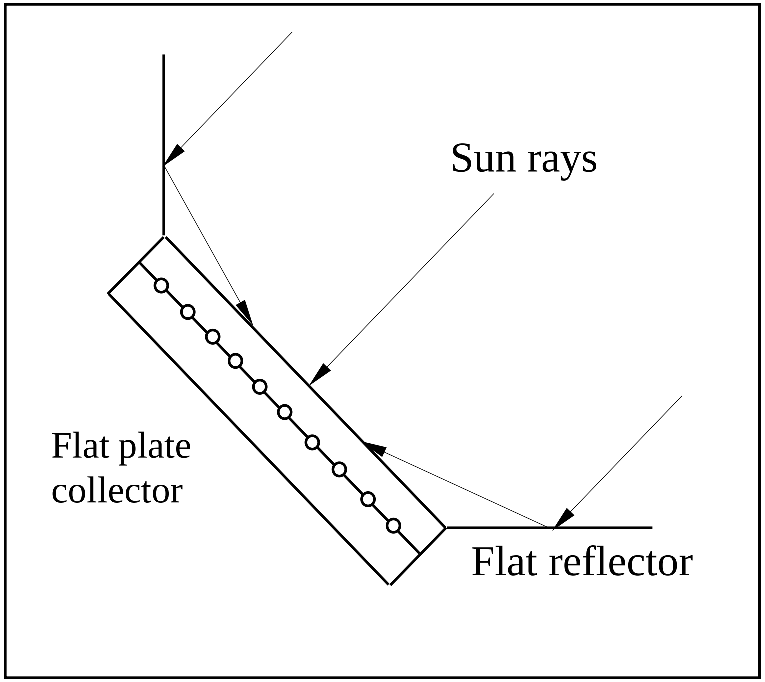
Types of Concentrating Collectors

- Flat plate collector with flat reflectors
- Compound parabolic concentrators
- Parabolic trough collectors
- Linear Fresnel collectors
- Central receiver systems
- Parabolic dish collectors

Flat Plate Collector With Flat Reflectors

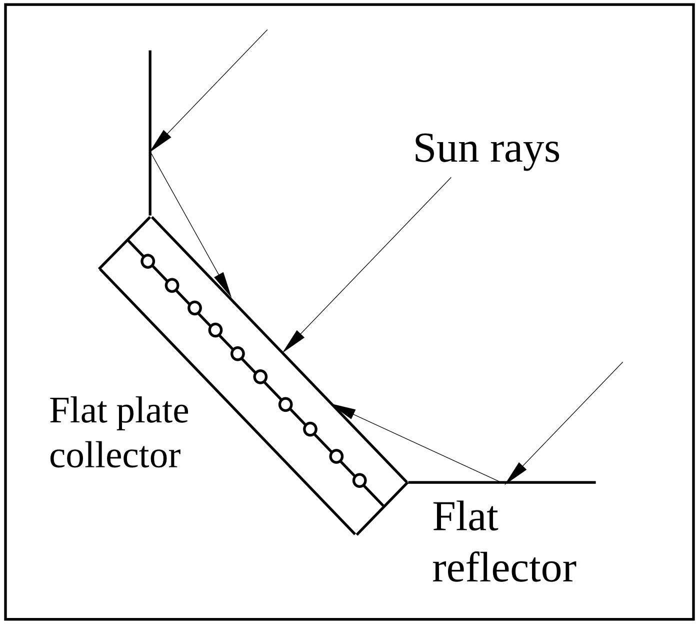
- Reflectors are attached to the edges of the flat collector.
- Some of the irradiation will fall directly on the collector (as usual)
- Some of the irradiation will fall on the side mirrors and be reflected to the collector.



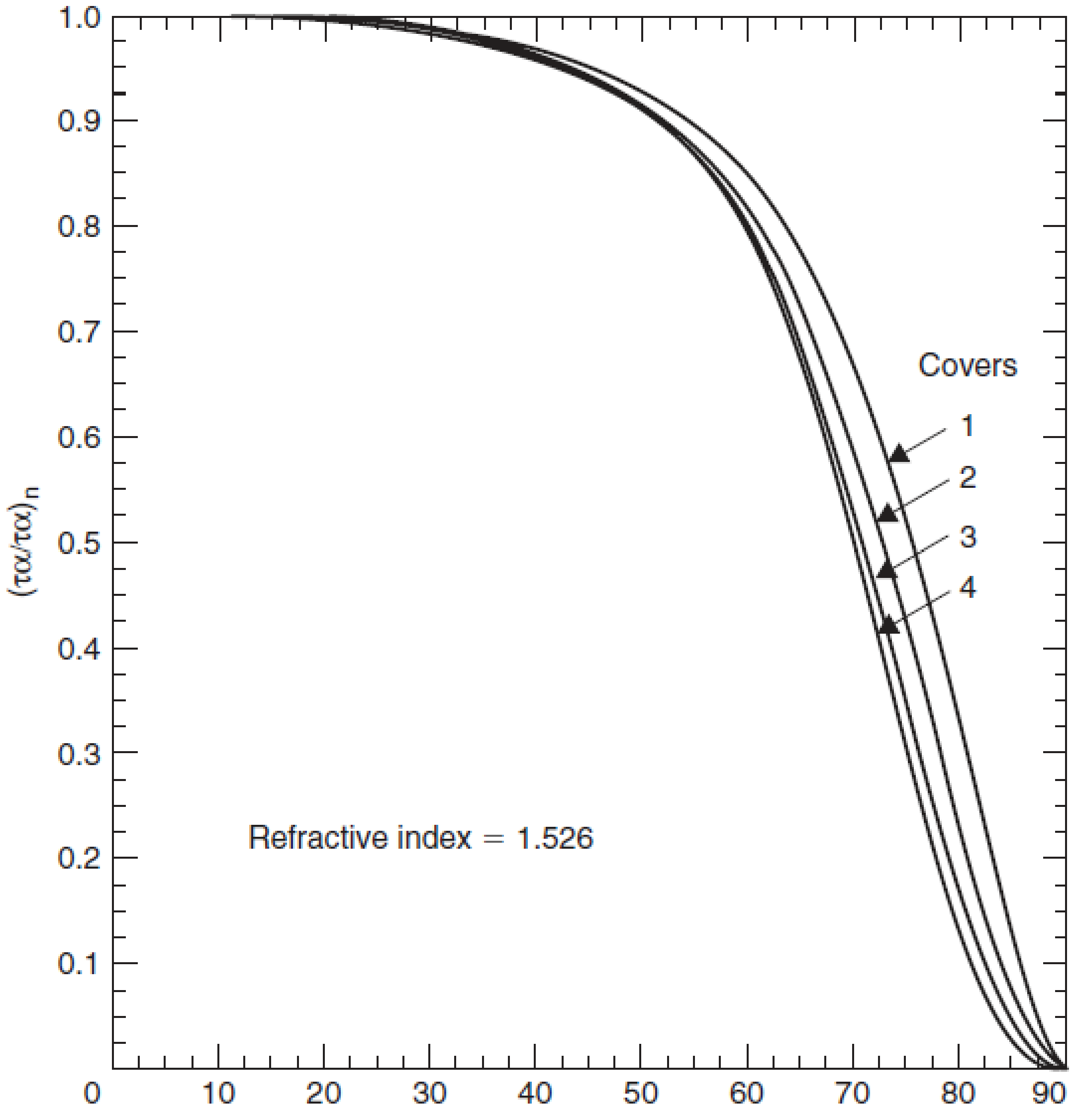


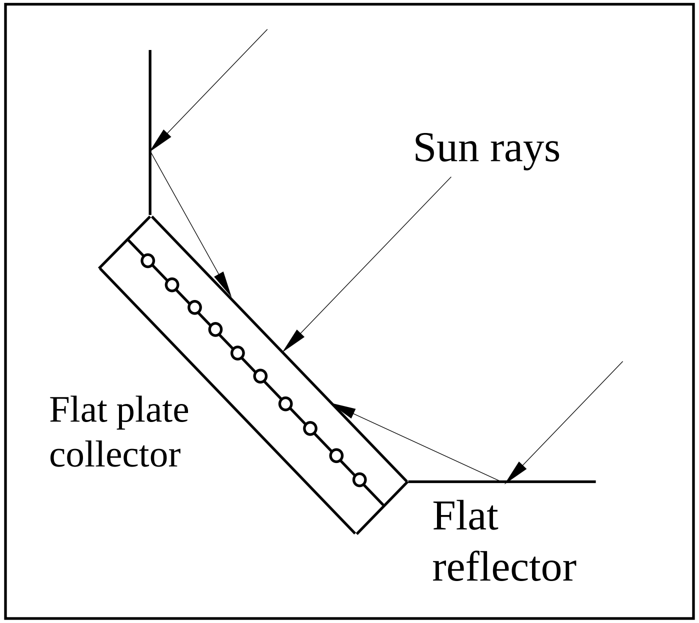
Flat Plate Collector With Flat Reflectors

- The main advantage is that the surface area is increased.
  - **More irradiation will be absorbed by the collector (higher concentration ratio).**
  - **The working fluid will gain more energy.**
- Disadvantages include:
  - **Reflector can cause shading.**
  - **Additional cost**
  - **The additional surface area is not fully utilized.**
  - **($\tau\alpha$) of glass at low incidence angles is lower.**
- This concept is not widely used.



Flat Plate Collector With Flat Reflectors





Types of Concentrating Collectors

- Flat plate collector with flat reflectors
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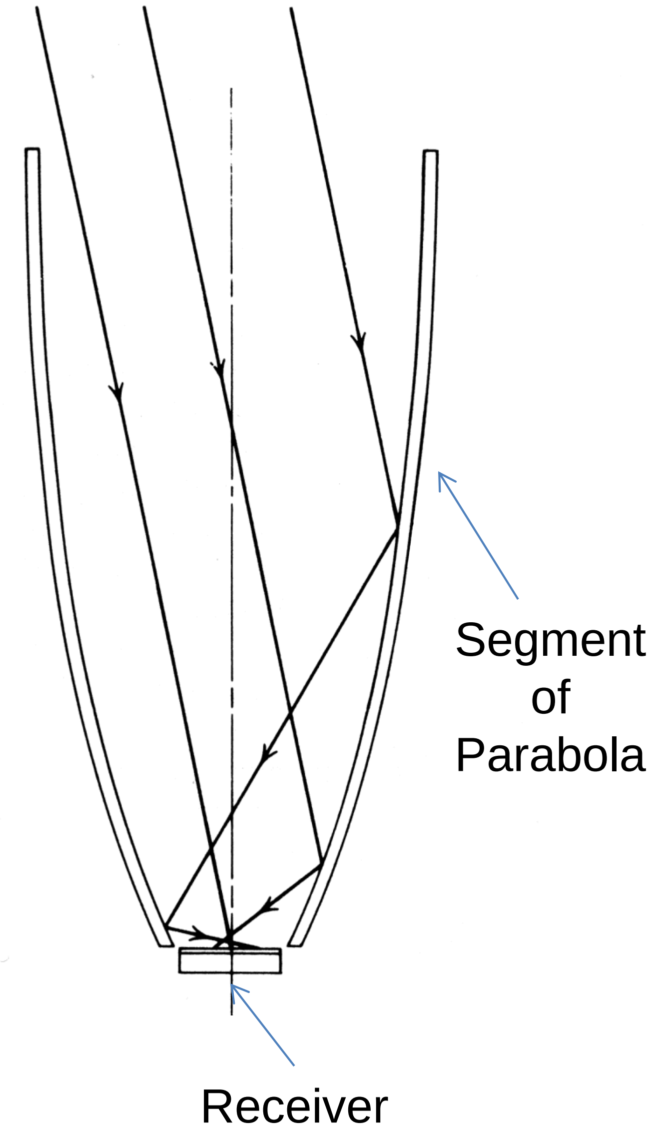
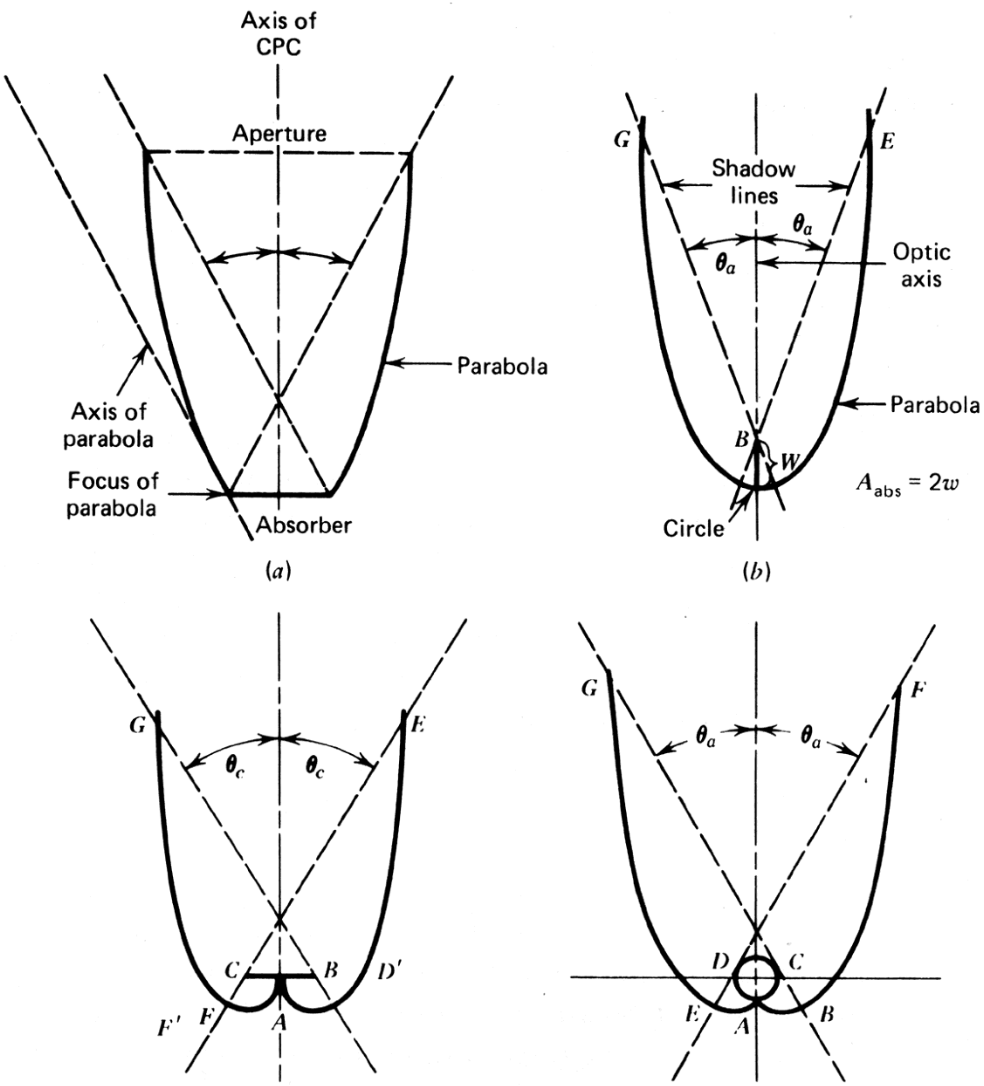
Compound Parabolic Concentrators (CPC)

- Mirrors shaped in the form of segments of parabolas are attached to the receiver (collector).
- Entering sun rays will either hit the receiver directly, or be reflected by the parabolic segments and hit the receiver.
- The concentration ratio can be as high as 5.

