Agenda

01 Foundations of geothermal energy, heat and flow properties

02 Multiphase flow, reservoir properties and energy conversion

03 Geothermal reserve estimation and unconventional geothermal systems

04 Oil and gas well conversions, future trends

Recap of Day 1

- Geothermal energy is energy from beneath the Earth.
- Conduction and convection are the dominant mechanisms of heat transfer in geothermal systems.
- It can be used to generate electricity, for direct use, and as a heat pump.
- Convection plays a significant role in geothermal systems.
- The rock has a high energy density.

Day 2

01 Foundations of geothermal energy, heat and flow properties

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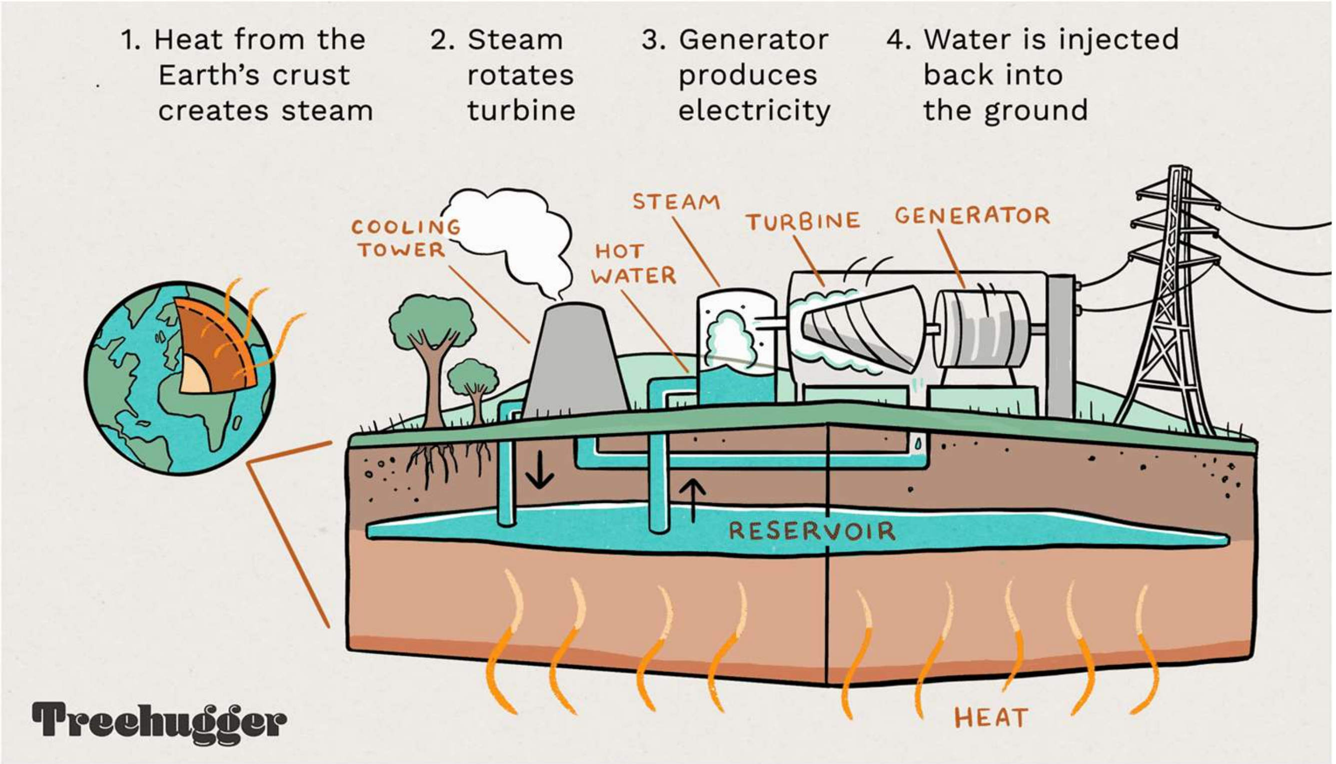
Geothermal Electricity

- From reservoir to ....power plant
  - energy stored in rock
  - heat transfer from rock to fluid
  - flow through porous media to well
    - fracture and matrix flow
  - power cycles (heat to electricity)
    - vapor dominated
    - liquid dominated
    - binary
  - reinjection



Flow Properties

Darcy’s Law

- The flow of a single fluid through a porous material is usually governed by Darcy’s Law:

$$\vec{u} = \frac{\overline{\overline{k}}}{\mu}\left(\nabla p - \rho \vec{g}\right)$$

- where *u* is the flux velocity (interstitial velocity divided by porosity), *k* is the permeability tensor, ∇p is the pressure gradient, ρ is the fluid density, μ is the viscosity, and g is the gravity vector.

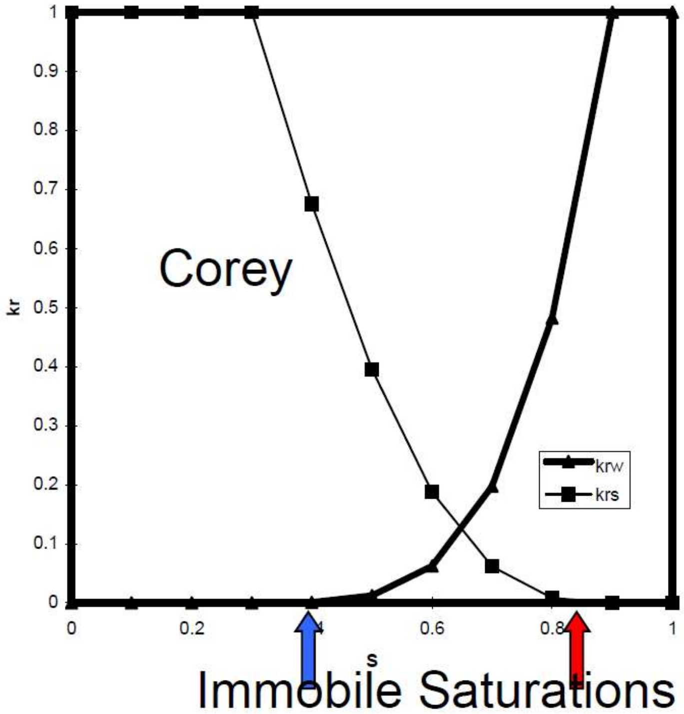
Two-Phase Flow

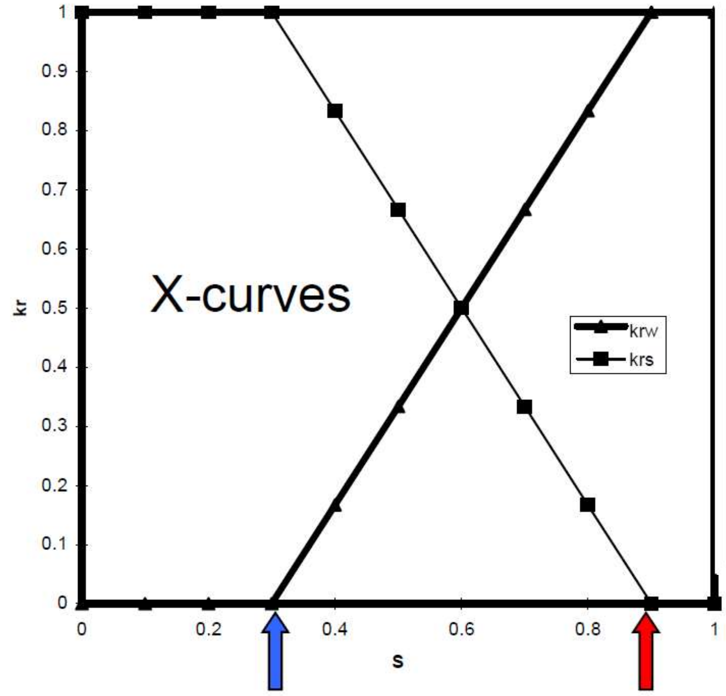
- In the case of two-phase flow, we need to take account of the fact that the presence of one phase may hinder the flow of the other, resulting in a reduction in the effective permeability to that phase as a function of the saturation (volume fraction) of the other. This concept is included by adding a modifier, known as the relative permeability k_r, multiplying the permeability of each phase, for example the water phase:

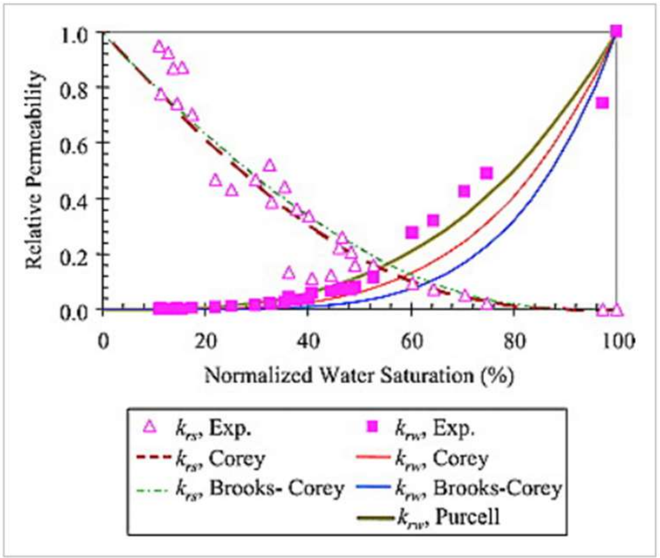
$$u_{w,x} = \frac{k_{rw} k_x}{\mu_w} \frac{\partial p}{\partial x}$$

Relative Permeability Curves

- Corey Type
- Fracture (X) Type







https://agupubs.onlinelibrary.wiley.com/doi/
10.1029/2005WR004482

Nomenclature for Steam Tables

- P = Pressure of the steam/water
- T = Saturation point of steam/water (boiling point)
- v_f = Specific volume of saturated water (liquid).
- v_g = Specific volume of saturated steam (gas).
- h_f = Specific enthalpy of saturated water (energy required to heat water from 0°C (32°F) to the boiling point)
- h_{fg} = Latent heat of evaporation (energy required to transform saturated water into dry saturated steam)
- h_g = Specific enthalpy of saturated steam (total energy required to generate steam from water at 0°C (32°F)).