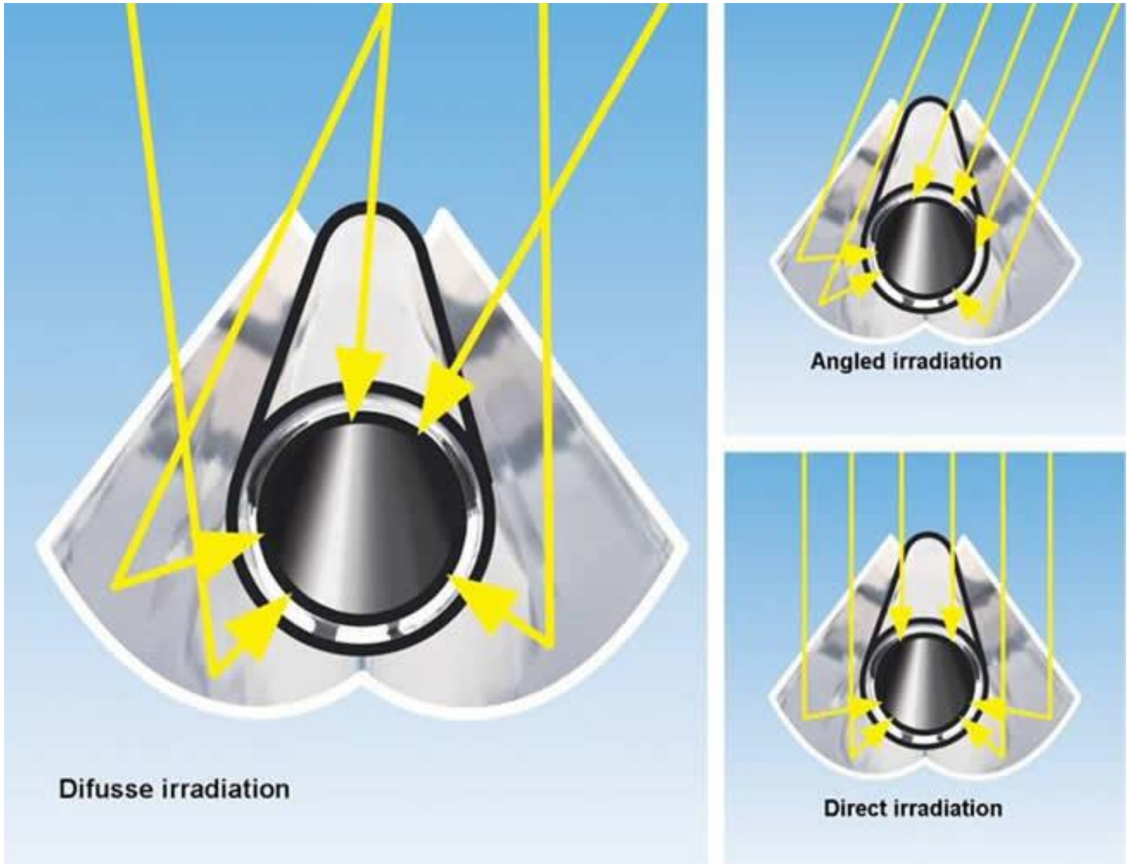


Variations of CPC

- One of the key parameters in CPC is the acceptance angle (θ_a).
- It is defined as the total angle the sun can move through without its image missing the receiver.



- If designed properly, CPC can absorb direct and diffuse irradiation.
- Direct irradiation can be normal to the aperture or angled.



Compound Parabolic Concentrators (CPC)

- For flat collectors, the useful energy gain is given by:

$$Q_u = A_c[G_t(\tau\alpha) - U_L(T_p - T_a)]$$

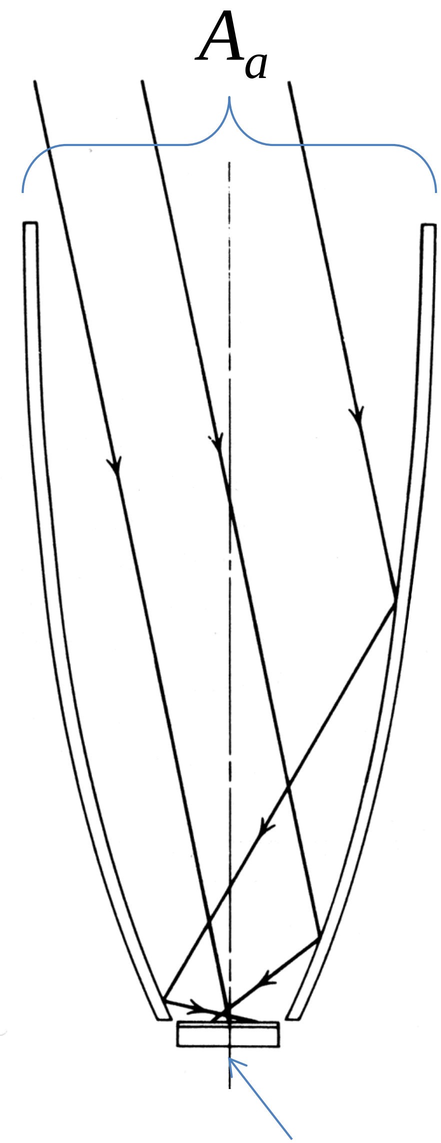
where A_c is the both the area of collector and the area of aperture, i.e. concentration ratio is 1.

- In CPC, the useful energy gain is given by:

$$Q_u = A_a\, G_t\, (\tau\, \alpha\, \rho_{eff}) - A_c\, U_L\, (T_p - T_a)$$

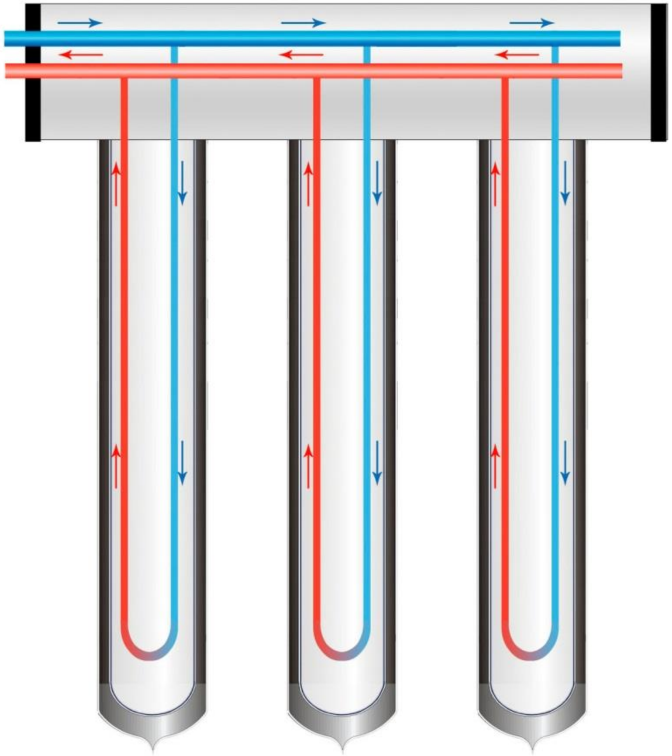
where ρ_{eff} is the effective reflectance of the parabolic segments.

- Q_u will be higher because $A_a > A_c$



Compound Parabolic Concentrators (CPC)

- The receiver tube can be a heat pipe (like evacuated tube collectors presented earlier)
- It can also have two small internal tubes to carry the working fluid itself (e.g. water).

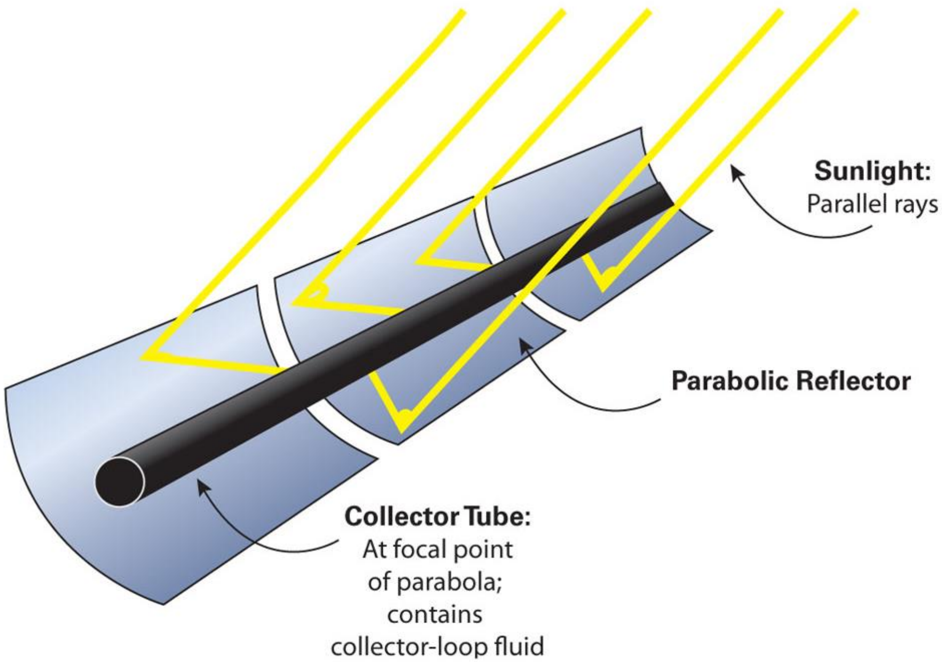


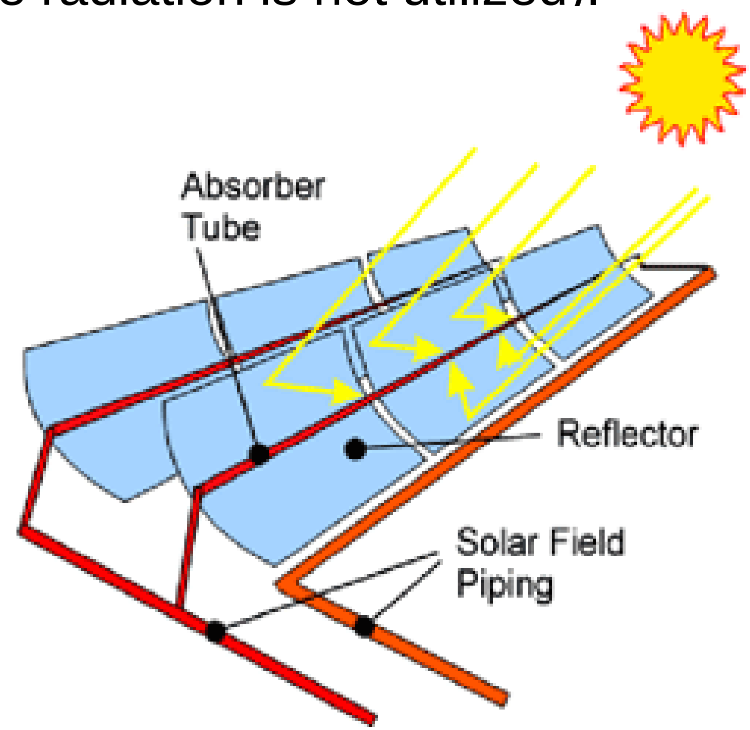
Types of Concentrating Collectors

- Flat plate collector with flat reflectors
- Compound parabolic concentrators
- Parabolic trough collectors
- Linear Fresnel collectors
- Central receiver systems
- Parabolic dish collectors

Parabolic Trough Collectors (PTC)

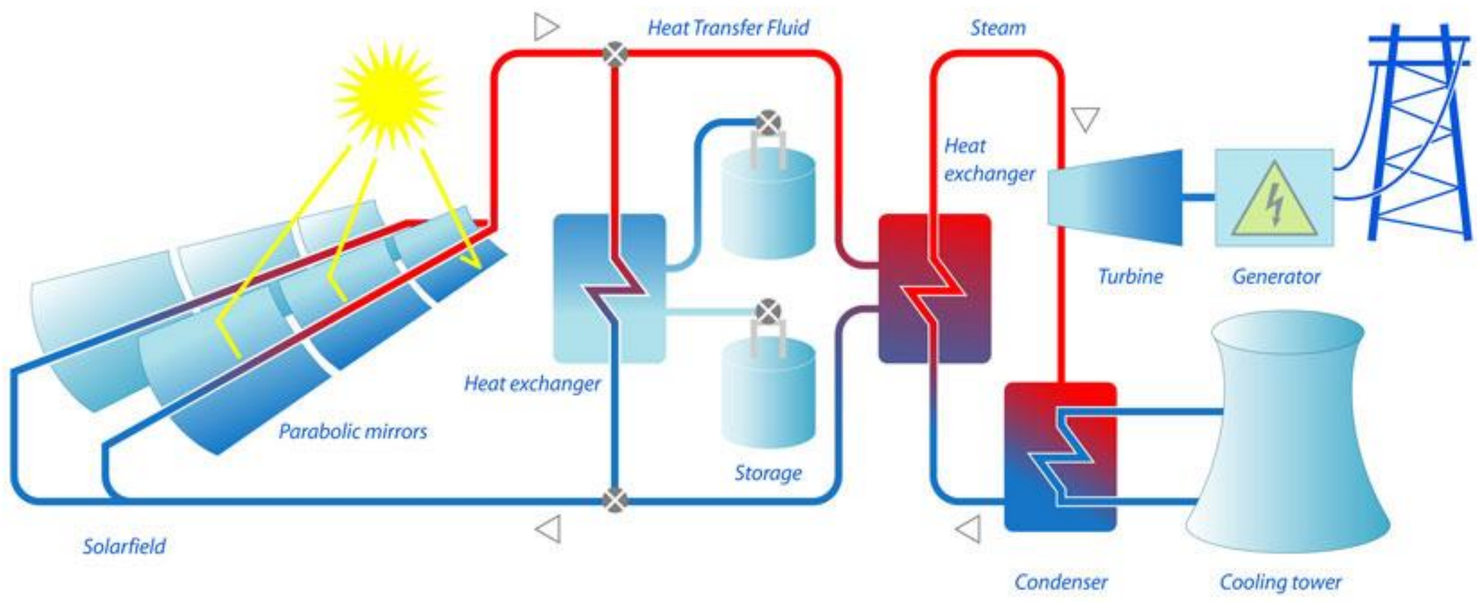
- A long parabolic-shaped mirror reflects sunlight to a focal line.
- Along the focal line, a receiver tube is placed.
- The receiver tube carries a working fluid, and the fluid is heated.
- The concentration ratio is usually about 70-80.
- Typically, the temperature can be as high as 400°C.
- PTCs only capture direct irradiation (diffuse radiation is not utilized).





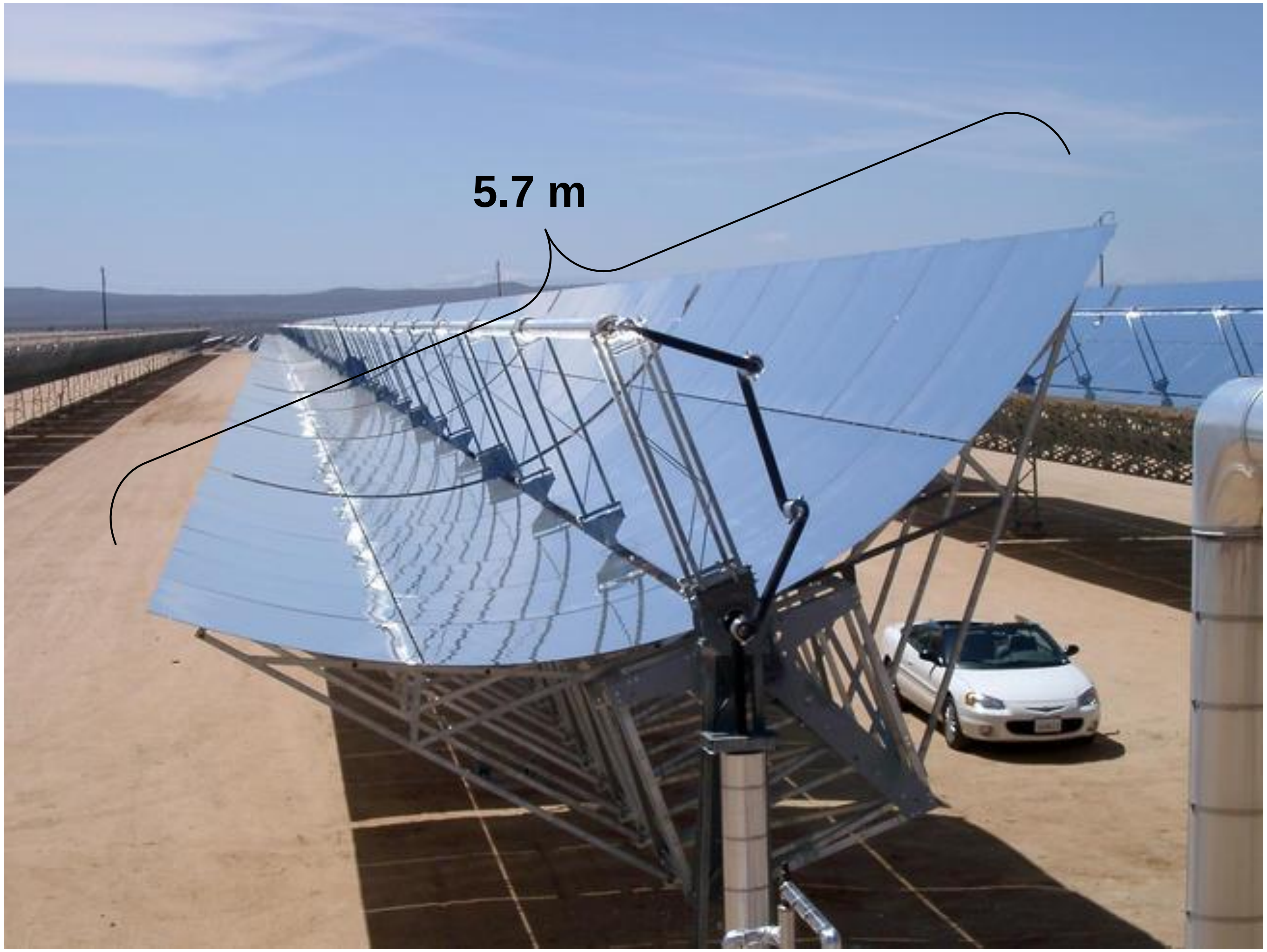
Parabolic Trough Collectors (PTC)

- The hot fluid exchanges heat with water and generates steam.
- The steam is fed to a steam turbine to generate power.
- Some of the hot fluid is stored in a tank.
- This idea is called ***thermal energy storage (TES)***.
- Once the sun sets, the fluid can be extracted from the hot storage tank to continue generating steam (and power) at night.



Parabolic Trough Collectors (PTC)

- The aperture width of a commercial PTC is about 5.7 m.

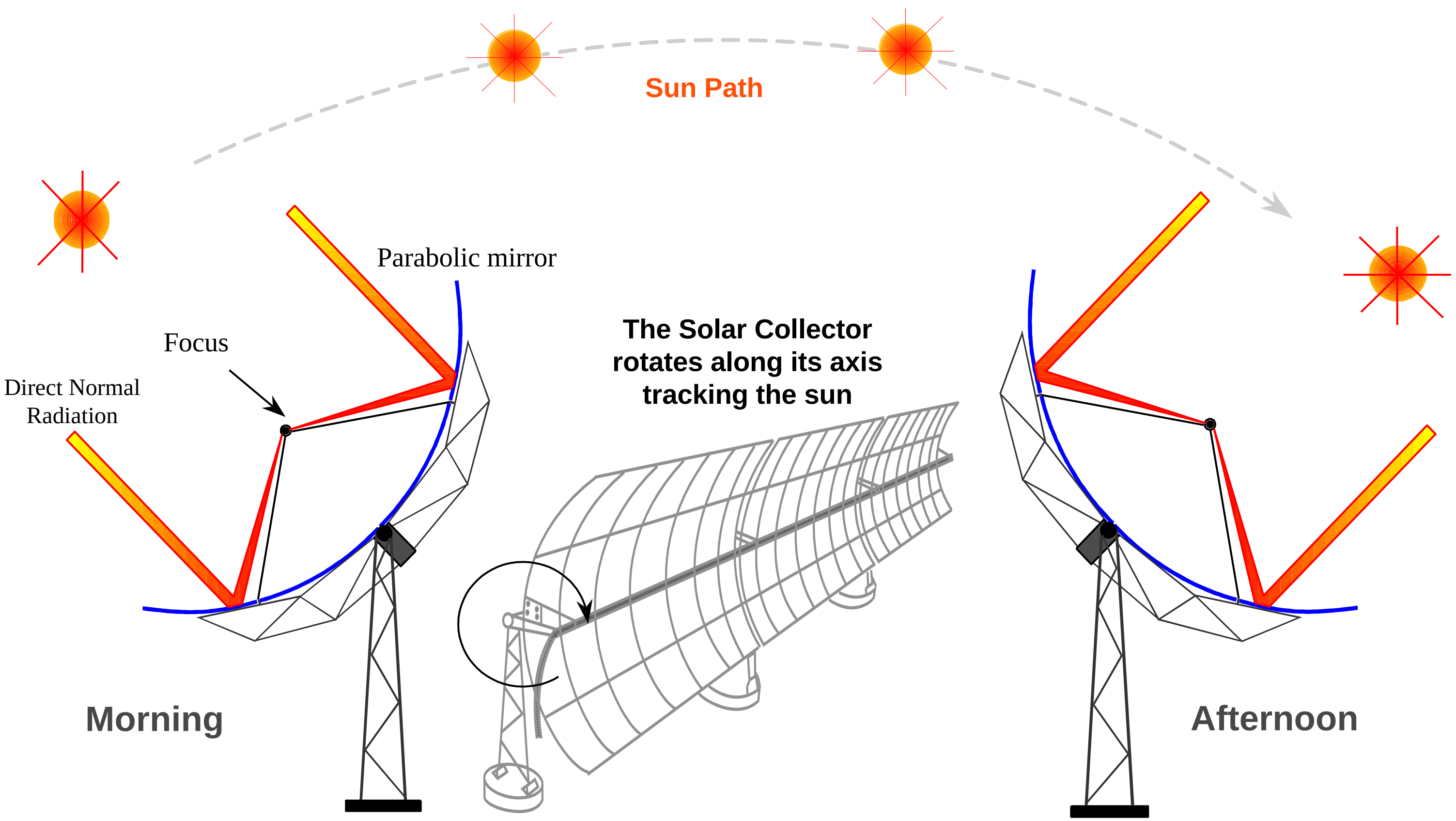


Parabolic Trough Collectors (PTC)

- Commercial PTC plants are large in size and capacity.
- Shams 1 in UAE produces about 100 MW of power.

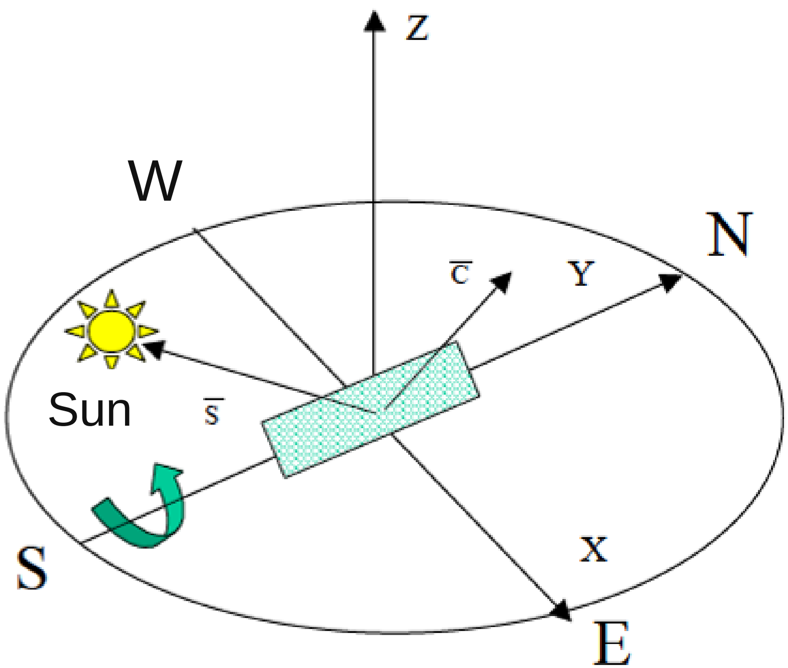
Parabolic Trough Collectors (PTC)

- In order for the PTC to focus sunlight on the receiver at all times, a tracking mechanism is needed.
- PTCs track the sun in only one axis.

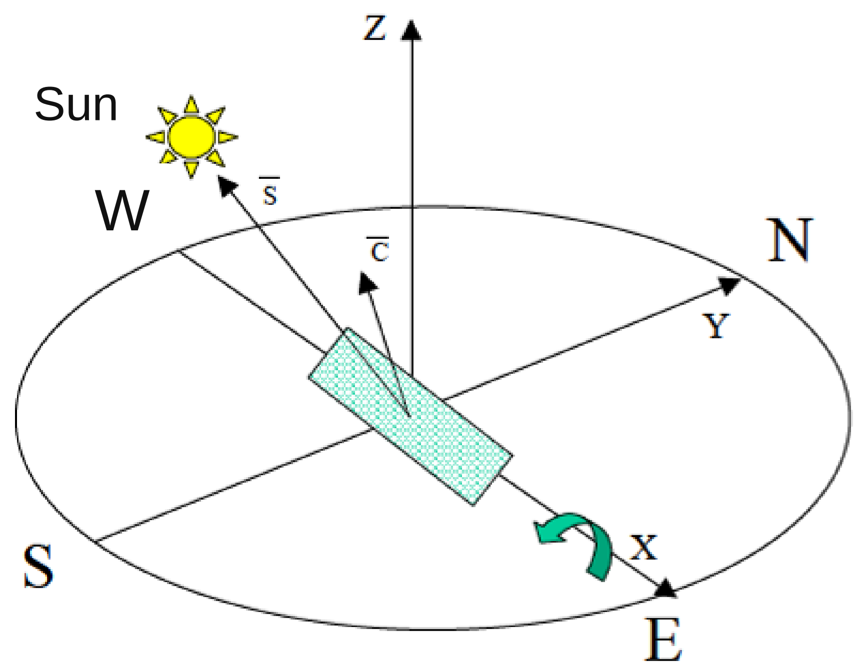


Parabolic Trough Collectors (PTC)

- Tracking could be along a north-south axis or an east-west axis.



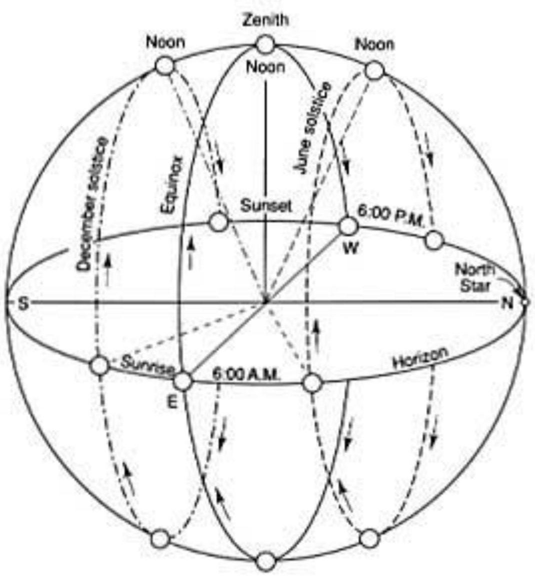
North-South collector axis orientation



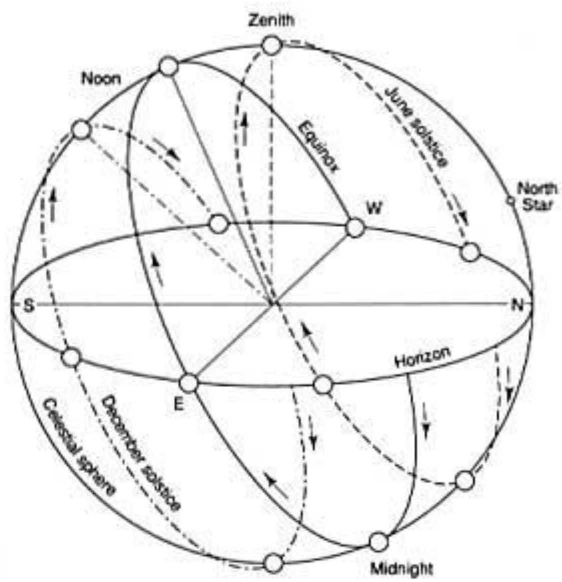
East-West collector axis orientation

Parabolic Trough Collectors (PTC)

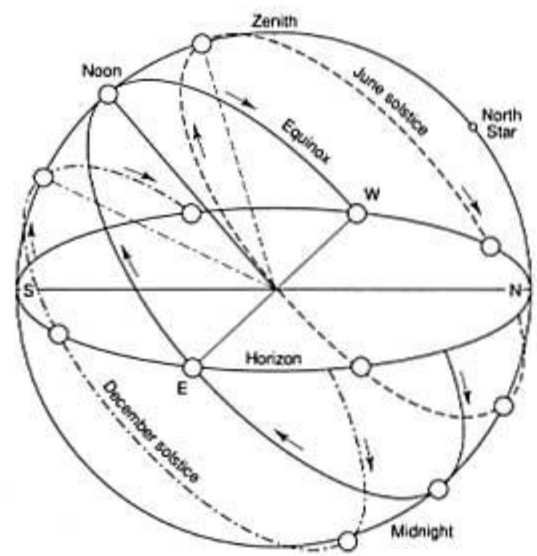
- Tracking on a north-south axis is more suitable for lower latitudes (e.g. Saudi Arabia, GCC, North Africa).
- Tracking on an east-west axis is more suitable for higher latitudes (e.g. Europe, North America).



Equator 0° Lat.



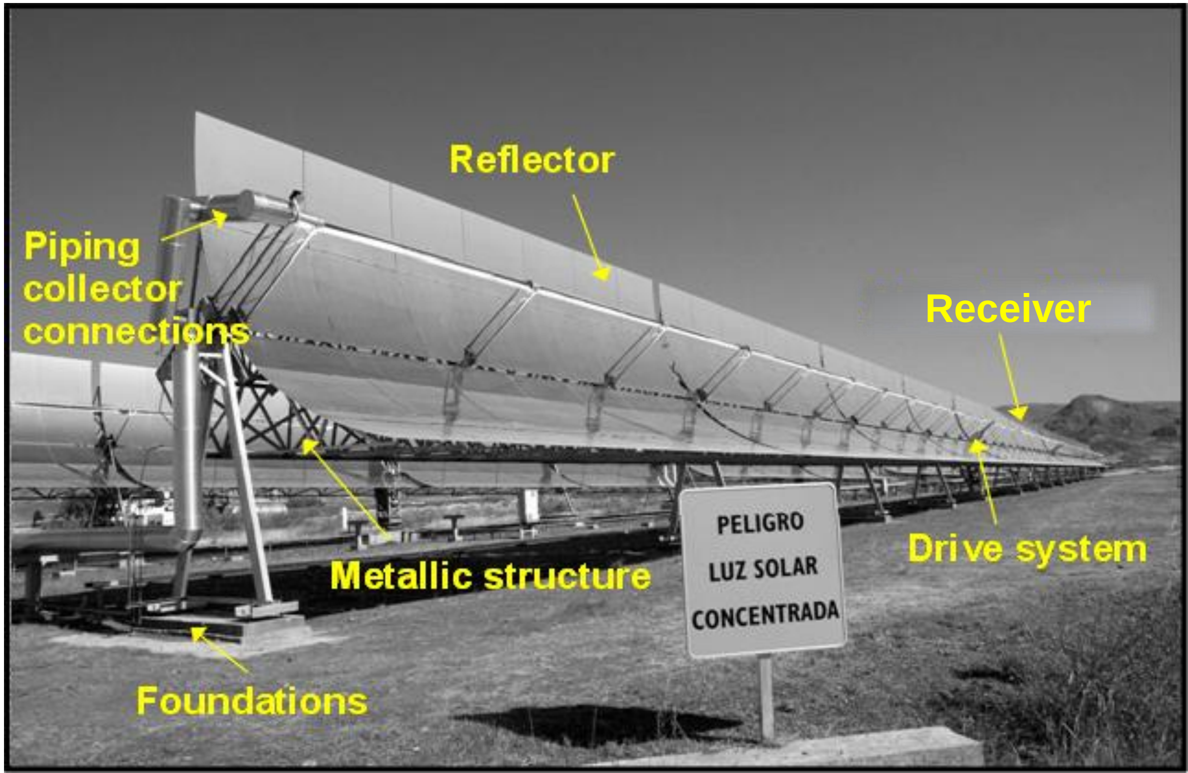
23½° N Tropic of Cancer



41° N New York City

Parabolic Trough Collectors (PTC)