$h_{fg}=h_g-h_f$

Two-phase compressibility

$$c_t = -\frac{1}{V}\frac{\Delta V}{\Delta p} = \frac{(1-\phi)\rho_r c_r + \phi S_w \rho_w c_w}{\phi \rho_s h_{fg}\left(dp_{sat} / dT \right)}$$

- e.g., At 250ºC, ø=0.1: ρr=2000 kg/m3, cr=1 kJ/kg-ºC, cw=4.86 kJ/kg-ºC
- Cw=1.3×10^{-6}kPa^{-1}, Cs= 3×10^{-4}kPa^{-1}
- For Sw=0.5, (Using dT = 2ºC) **What is Ct? What can you deduce?**
- Ct=8.24×10^{-2}kPa^{-1}

Two-phase viscosity

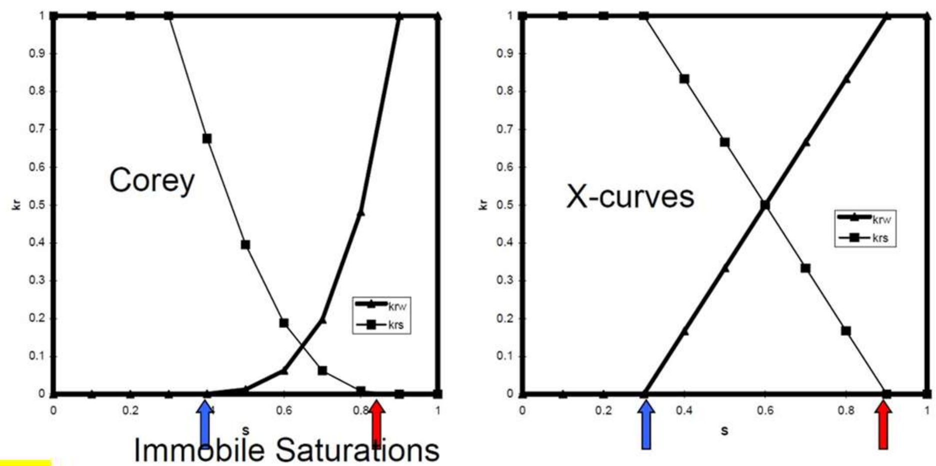
https://www.peacesoftware.de/einigewerte/wasser_dampf_e.html

$$\frac{1}{\mu_t} = \frac{1-x}{S_w}\frac{k_{rw}}{\mu_w} + \frac{x}{1-S_w}\frac{k_{rs}}{\mu_s}$$

- If using X curves

$$\frac{1}{\mu_t} = \frac{1-x}{\mu_w} + \frac{x}{\mu_s};$$

$$So,\quad \mu_t = \frac{\mu_w \mu_s}{(1-x)\mu_s + x\mu_w}$$



In Place Saturation

$$S_w = \frac{V_w}{V_w + V_s} = \frac{1-x}{(1-x) + x\,{\rho_w}/{\rho_s}}$$

$$or,\ S_w = 1 - \frac{x\upsilon_s}{x\upsilon_s + (1-x)\upsilon_w}$$

$$Also,\ x = (h - h_w)/(h_s - h_w)$$

$$\therefore S_w = \frac{(h_s - h)\upsilon_w}{(h - h_w)\upsilon_s + (h_s - h)\upsilon_w}$$

In Place and Flowing Enthalpy

- Because of relative permeability effects, the flowing volumes of steam and water are not in the same proportion as the total (static) volumes.

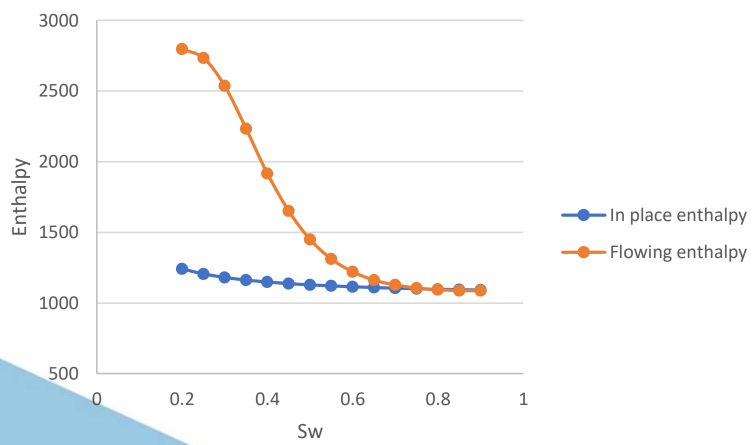
In-place enthalpy: $h = xh_s + (1-x)h_w$

Flowing enthalpy:

$$h_{flowing} = \frac{W_w h_w + W_w h_s}{W_w + W_s}$$

$$W_w = \frac{1}{\upsilon_w}\frac{kk_{rw}}{\mu_w}A\frac{\partial p}{\partial x};\quad W_s = \frac{1}{\upsilon_s}\frac{kk_{rs}}{\mu_s}A\frac{\partial p}{\partial x}$$

$$h_{flowing} = \frac{\dfrac{k_{rw}}{\upsilon_w\mu_w}h_w + \dfrac{k_{rs}}{\upsilon_s\mu_s}h_s}{\dfrac{k_{rw}}{\upsilon_w\mu_w} + \dfrac{k_{rs}}{\upsilon_s\mu_s}}$$



Reinjection

Reinjection

- Why do we reinject?
- Thermal pollution
- Chemical pollution
- Maintenance of reservoir pressure, temperature and fluid volumes

- Reinjection avoids environmental damage and can improve reservoir performance
- Does Reinjection always improve performance?

- (Can also damage reservoir performance therefore proper reinjection design is an important reservoir engineering task.)

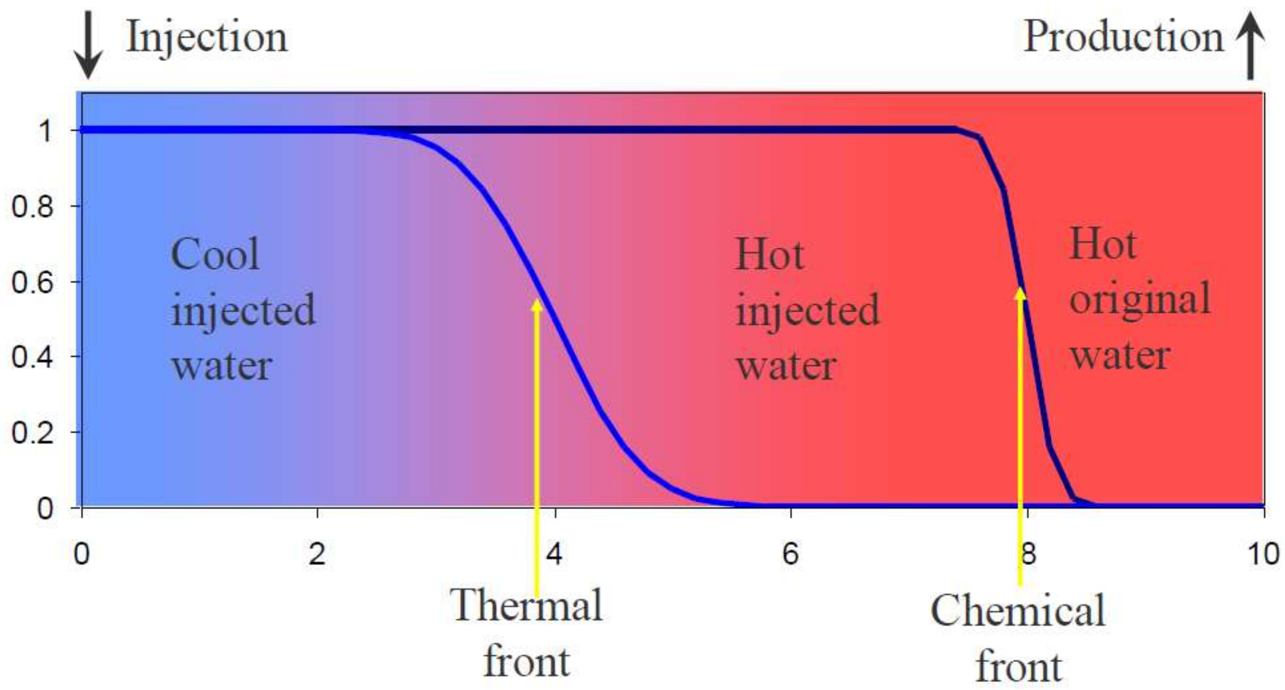
Reinjection

- Flow of Fluid and Heat
- Pressure, fluid and thermal fronts
- Porous medium flow models
- Fracture flow models

- Tracers

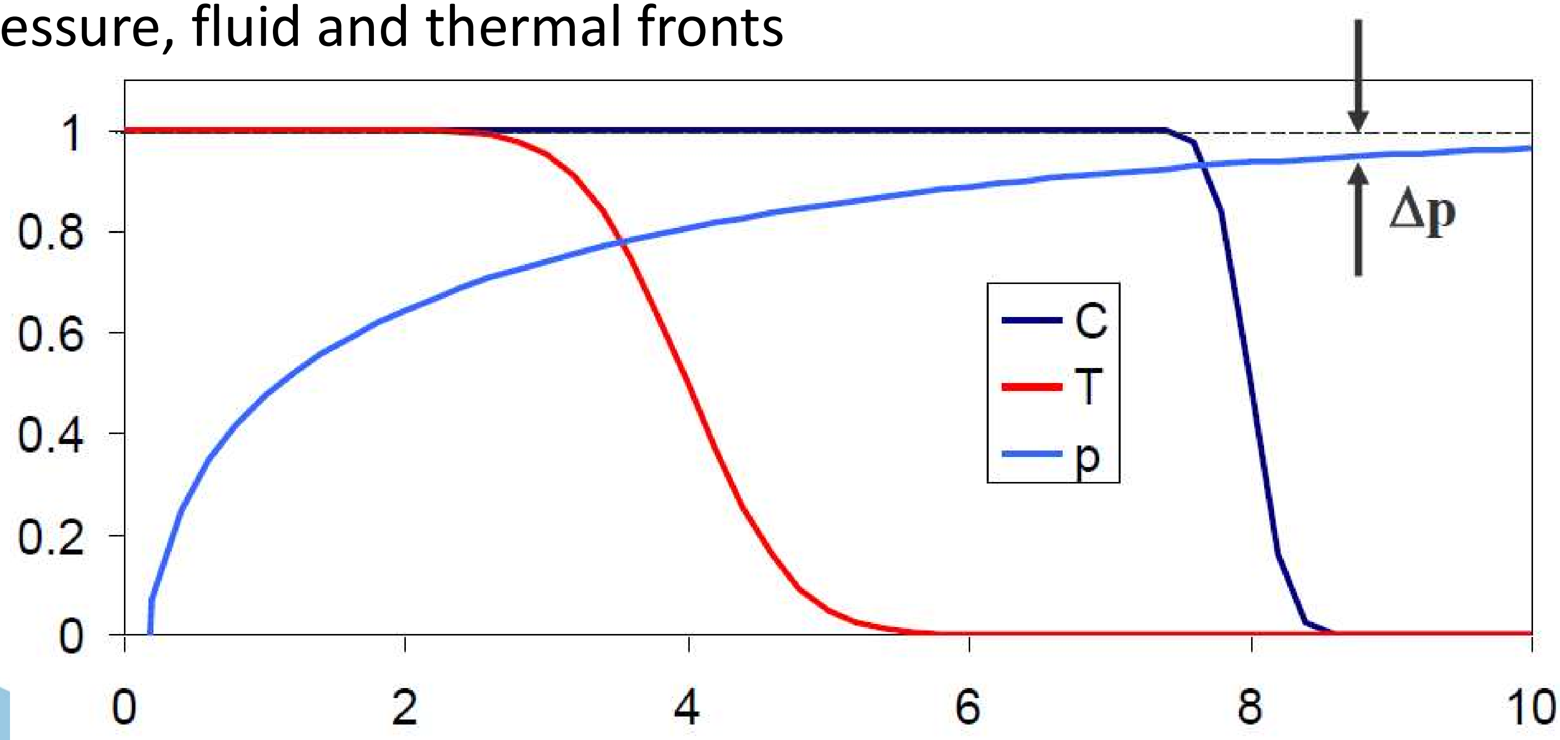
Reinjection: Fronts

- Pressure, fluid and thermal fronts



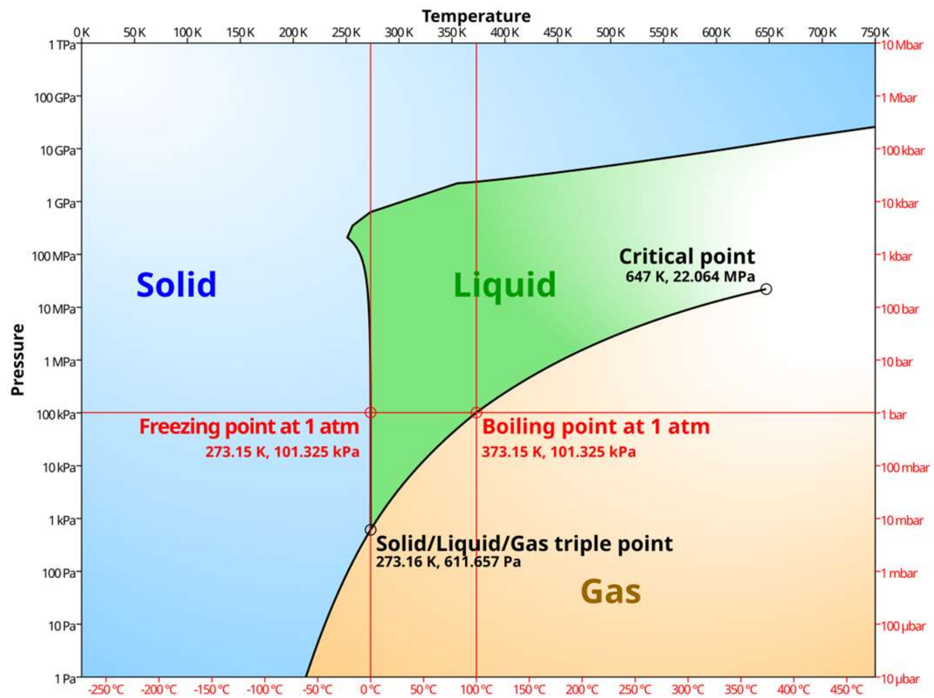
Reinjection: Fronts

- Pressure, fluid and thermal fronts



Pressure Changes

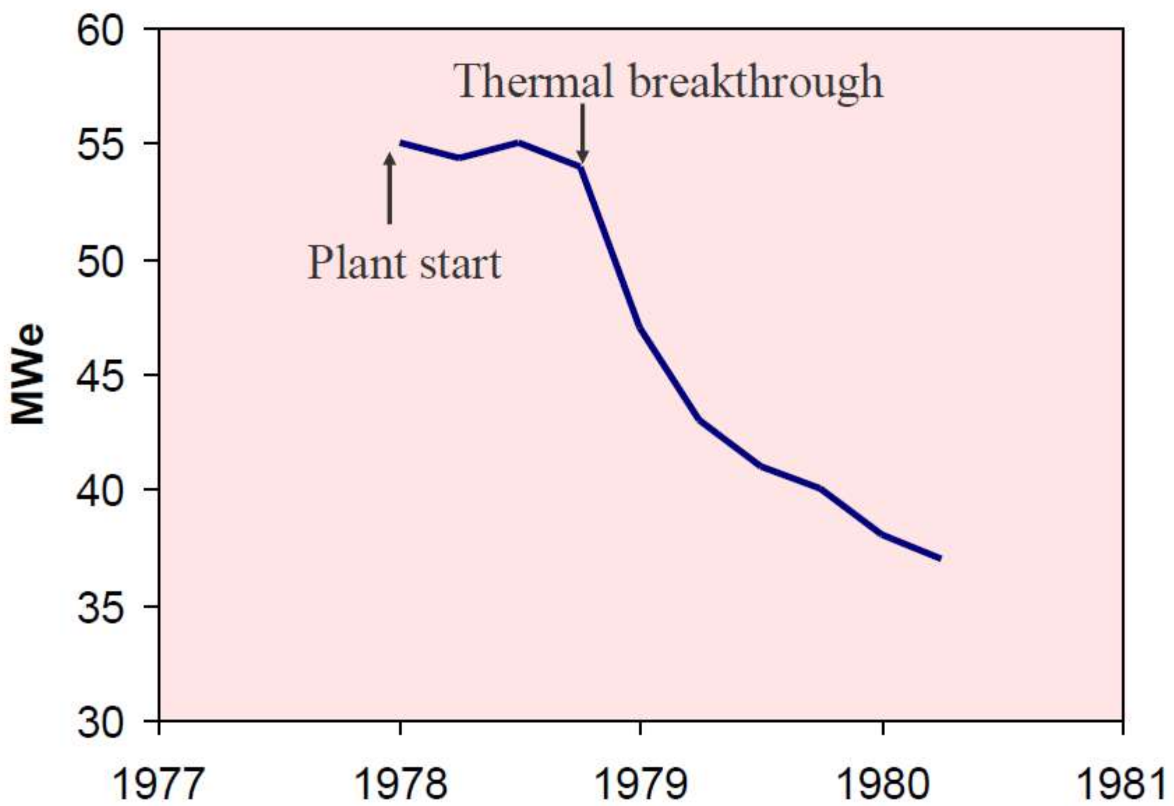
- Pressure may rise at injection point in liquid-dominated reservoir.
- Pressure may fall at injection point in two-phase or vapor-dominated reservoir.
- Pressure changes are transmitted through the reservoir but may not be correlated with thermal effects.



Chemical Changes

- Reinjection water has high content of dissolved materials.
- Artificial tracers may be injected.
- Extraneous substances may be added (e.g., air, inhibitors).
- Chemical breakthrough a precursor of thermal breakthrough since transport mechanisms are similar.