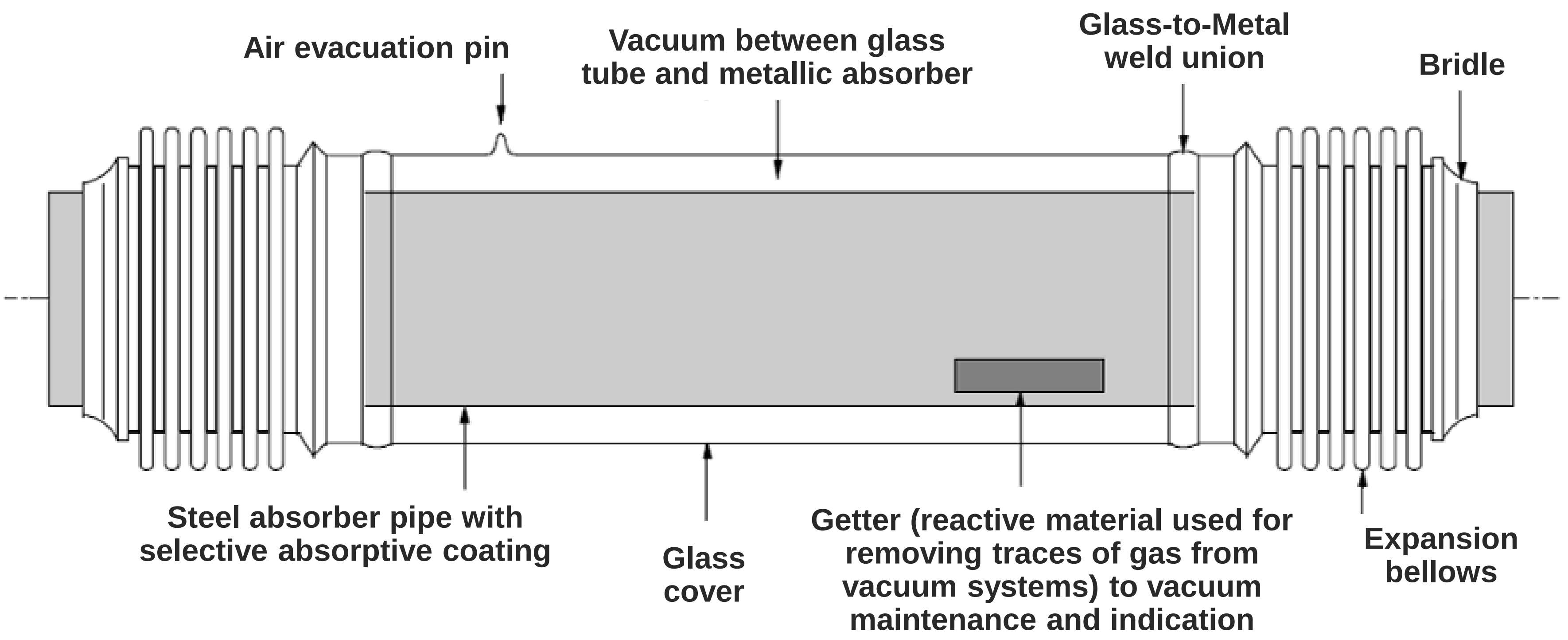
- The main components of a PTC are:
  - **Reflector**
  - **Receiver**
  - **Support structure**
  - **Piping**
  - **Drive system**



Parabolic Trough Collectors (PTC)

RECEIVER

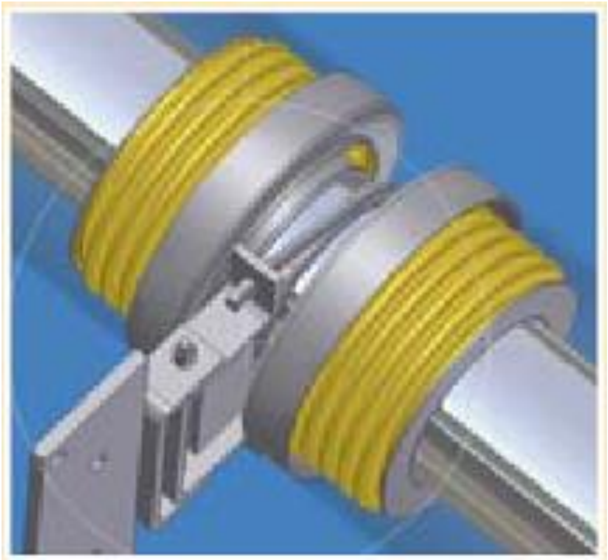
- The receiver is made of a metal tube (usually steel).
- Metal tube is enclosed in a glass tube, and the space between them is evacuated to eliminate conduction and convection heat losses.

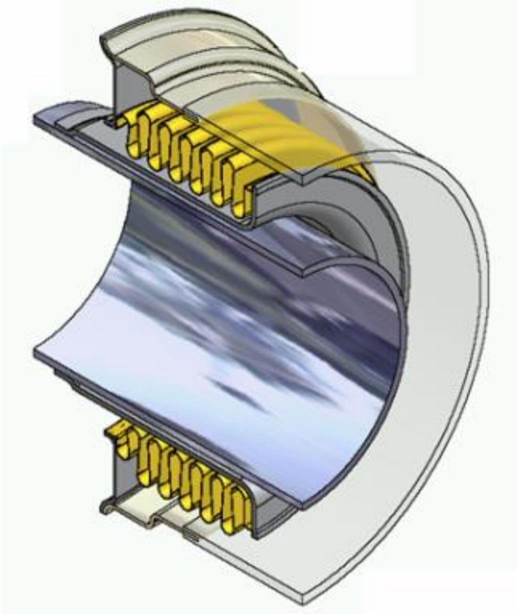


Parabolic Trough Collectors (PTC)

RECEIVER

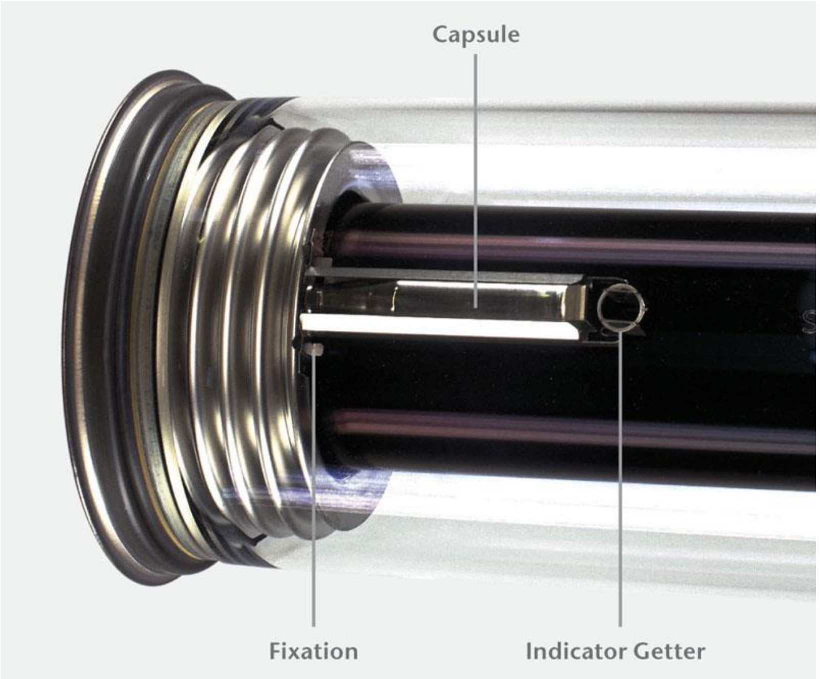
- The metal tube has selective coating (high absorptance and low emittance) to maximize energy gain and minimize radiation heat loss.
- Bellows allow the metal tube to expand without affecting the glass tube (whose thermal expansion is much lower) to avoid breaking the glass.

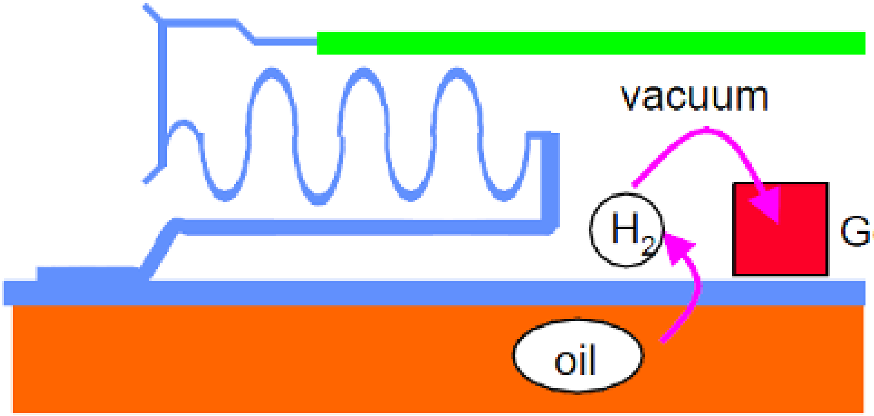




RECEIVER

- The Getter absorbs hydrogen that leaves the working fluid (oil), penetrates the metal tube, and gets to the space between the metal and glass tubes.
- If hydrogen builds up in the annular region, conduction and convection losses will increase.





WORKING FLUIDS

- The most common working fluids are synthetic oils.

Advantages

- Good heat transfer and chemical stability.
- Low viscosity at high temperatures.

Disadvantages

- Limited maximum temperature (about 390 C).
- Pollution and fire hazards.

WORKING FLUIDS

- New working fluids are being investigated:
  - **Molten salts**
  - **Direct steam generation**
  - **Gas**

Parabolic Trough Collectors (PTC)

WORKING FLUIDS

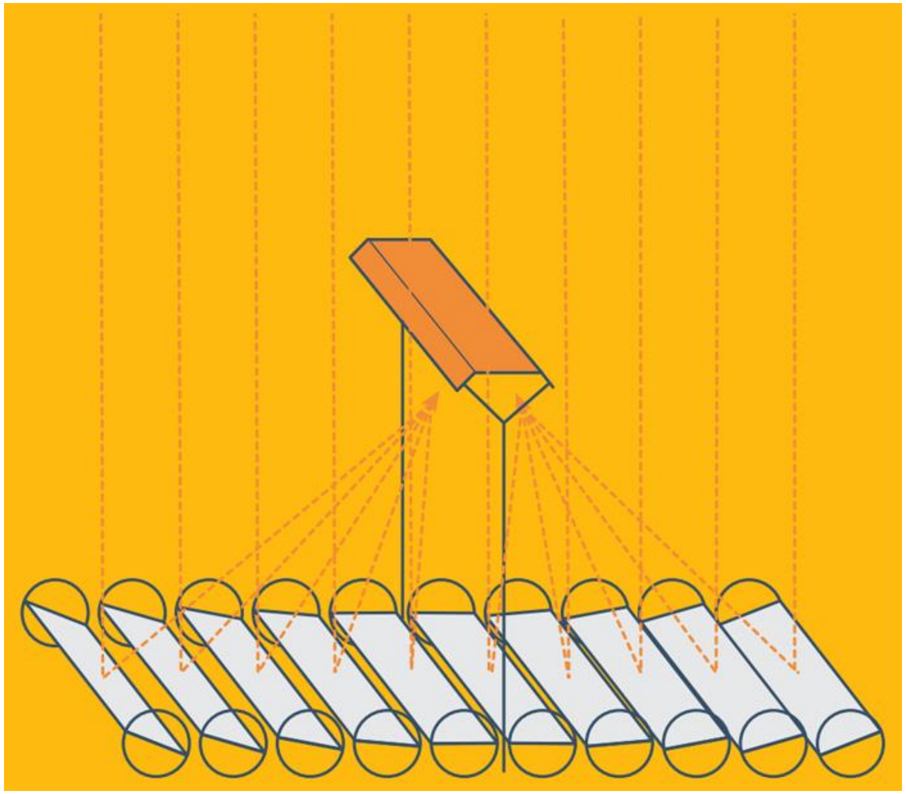
Fluid	Advantages over thermal oil	Disadvantages compared to oil
Molten salts	- More efficient heat storage - Higher steam temperature - No pollution or fire hazards	- High crystallization point - More complex solar field design - Higher electricity consumption
Direct Steam Generation	- Simple plant design - Higher steam temperature - No pollution or fire hazards	- Lack of suitable storage system - More complex solar field control - Solar field higher pressure
Gas	- Higher steam temperature - No pollution or fire hazards	- Poor heat transfer in the receiver tubes - Solar field higher pressure

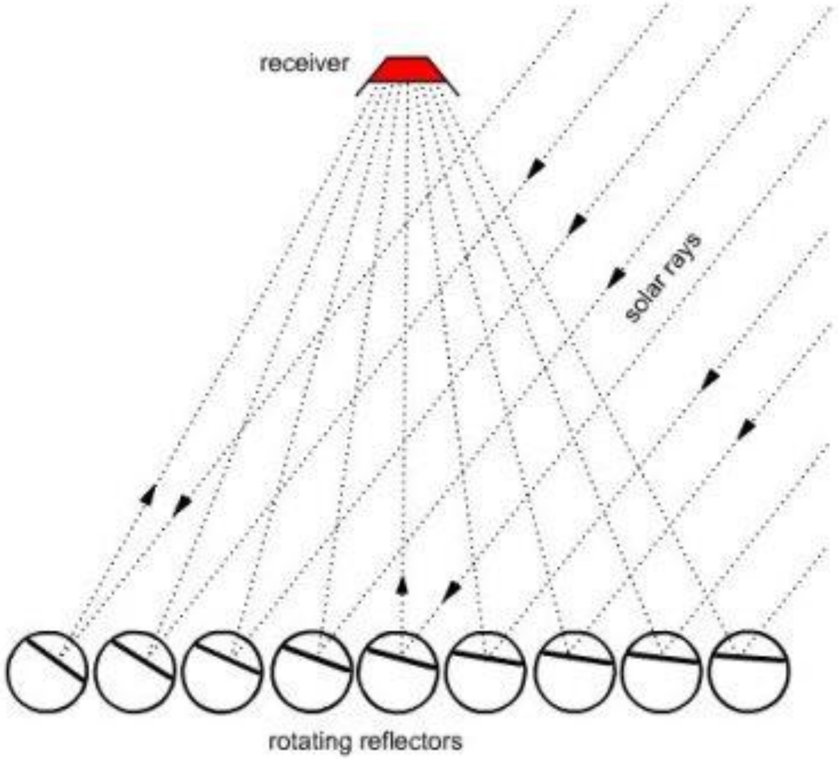
Types of Concentrating Collectors

- Flat plate collector with flat reflectors
- Compound parabolic concentrators
- Parabolic trough collectors
- Linear Fresnel collectors
- Central receiver systems
- Parabolic dish collectors

Linear Fresnel Collectors (LFC)

- LFCs are similar to PTCs, but the parabola is divided into many small, nearly flat, and long mirrors.
- Each mirror moves independently, but all the mirrors move simultaneously to concentrate sunlight on the linear absorber located in optical focus.