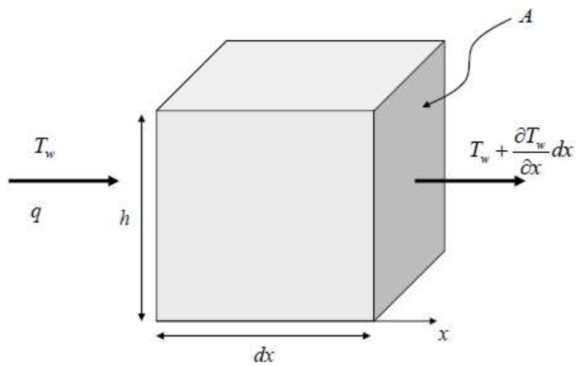
Thermal Breakthrough



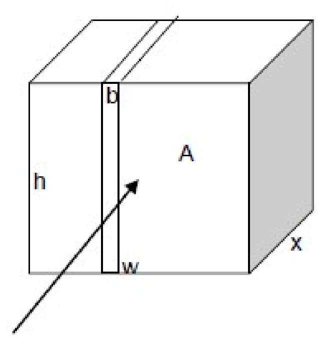
Thermal Breakthrough

- Rapid chemical breakthrough signifies a greater risk of rapid thermal breakthrough.
- How can we relate thermal breakthrough to chemical breakthrough?
- How can we determine chemical breakthrough?

- Porous media



Fracture Model



Thermal Breakthrough

Water velocity $$\frac{q}{A} = v_w \phi$$

Thermal velocity $$v_{th} = \frac{\rho_w C_w}{\rho_A C_A} v_w \phi$$

$$\frac{v_{th}}{v_w} = \frac{\rho_w C_w}{\rho_A C_A} \phi$$

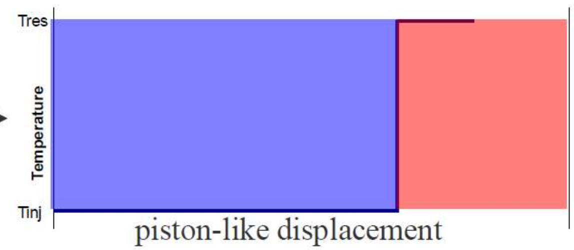
- The thermal front would take 4.6 times longer than the chemical (tracer) front.
- This is, however, a pessimistic estimate of thermal breakthrough.

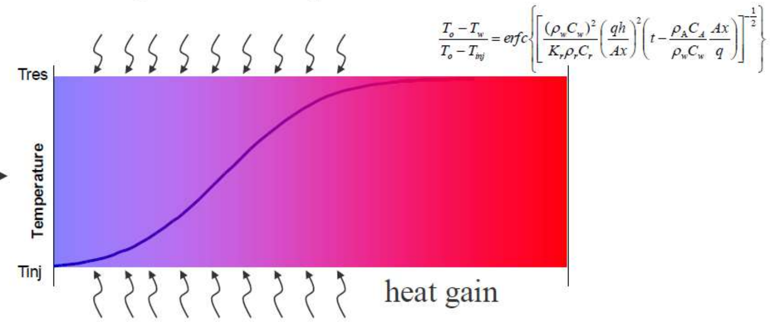
$$\frac{v_{th}}{v_w} = 0.2171$$

Thermal Breakthrough

- Considering heat loss / gain

$$v_{th}^{*} = \frac{v_{th}}{1 + 4.234 \dfrac{x}{h^2} \dfrac{K_r \rho_r C_r}{(\rho_A C_A)^2} \dfrac{1}{v_{th}}}$$





Typical values $v_{th}^{*} = 0.0686\, v_{th}$

- Fracture models:
- t_c= mean tracer arrival time

$$t_{th} = t_c + 4.234 \left(\frac{t_c}{b} \right)^2 \frac{K_r \rho_r C_r}{(\rho_w C_w)^2}$$

Tracers: Overview

- Tracer testing: injecting one or more tracers—usually chemical compounds—into the subsurface in order to estimate its flow and storage properties.
- A tracer test is an indirect method for characterizing subsurface properties.
- We invariably compare observed behavior with a mathematical (or numerical) model and infer subsurface properties from the comparison.

Tracers

- Needs to be:
- Similar to transport fluid (water or steam)
- Distinguishable
- Three main classes:
- Dyes
- Radioactive tracers
- Chemical tracers

Tracers

- Dye Tracers
- Fluorescein
- Hatchobaru 220°C
- Fenton Hill 150°C
- Salak 240°C OK, 290°C not OK.
- Rhodamine WT
- Svartsengi 240 °C
- Ohaaki 230 °C not detected
- Cheap and easy to measure, but not stable beyond a few days.

Tracers

- Radioactive tracers
- I_{131}(8 days)
- Br_{82}(1.5 days)
- H_3tritium (12.4 years)
- Detectable in small amounts.
- Safety and regulation may be issues.

- Chemical Tracers
- Halides (KI and NaBr)
- Fluorocarbon tracers

- Natural tracers:
    - Chloride
    - Nitrogen

Tracer Design

- Choice of tracer.
- Quantity to be injected.
- Seek a return concentration at least three times greater than background.
- Seek a return concentration at least three times greater than detection limit.
- Need to estimate maximum and minimum exit concentration.

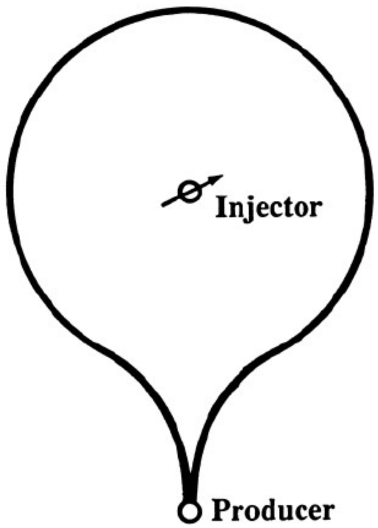
Tracer Design

- Minimum Concentration

$$C_{min} = \frac{V_{inj}}{1.076\, D^2 h \phi}$$

- Maximum Concentration

$$C_{max} = \frac{V_{inj}}{q\,t}\sqrt{\frac{Pe}{\pi}}$$



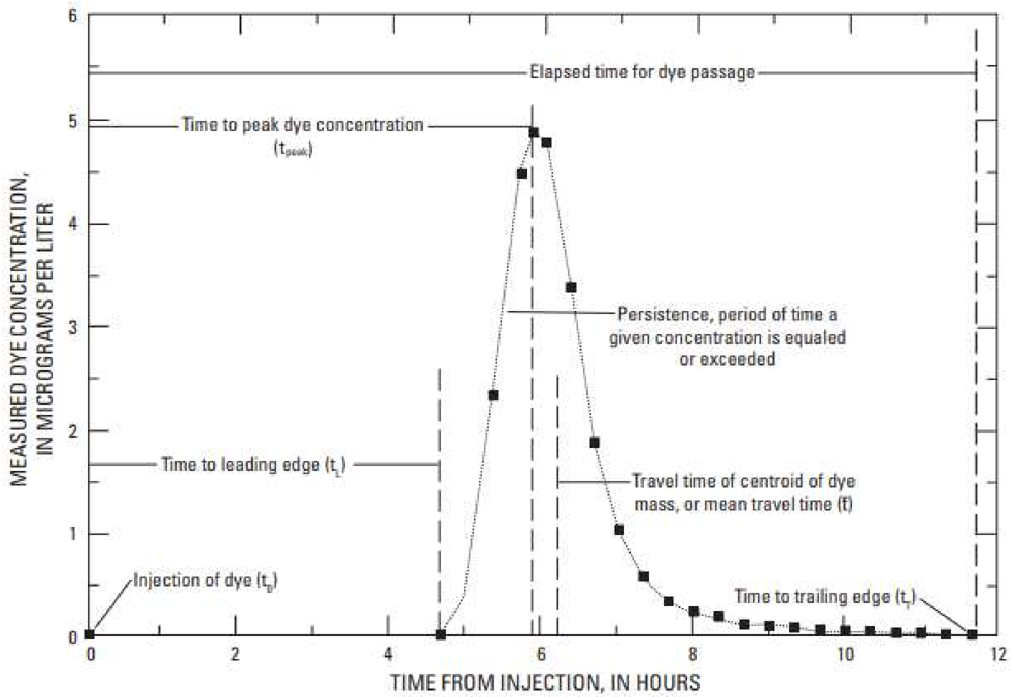
- Based on linear flow in a fracture

Tracer Design

- Example
- 100 t/h injected with 1 tonne of KI.
- Well separation D= 100 m
- Thickness h= 500m, porosity 0.05
- Cmin= 3.7 ppm
- Assuming breakthrough 5 days, Pe= 40
- Cmax= 297 ppm

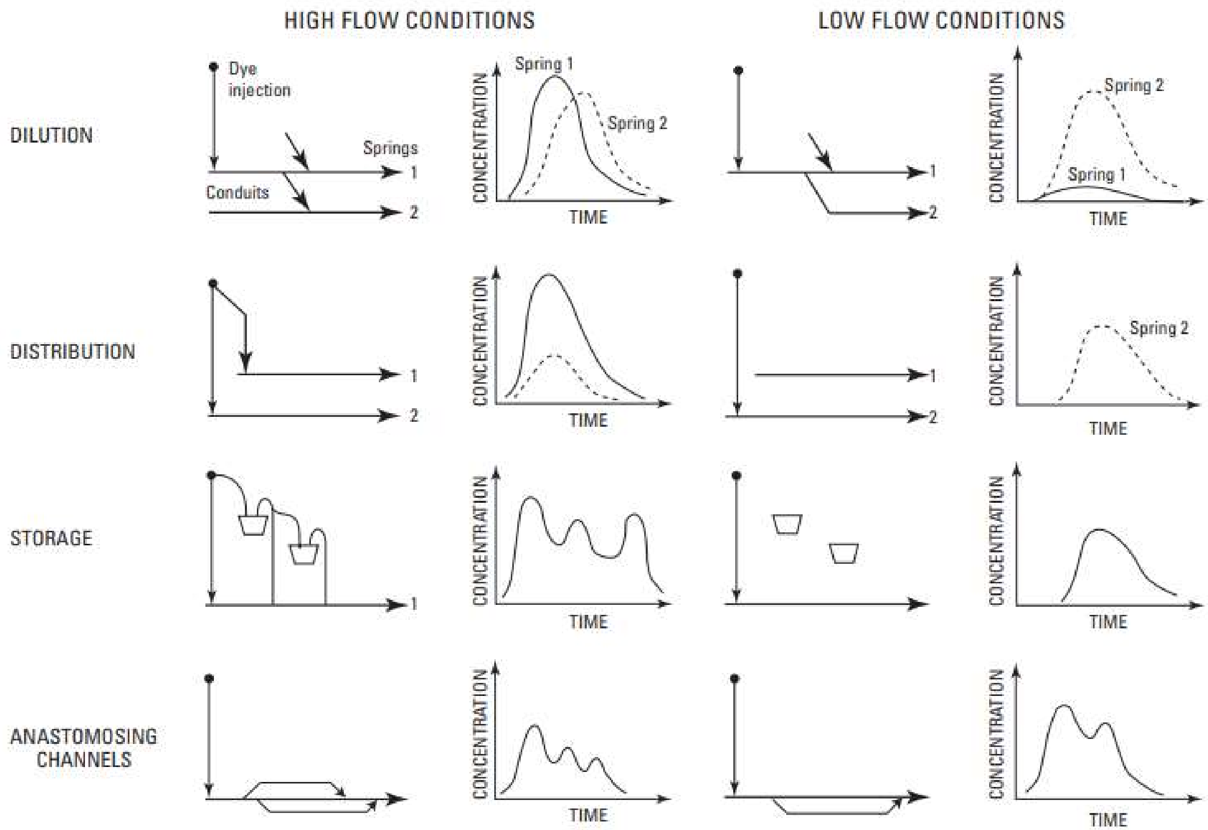
Tracer Test Interpretation

- Tracer Breakthrough Curve Analysis
- Integrating the area under the dye-breakthrough curve allows for estimation of the mass of tracer recovered.
- Evaluation of the shape of the dye breakthrough curve provides data needed to estimate hydraulic properties such as longitudinal dispersion, Reynolds and Peclet numbers, and discharge.

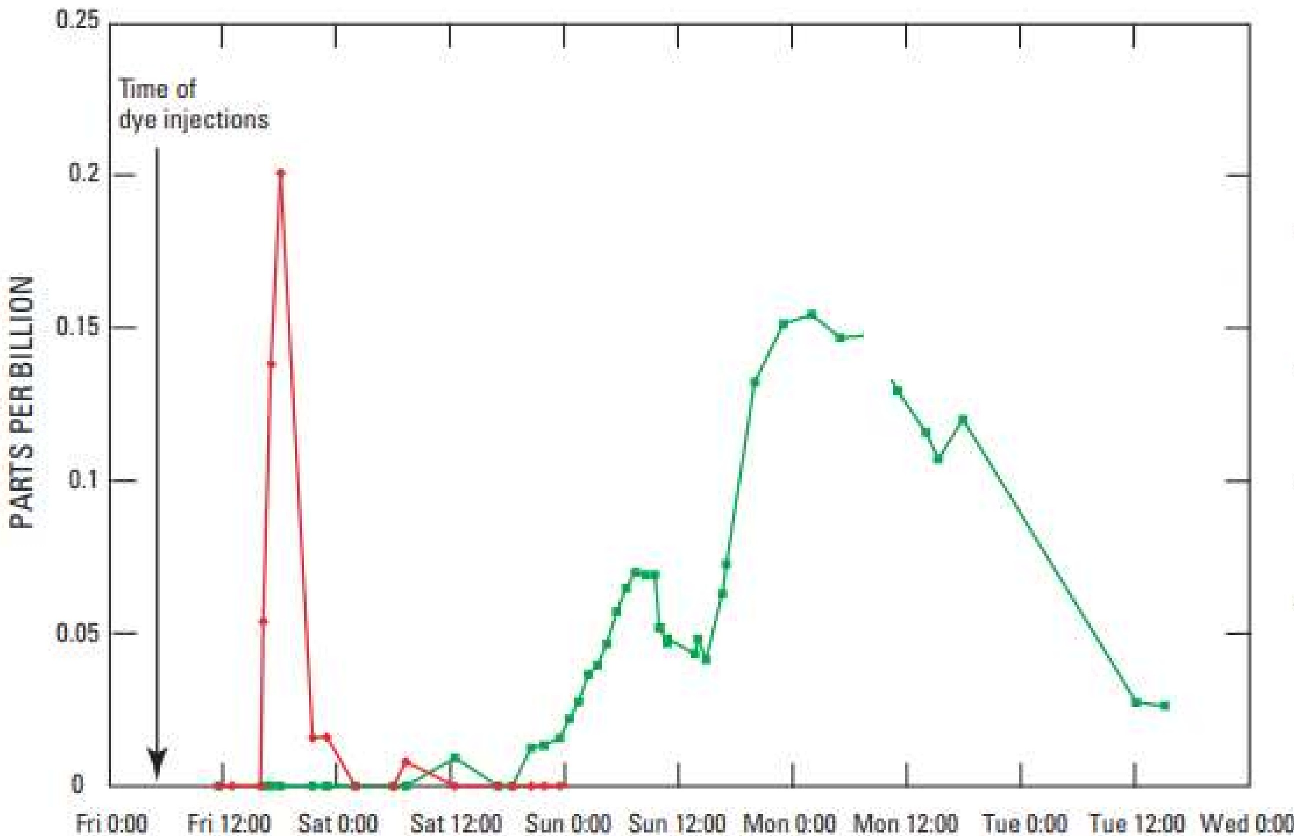


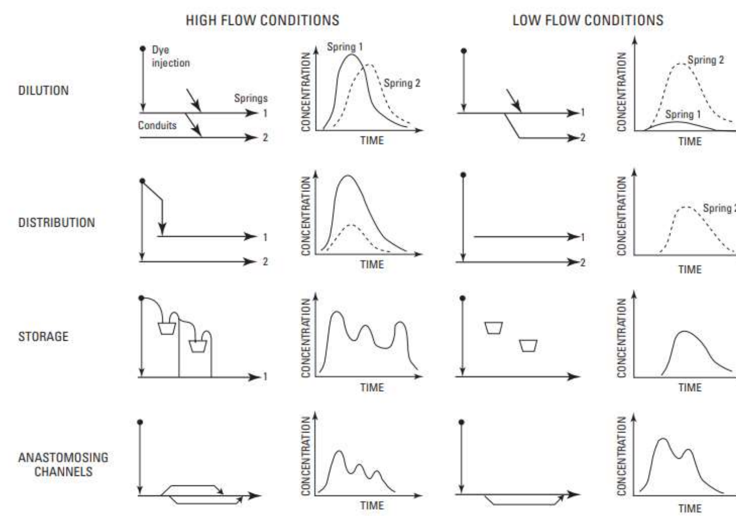
Tracer Test Interpretation

- Interpretation of the physical characteristics of the breakthrough curves usually cannot be based solely on the pattern of recovery of dye, but also on knowledge of the geology under study



Tracer Test Interpretation



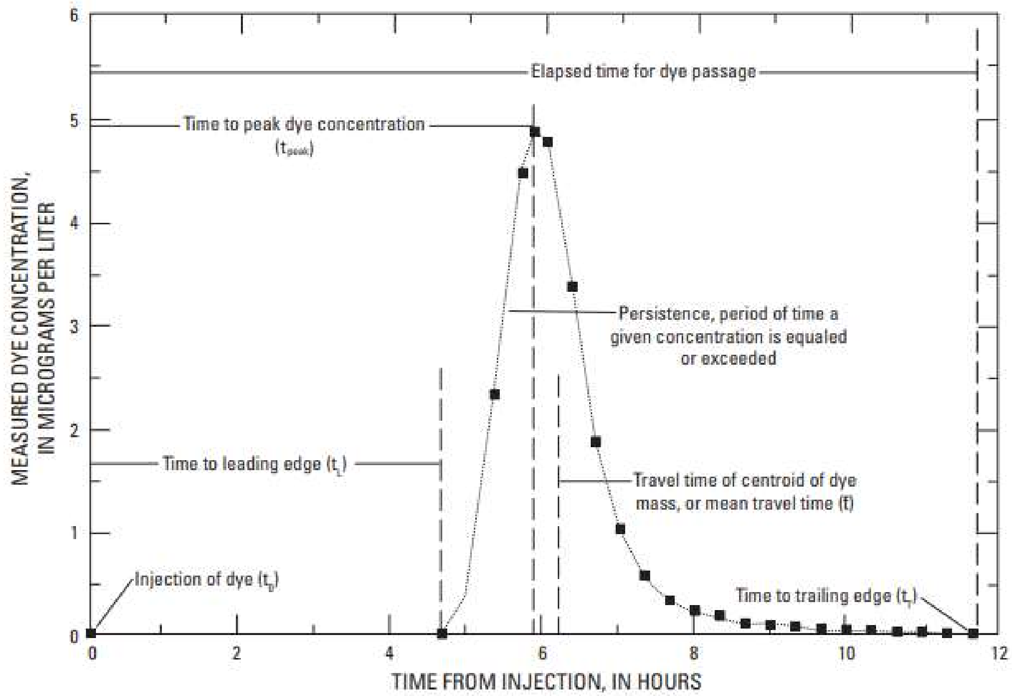


Tracer Test Interpretation – Example

- Calculate *tc*, the mean tracer arrival (chemical breakthrough) time, using **moment analysis** (centroid of concentration vs. time).