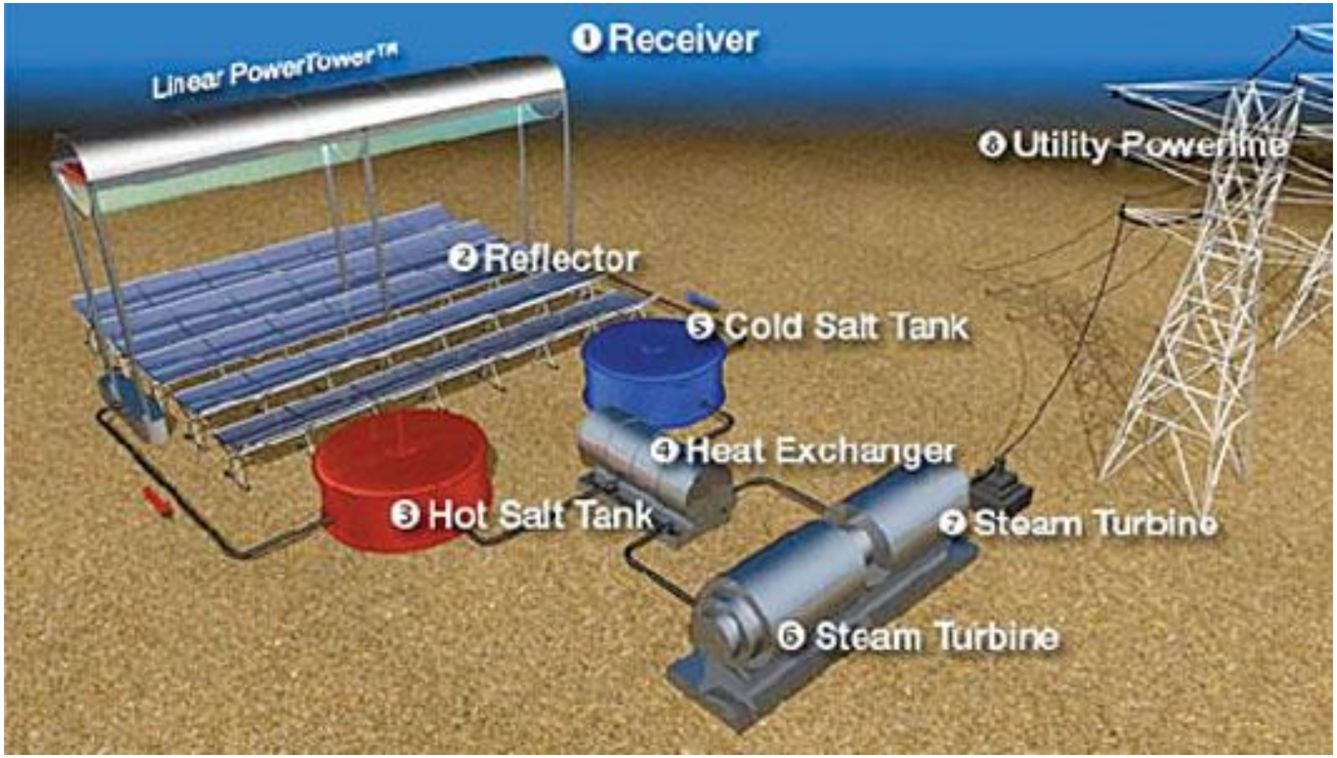


Linear Fresnel Collectors (LFC)

- LFCs have one-axis tracking, just like PTCs.
- The focal line is usually high above the mirrors.
- Along the focal line, a receiver tube is placed.

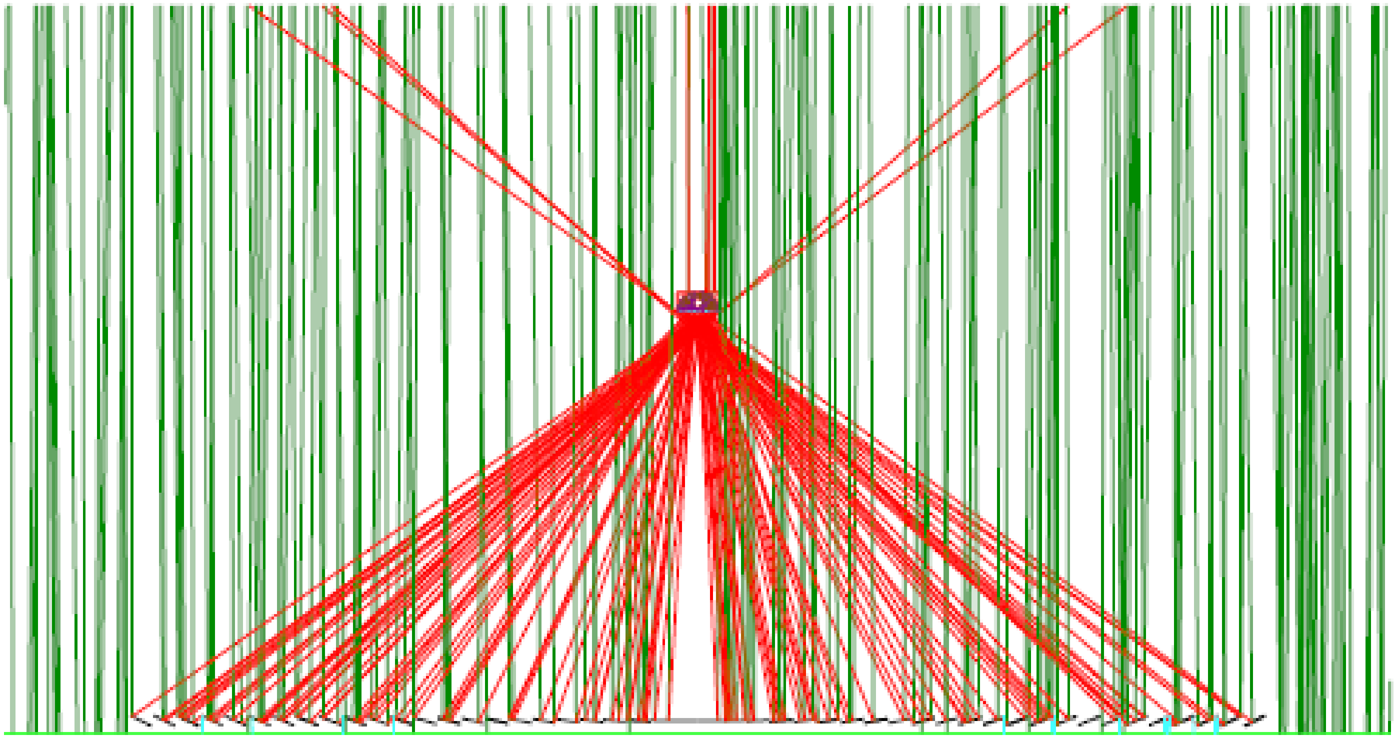
Linear Fresnel Collectors (LFC)

- The receiver tube carries a working fluid, and the fluid is heated.
- The rest of the system is similar to PTCs.
- The concentration ratio is usually about 50-60.
- Typically, the temperature can be as high as 400°C.
- LFCs only capture direct irradiation (diffuse radiation is not utilized).



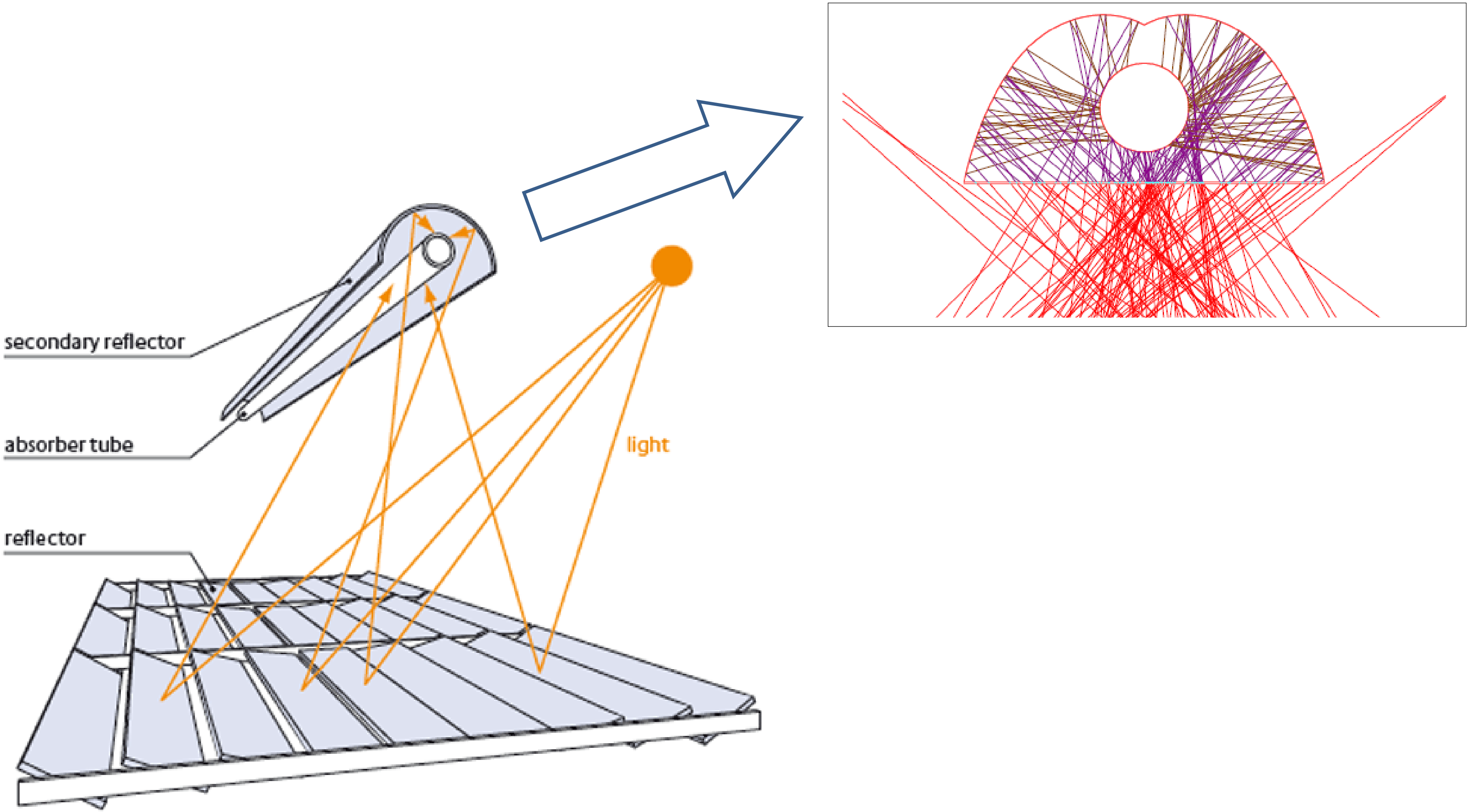
Linear Fresnel Collectors (LFC)

- The large height can cause reflected sunlight not to hit the receiver directly:
    - **Tracking error.**
    - **Dispersion of light by imperfect mirror surface.**
    - **Dispersion of light by particulates in the atmosphere.**



Linear Fresnel Collectors (LFC)

- In many cases, a secondary reflector is needed to capture scattered sunlight.



Linear Fresnel Collectors (LFC)

ADVANTAGES

- Flat (or slightly curved mirrors) are less expensive than parabolic mirrors.
- Wind effect is minimal because mirrors are small and close to the ground.
- Less land space is needed.

Linear Fresnel Collectors (LFC)

DISADVANTAGES

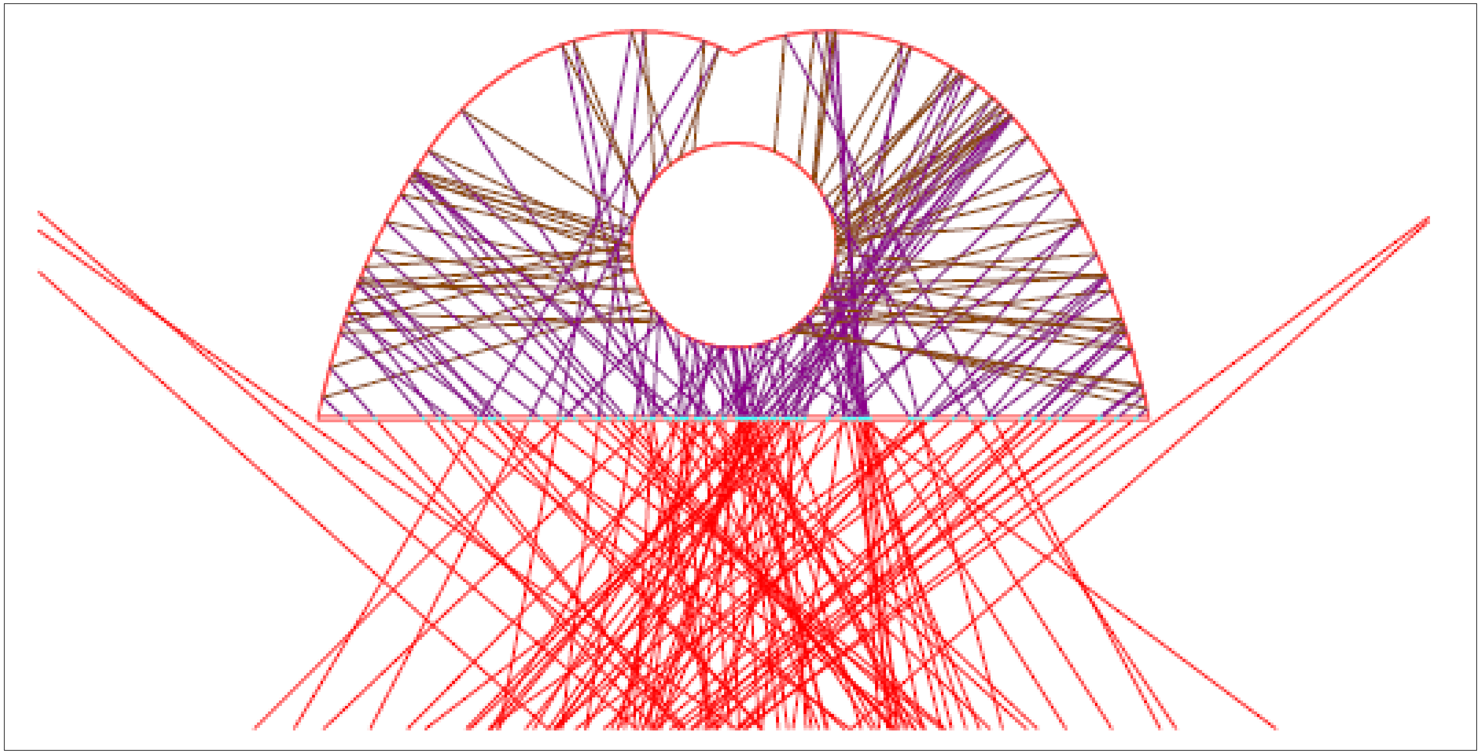
Lower efficiency than PTCs

- **Shading in the early morning and late afternoon is significant.**

DISADVANTAGES

Lower efficiency than PTCs

- **Energy loss due to reflectance of secondary reflector.**

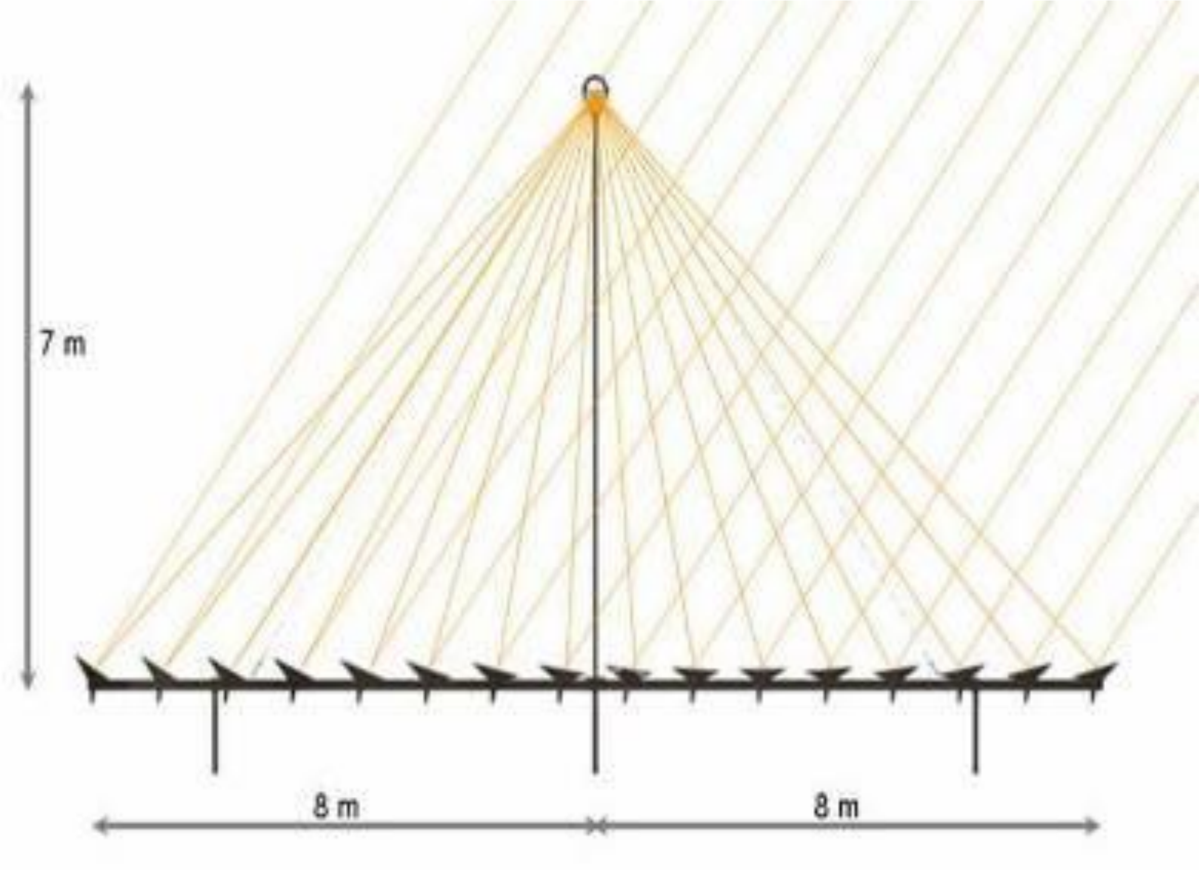


Linear Fresnel Collectors (LFC)