$$t_c = \frac{\sum(t_i \cdot C_i)}{\sum C_i}$$

- Comment on your answer



Thermal Breakthrough

- Considering heat loss/gain

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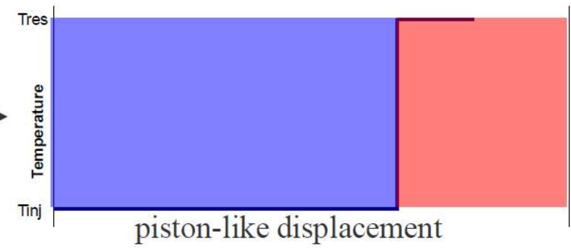
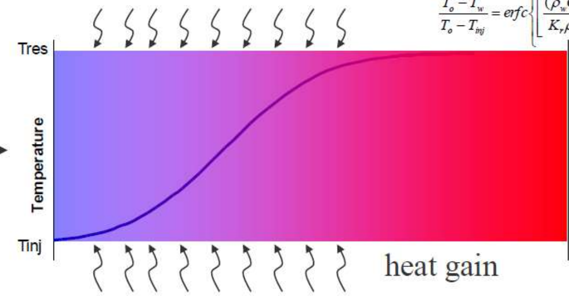
Typical values $\quad v_{th}^{*} = 0.0686\, v_{th}$



$$\frac{T_o - T_w}{T_o - T_{inj}} = erfc\left\{\left[\frac{(\rho_w C_w)^2}{K_r \rho_r C_r}\left(\frac{qh}{Ax}\right)^2\left(t - \frac{\rho_A C_A}{\rho_w C_w}\frac{Ax}{q}\right)\right]^{-\frac{1}{2}}\right\}$$



- Fracture models:
- t_c= mean tracer arrival time

$$t_{th} = t_c + 4.234\left(\frac{t_c}{b}\right)^2 \frac{K_r \rho_r C_r}{(\rho_w C_w)^2}$$

Conversion

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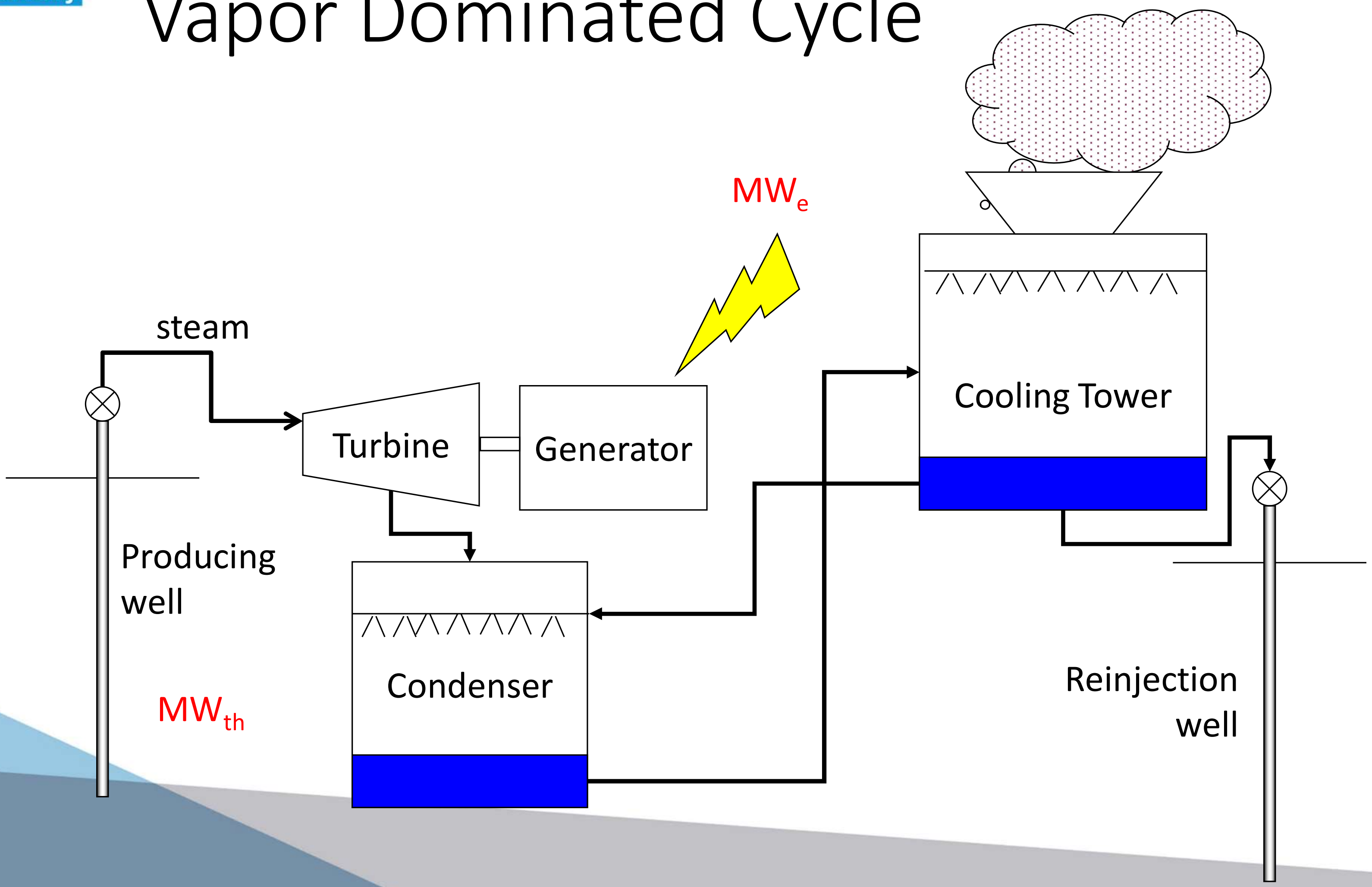
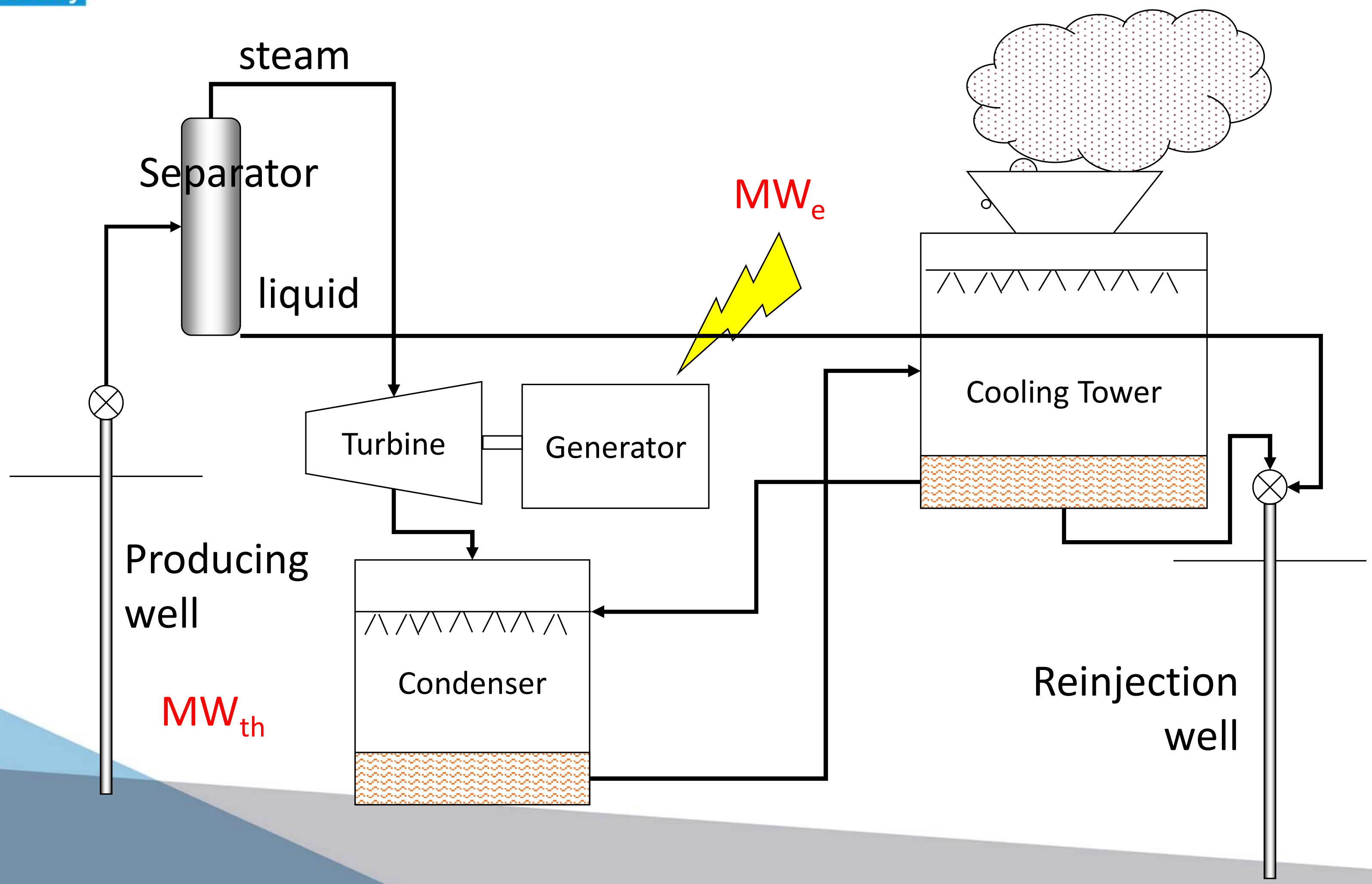
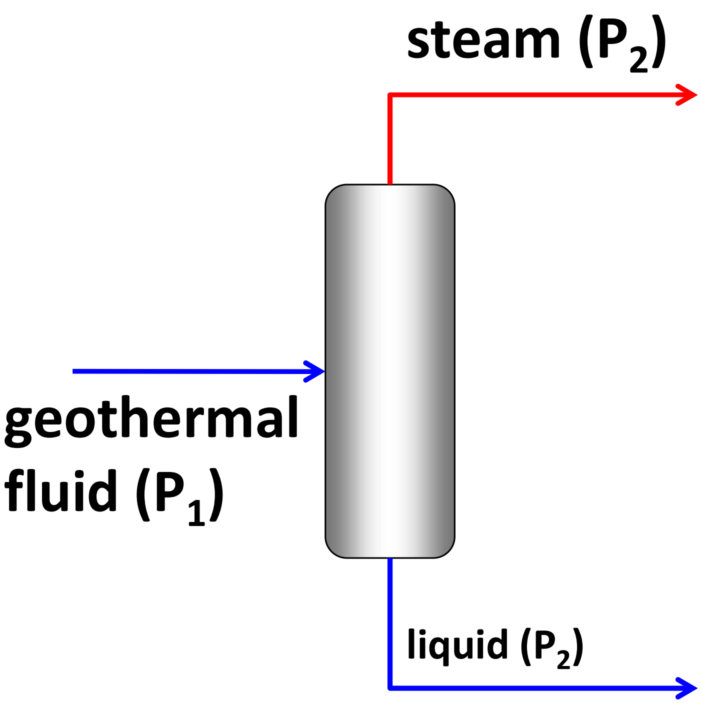
Vapor Dominated Cycle