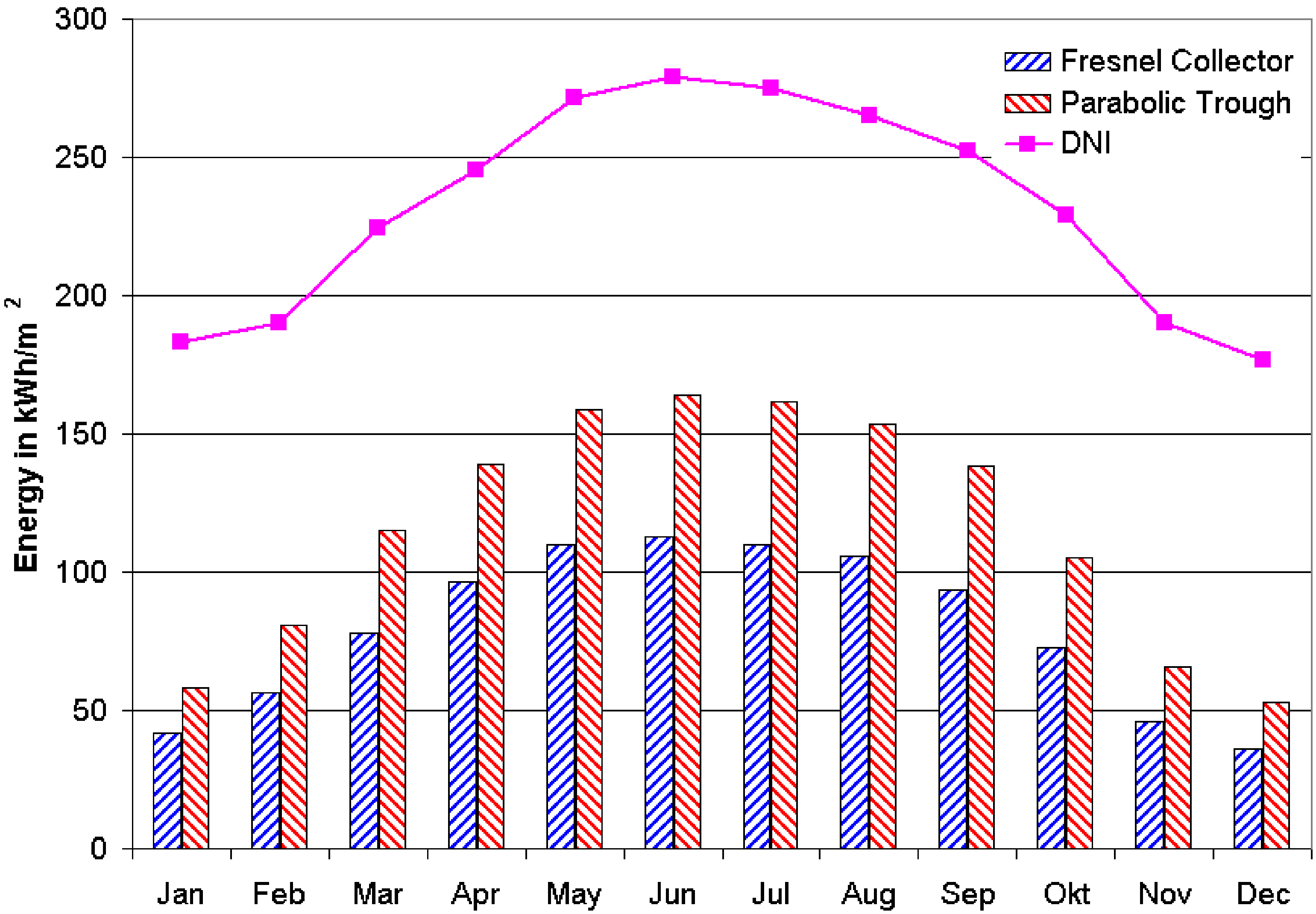
DISADVANTAGES

Lower efficiency than PTCs

- **Larger incidence angles.**



LFC/PTC Performance Comparison



Examples of LFC Power Plants

Capacity: 1.4 MW
Solar Field Size: 18,000 m²
Location: Murcia, Spain

Examples of LFC Power Plants

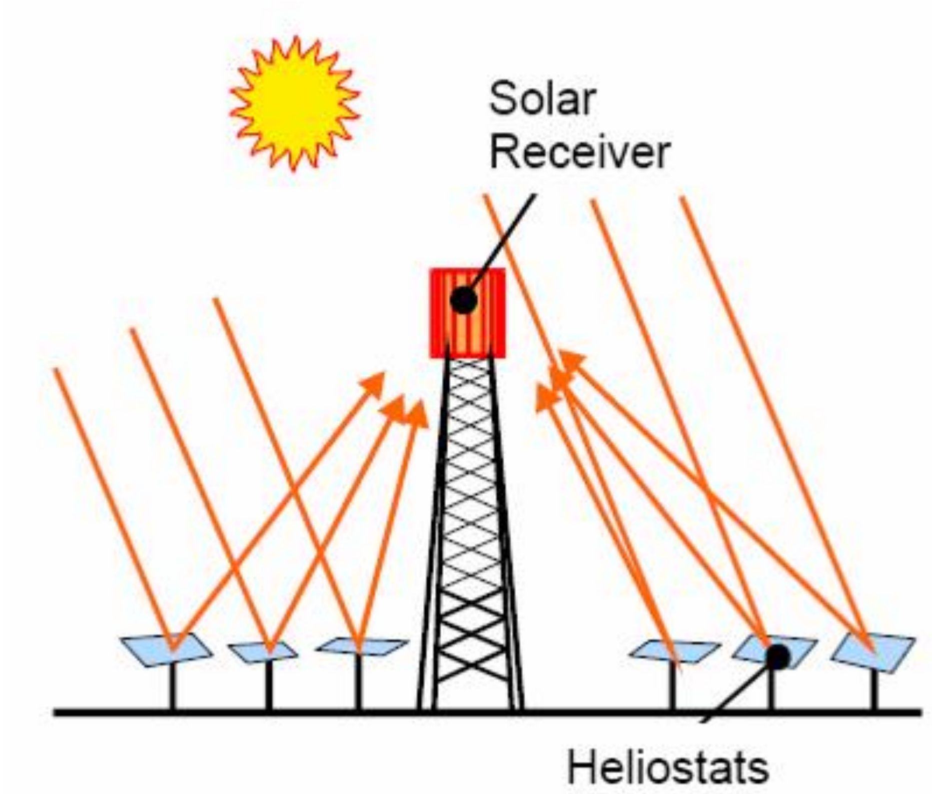
Capacity: 5 MW
Solar Field Size: 26,000 m²
Location: Bakersfield, California, USA

Types of Concentrating Collectors

- Flat plate collector with flat reflectors
- Compound parabolic concentrators
- Parabolic trough collectors
- Linear Fresnel collectors
- Central receiver systems
- Parabolic dish collectors

Central Receiver Systems

- Large mirrors (called heliostats) concentrate sunlight on the top of a central receiver mounted at the top of a tower.
- A working fluid passes through the receiver and absorbs the highly concentrated sunlight reflected by the heliostats.



Central Receiver Systems

- The thermal energy is used to generate superheated steam for the turbine.
- To keep sunlight focused on the central receiver, the heliostats need to track the sun in two axes.
- The concentration ratio is usually higher than 500.
- Theoretically, temperature can be very high (>1000°C).
- Central receiver systems only capture direct irradiation.

Central Receiver Systems

ADVANTAGES

- The attainment of high temperatures makes possible the achievement of higher efficiencies in power cycles.

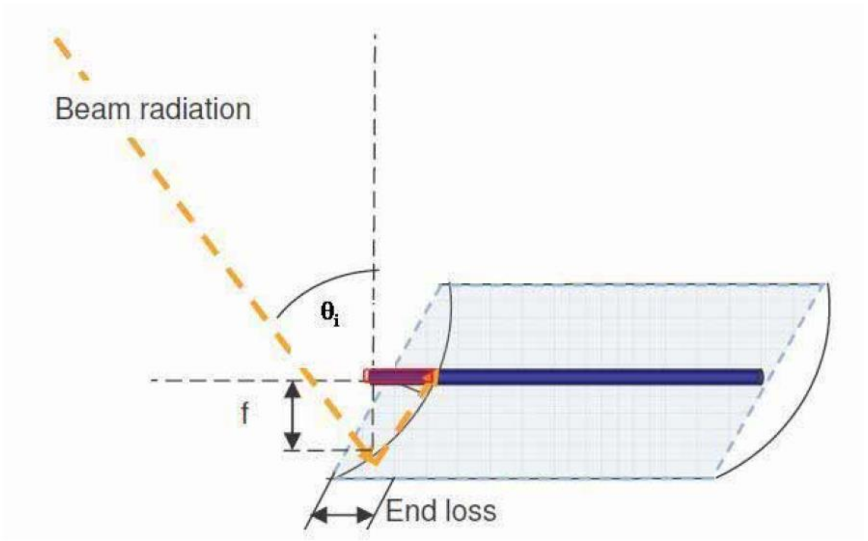
Concentration Ratio	η_{max} (%)	T_{opt} (ºC)
50	*23*	*330*
500	*39*	*700*

Central Receiver Systems

King Saud University

ADVANTAGES

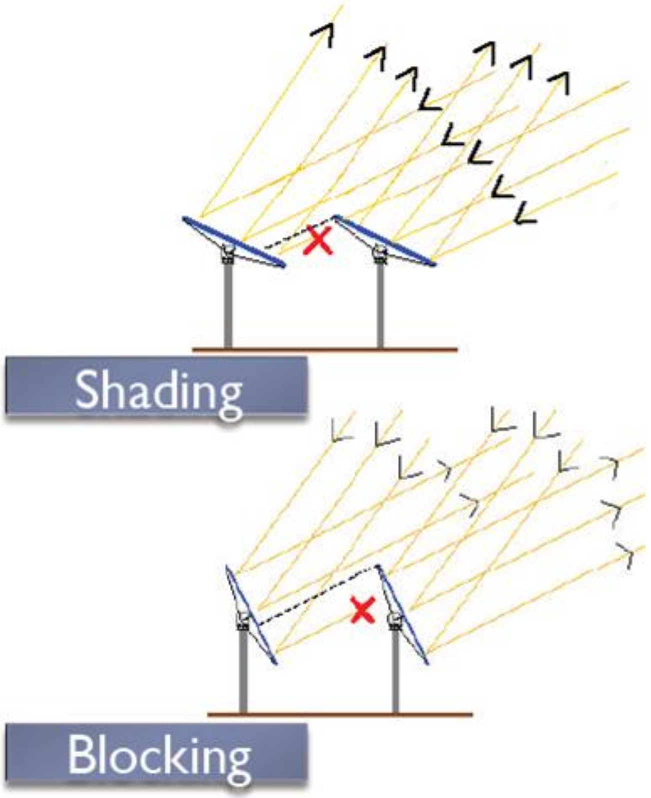
- Two-axis tracking means that more the incident irradiance can be reflected to the receiver than PTC or LFC.
  - **PTC and LFC can have end losses.**



Central Receiver Systems

DISADVANTAGES

- High land requirement (only 20% of land is utilized by heliostats) to avoid shading and blocking, especially for the far-field heliostats.
- Possibility of higher operation and maintenance cost due to higher distribution of the solar field.



Central Receiver Systems

DISADVANTAGES

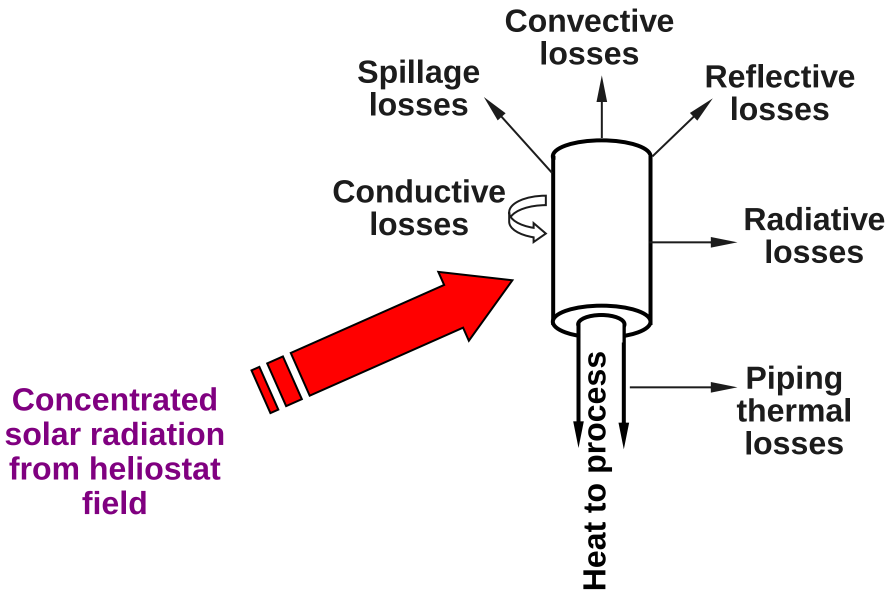
- Tracking error and atmospheric dispersion (attenuation) can lead to ***spillage***, especially from far heliostats.
  - **A percentage of the reflected sunlight will not hit the receiver.**

Central Receiver Systems

DISADVANTAGES

- High efficiency at high temperature requires high absorptance and low emittance values.
  - **There are no selective coatings that can operate at such high temperatures without vacuum.**

This problem and the associated thermal losses from an ***external receiver*** *can be solved by using a* ***cavity receiver***



CAVITY RECEIVER DESIGN

- Tubes are placed inside a cavity.
- The cavity reduces convection losses.
- It also reduces radiation losses:
- Radiation reflected or emitted by one tube will have a higher possibility of hitting another tube.

FIELD DESIGNS

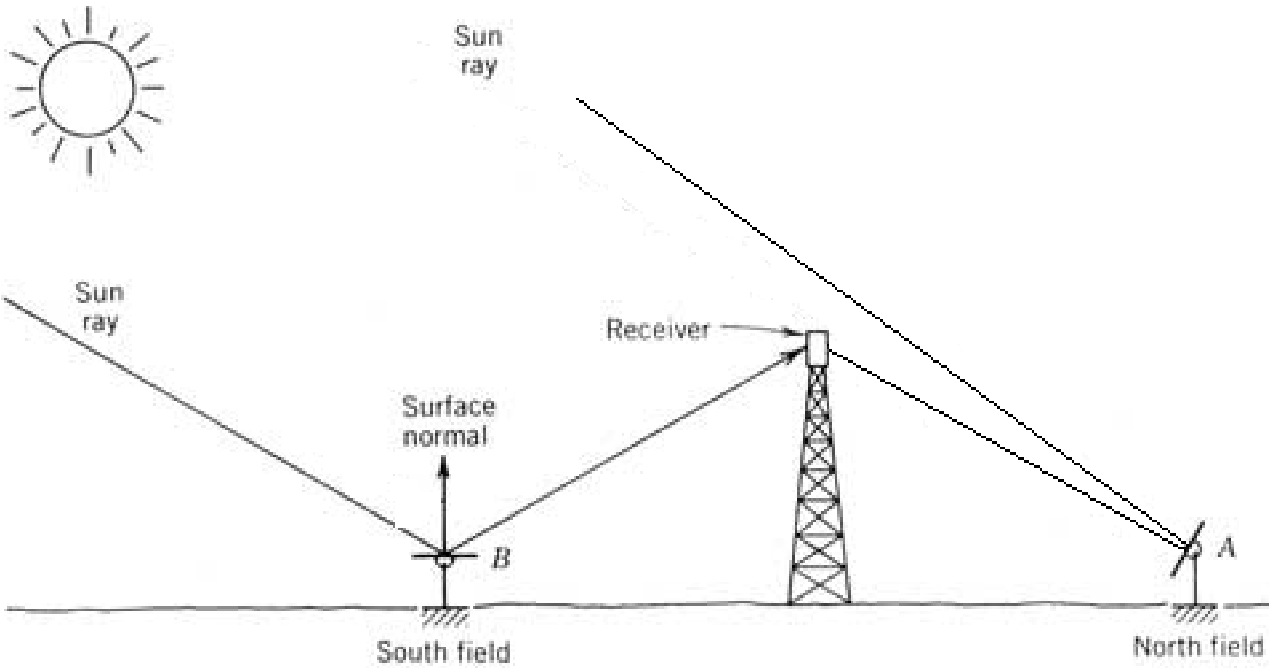
- There are two types of field designs:
  - **Surround field**
  - **North field**

Surround Field

North Field

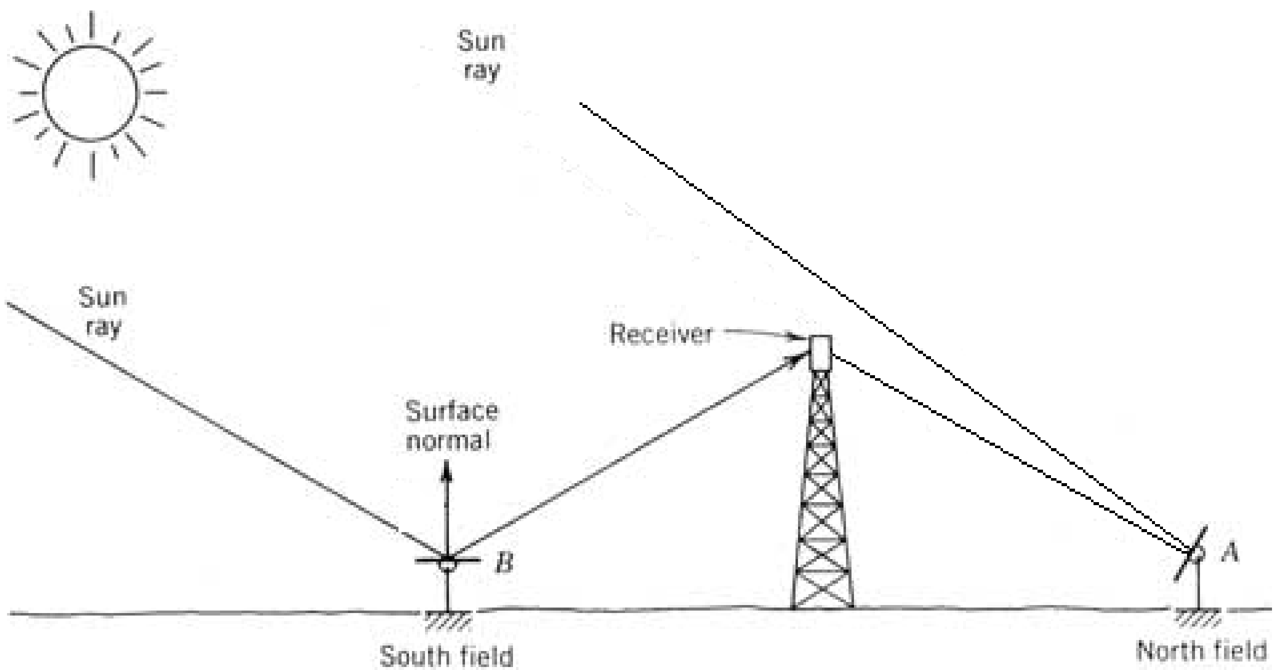
SURROUND FIELD

- More mirror surface area → Larger capacity plants
- The mirrors on the south side of the field are not as useful as the mirrors on the north side (large incidence angles)
- Cavity design is not practical.



NORTH FIELD

- Most mirrors have low incidence angles → More radiation is reflected.
- Cavity design is possible.
- Land use is high.

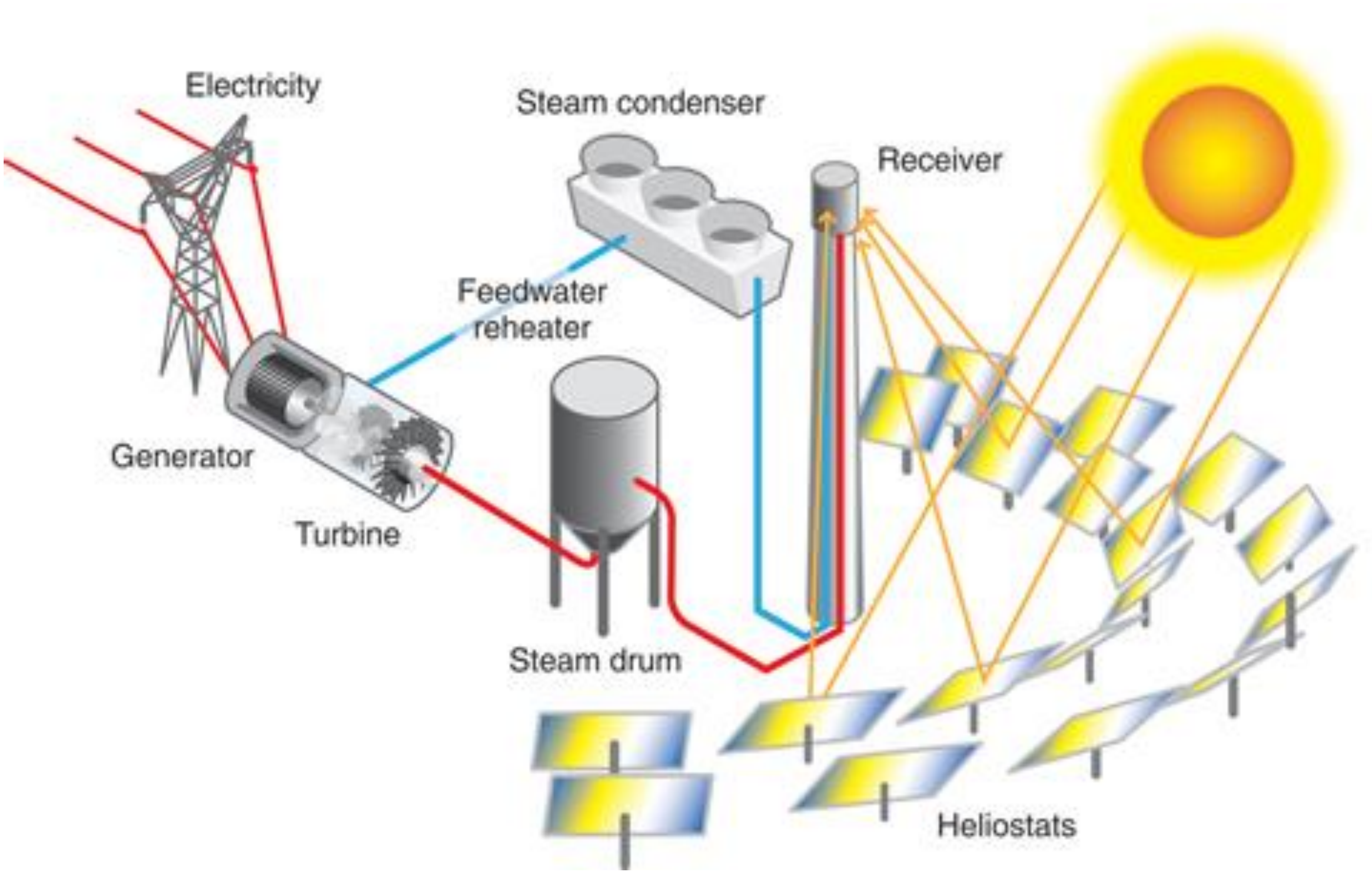


WORKING FLUIDS

- System configuration varies depending on the working fluid.
- Most common working fluids are:
  - **Steam**
  - **Molten Salt**
- Other fluids being investigated are:
  - **Air**
  - **Solid particles**

Central Receiver Systems

STEAM PLANTS



Central Receiver Systems

STEAM PLANTS

PS10 and PS20 in Seville, Spain

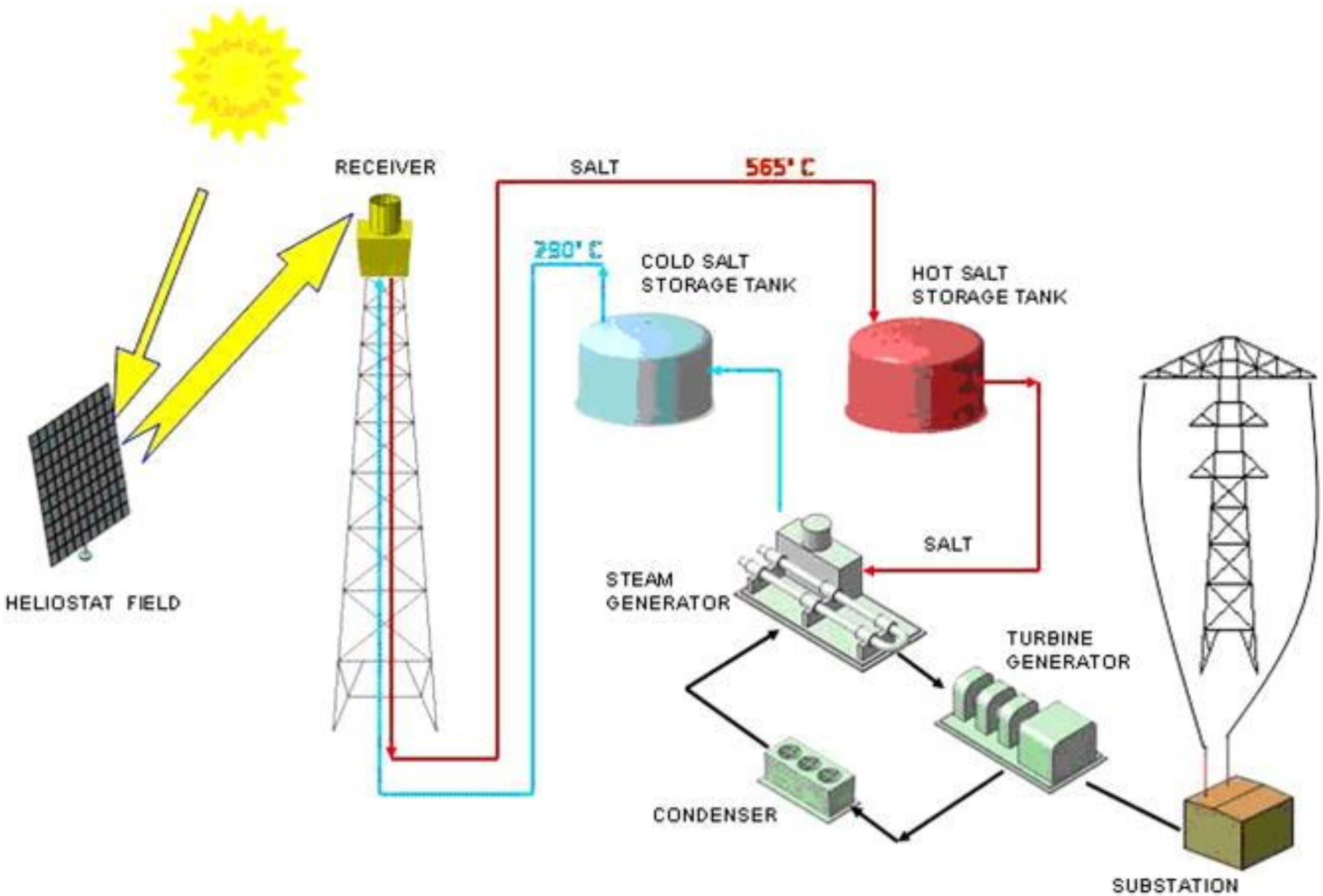
Capacity: 11 MW and 20 MW

STEAM PLANTS

Ivanpah Solar Power Facility, California, USA

Capacity: 392 MW

MOLTEN SALT PLANTS



Central Receiver Systems

MOLTEN SALT PLANTS

Gemasolar: Seville, Spain

Capacity: 20 MW

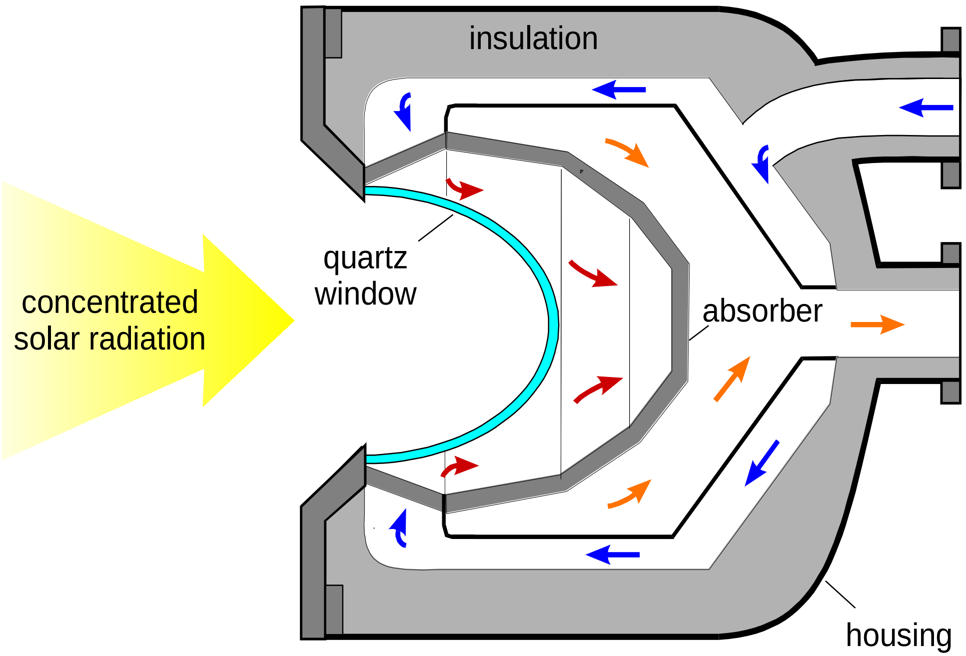
15 hours of storage

ATMOSPHERIC AIR RECEIVERS

- Concentrated sunlight hits a porous structure.
- Air is drawn into the porous structure and gets directly heated.
- Hot air goes to a steam generator.