Liquid-Dominated Power Cycle

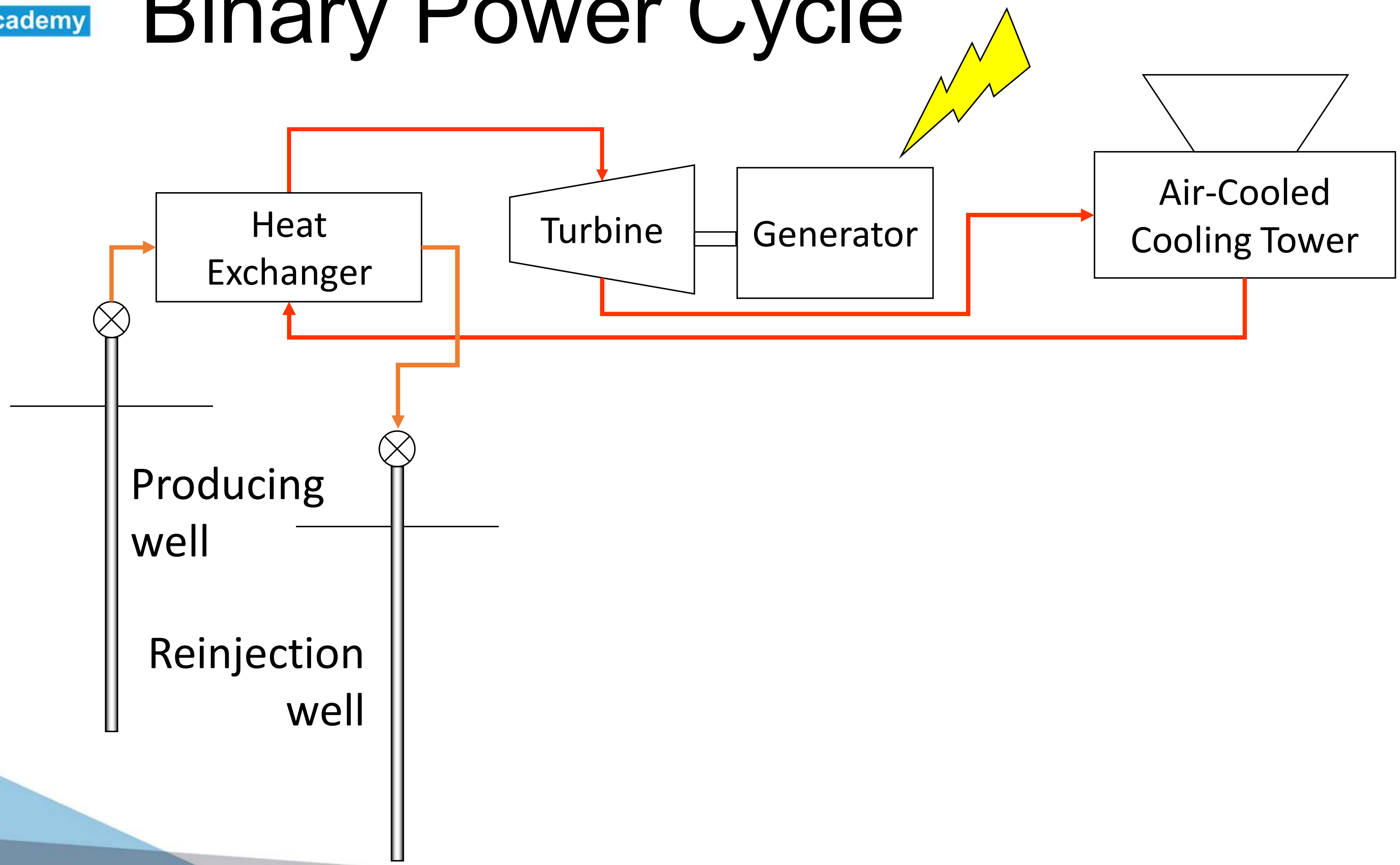


Flash Tank



- $P_1 > P_2$ the fluid boils (or flashes) at the lower pressure
- steam quality X results
- the enthalpy equals
- $h_{feed} = xh_s + (1-x)h_w$

Binary Power Cycle



Thermal Power vs Generated Power

- Given a system where the downstream temperature is 25 ° C and the reservoir temperature is T = 165 ° C.

- If you want to generate 40 MW_e , how much thermal power from the geothermal resource do you need?

Thermal Power vs Generated Power

- Given a system where the downstream temperature is 25 ° C and the reservoir temperature is T = 165 ° C.

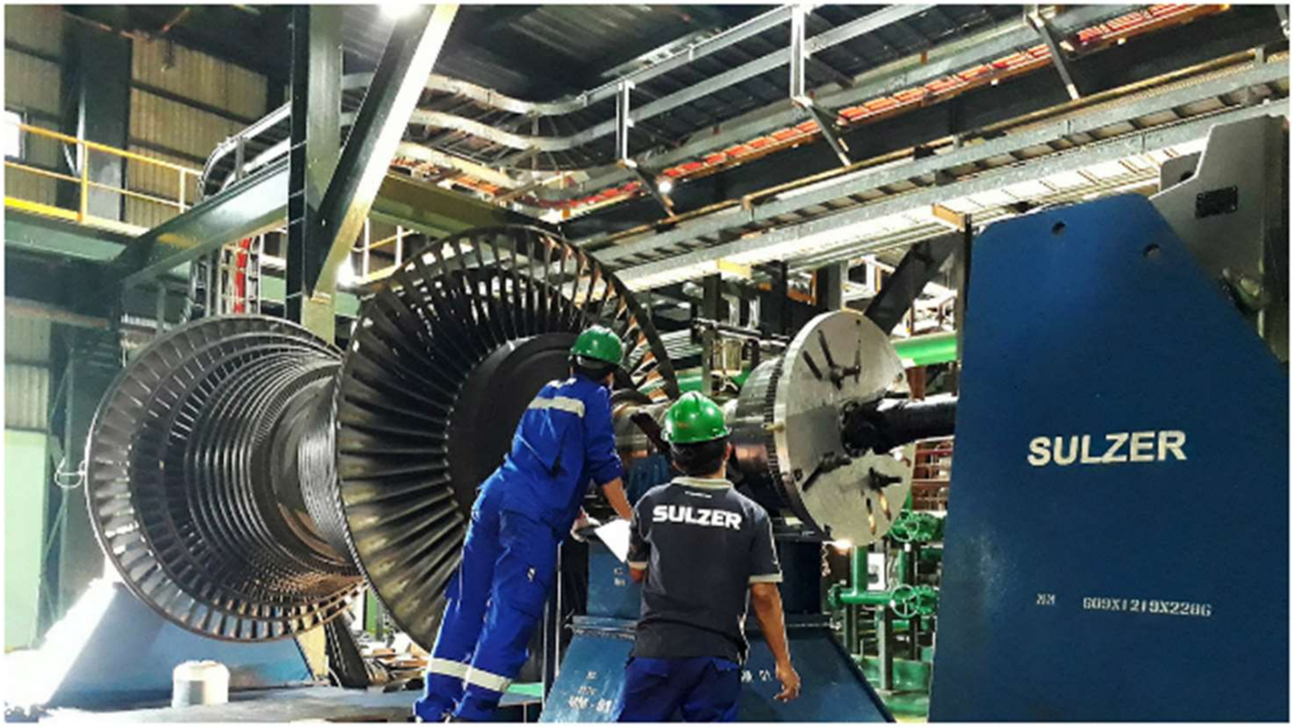
- If you want to generate 40 MW_e , how much thermal power from the geothermal resource do you need?