PRESSURIZED AIR RECEIVERS

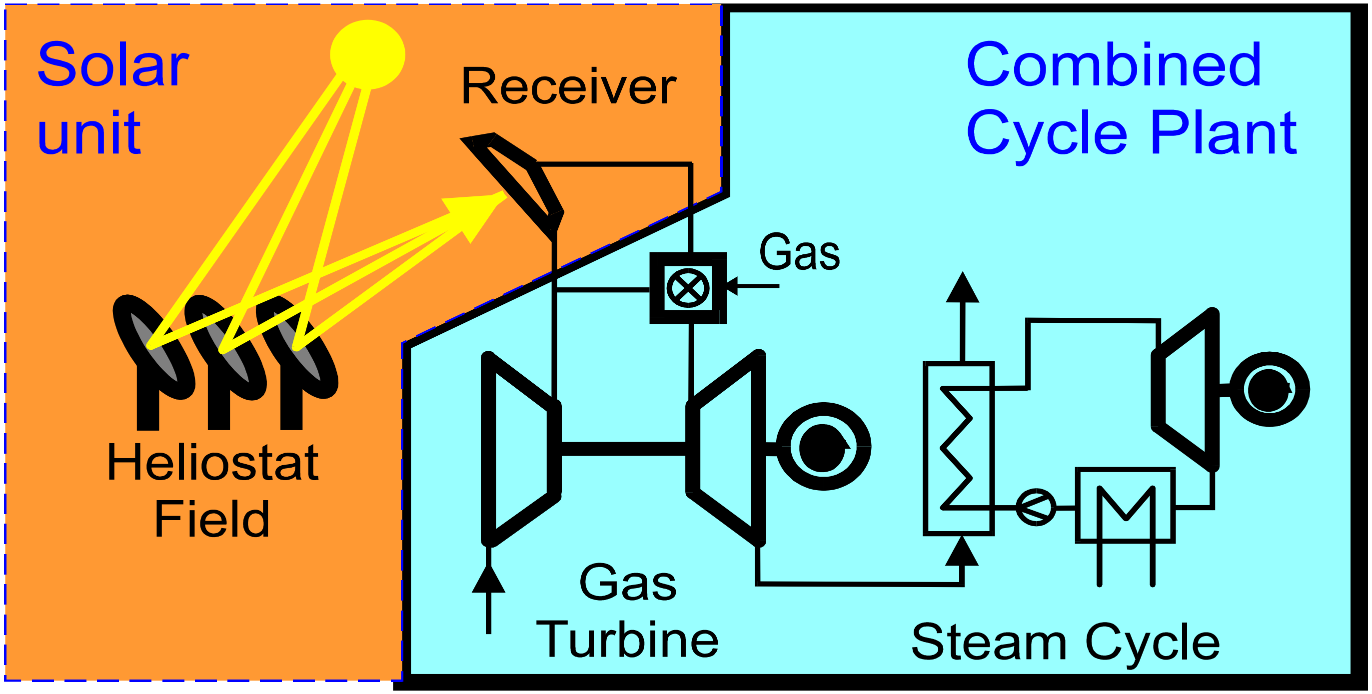
- Concentrated sunlight enters a sealed cavity through a quartz window and hits an absorber.
- Pressurized air is pushed through the cavity and gets heated as it passes by the absorber.



Central Receiver Systems

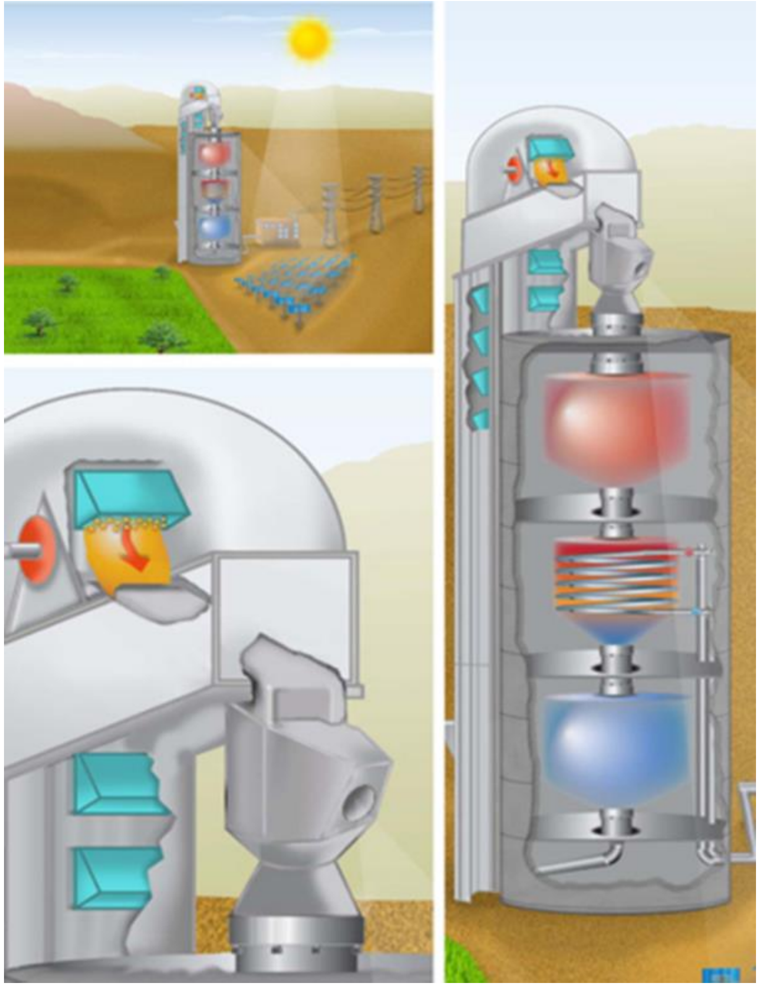
PRESSURIZED AIR RECEIVERS

- Hot air can go directly to a gas cycle or it can serve as a preheater for a conventional natural gas burner.
- Combined cycle operation is possible to increase overall thermal efficiency.



SOLID PARTICLE RECEIVERS

- Solid particles are released from the top of the tower.
- Particles absorb sunlight.
- A part is stored inside the tower.
- Another part is forwarded to a particle/gas heat exchanger.
- Hot gas drives a gas turbine.
- Colder particles are recirculated using a lift mechanism.

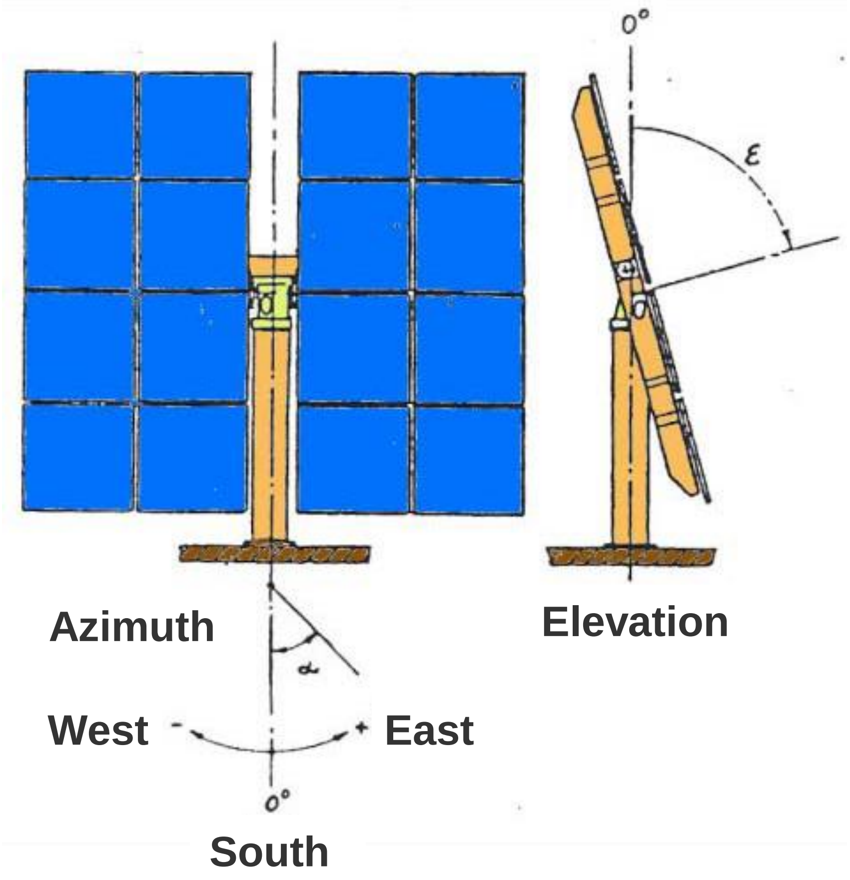


Central Receiver Systems

Fluid	Advantages	Disadvantages
Molten salts	- Temperatures up to 565°C - Efficient heat storage - No pollution or fire hazards	- High crystallization point - More complex solar field design - Higher electricity consumption
Steam	- Temperatures higher than 500°C can be achieved. - Simple plant design - No pollution or fire hazards	- Lack of suitable storage system due to high pressure. - More complex solar field control
Air	- Temperatures as high as 1000°C can be achieved. - Easy integration with natural gas burners. - No pollution or fire hazards	- Poor heat transfer characteristics. - Needs another medium for storage.
Solid Particles	- Temperatures as high as 1000°C can be achieved. - Easy integration with natural gas burners. - No pollution or fire hazards	- Limited options for heat transfer with air or other gases. - Poor heat transfer characteristics. - Electricity consumption by particle lift mechanism.

HELIOSTAT DESCRIPTION

- A heliostat is a reflective device that tracks the sun in two the azimuth and elevation directions.
- The tracking motors move the reflective surfaces in such a way that they are always reflecting sunlight to the top of the tower.



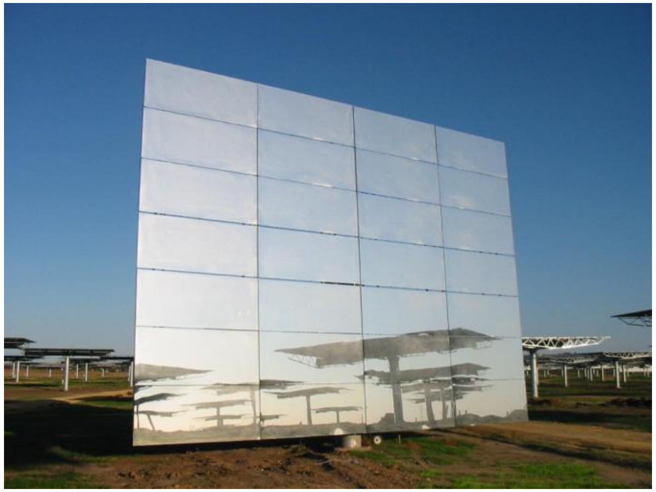
HELIOSTAT COMPONENTS

- Each heliostat consists of:
  - **A number of slightly curved mirrors.**
  - **Support structure.**
  - **Tracking motors.**
  - **Control mechanism.**

TYPES OF HELIOSTAT ARRANGEMENTS

Two wings

Continuous



Semi-continuous

Types of Concentrating Collectors

- Flat plate collector with flat reflectors
- Compound parabolic concentrators
- Parabolic trough collectors
- Linear Fresnel collectors
- Central receiver systems
- Parabolic dish collectors

Parabolic Dish Collectors

- Mirrors (or other reflective surfaces) that form the shape of a parabolic dish concentrate sunlight on a focal point.
- The concentration ratio can be as high 2000-3000.
- Temperature can reach 800°C

Parabolic Dish Collectors

- At the focal point, a Stirling engine absorbs the concentrated sunlight and generates electricity directly.
- Both the mirrors and the Stirling engine are attached to the same structure.
- Two-axis tracking is needed to keep the sunlight concentrated on the Stirling engine at all times.

Parabolic Dish Collectors

ADVANTAGES

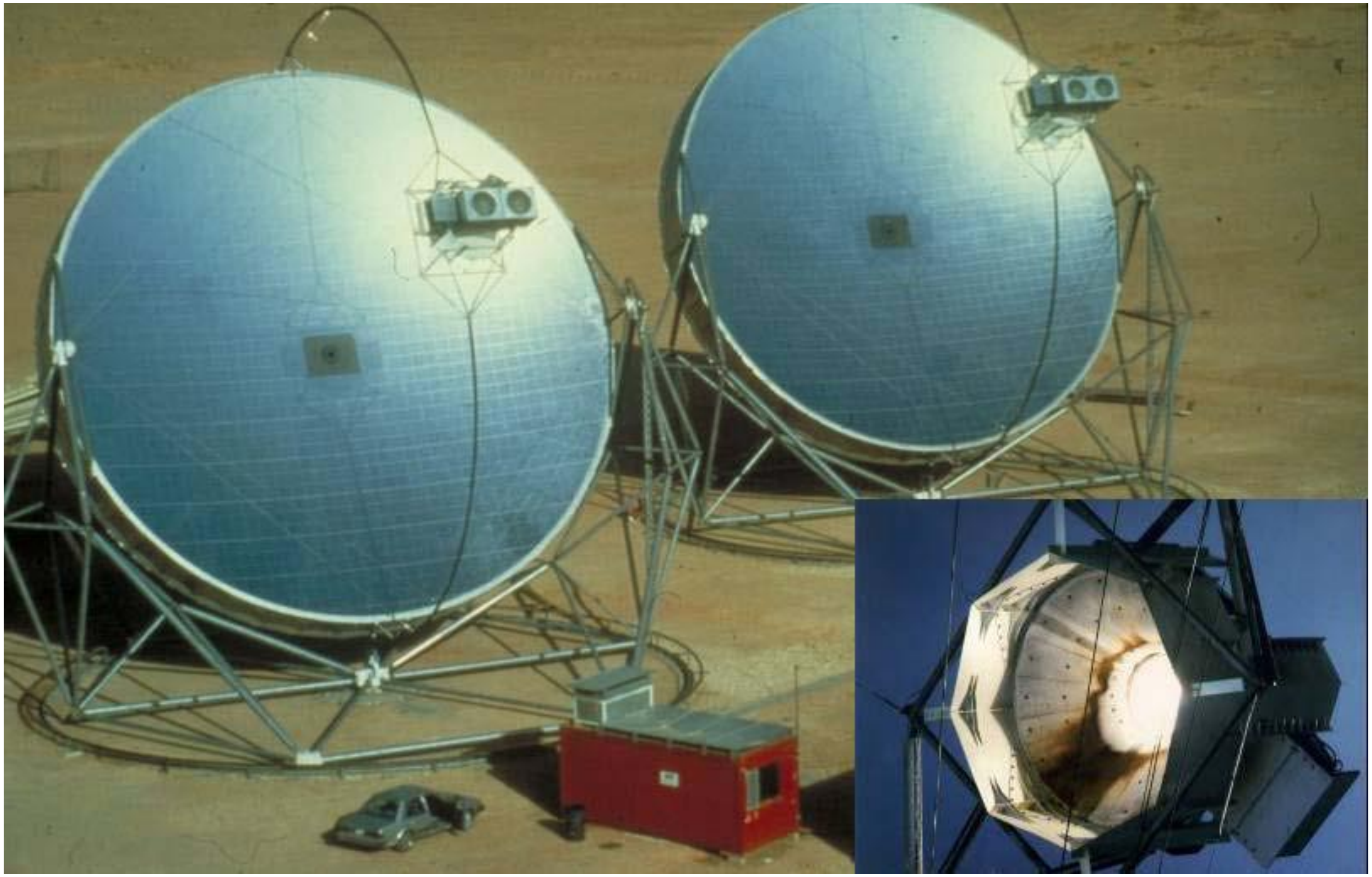
- High efficiency can be achieved due to high temperature.
- Electricity is generated directly → Less system complexity.
- Modular design → Each dish produces about 25 kW of power.

DISADVANTAGES

- Cost of engine is high because of its small size.
  - **Engineering systems are usually less expensive per unit of product when they are larger (*economies of scale*).**
- Overall system cost is high.
- Thermal energy storage is not practical.

Example of Parabolic Dish Systems

Capacity: 50 kW
Location: Solar Village, Saudi Arabia



Example of Parabolic Dish Systems

Capacity: 1.5 MW
Location: Tooele, Utah, USA

Comparison of Solar Collector Performance