- Calculate the Carnot efficiency, η
- To compute the amount of thermal power, we divide the electrical power by the efficiency.

$$\eta = 1 - \frac{T_c}{T_h} = 1 - \frac{273+25}{273+165} = 0.32$$

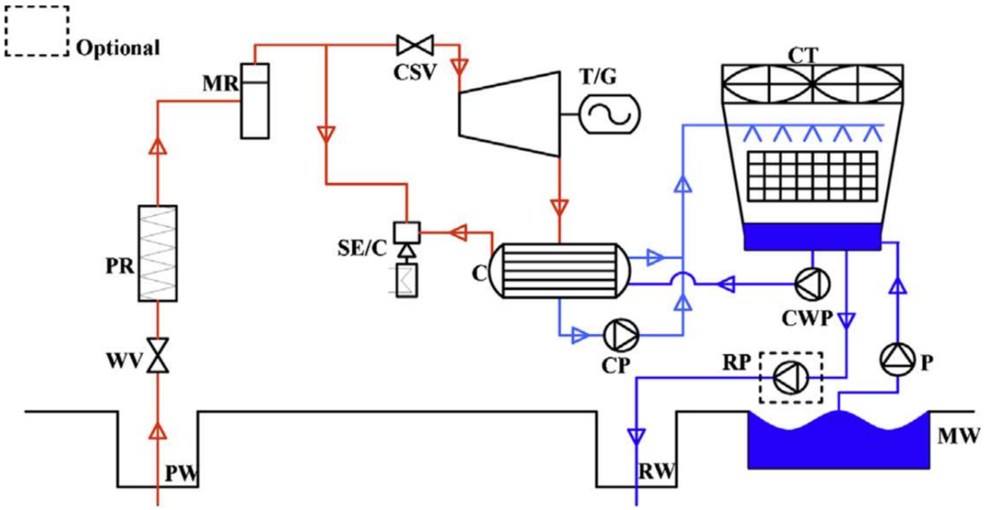
$$\eta = \frac{MW_e}{MW_{th}} \Rightarrow MW_{th} = \frac{MW_e}{\eta} = 125 MW_{th}$$

Steam Turbine



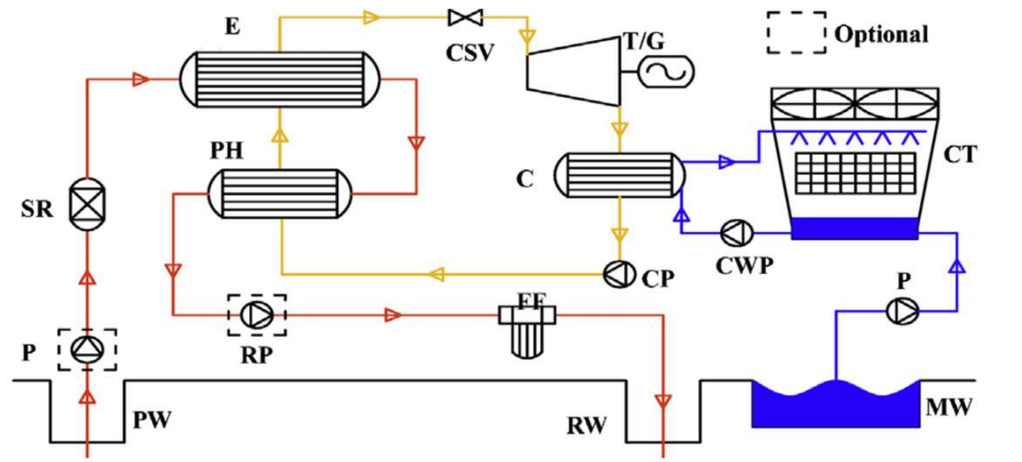
https://empoweringpumps.com/sulzer-on-site-overhaul-of-55-mw-geothermal-steam-turbine/

Power Plant Efficiency



PW	Production well	WV	Wellhead valve	PR	Particulate remover
MR	Moisture remover	C	condenser	CP	Condensate pump
CSV	Control and stop valve	SE/C	Steam ejector/condenser	T/G	Turbine and generator
CT	Cooling tower	CWP	Cooling water pump	RP	Reinjection pump
RW	Reinjection well	P	Pump	MW	Make-up water

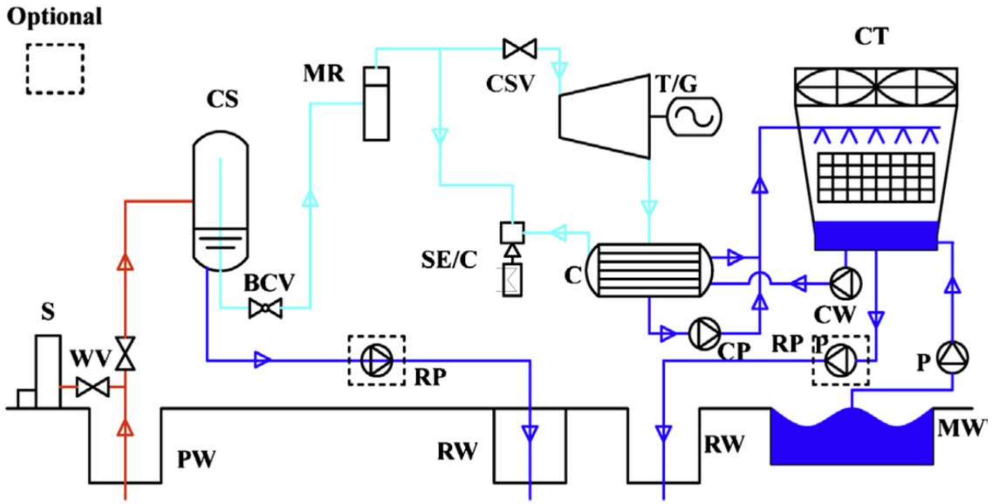
- Dry Steam Power Plant



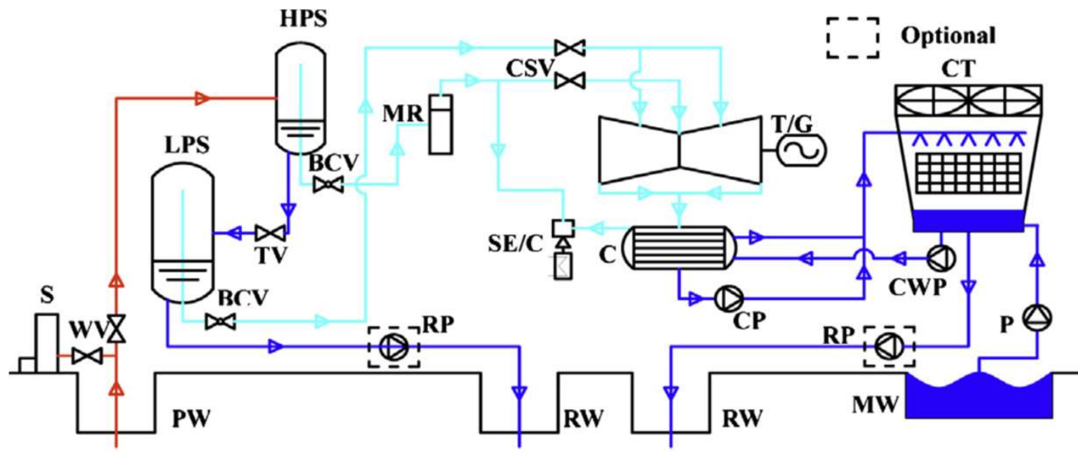
PW	Production well	P	Pump	SR	Sand remover
E	Evaporator	PH	Pre-heater	C	Condenser
CP	Condensate pump	RP	Reinjection pump	FF	Final filter
CSV	Control / stop valve	T/G	Turbine / generator	CWP	Cooling water pump
CT	Cooling tower	RW	Reinjection well	MW	Make-up water

Binary Power Plant

Power Plant Efficiency



PW	Production well	WV	Wellhead valve	S	Silencer
CS	Cyclone separator	BCV	Ball check valve	MR	Moisture remover
CSV	Control / stop valve	T/G	Turbine / generator	SE/C	Steam ejector/condenser
C	condenser	CT	Cooling tower	CWP	Cooling water pump
CP	Condensate pump	RP	Reinjection pump	RW	Reinjection well
P	Pump	MW	Make-up water		



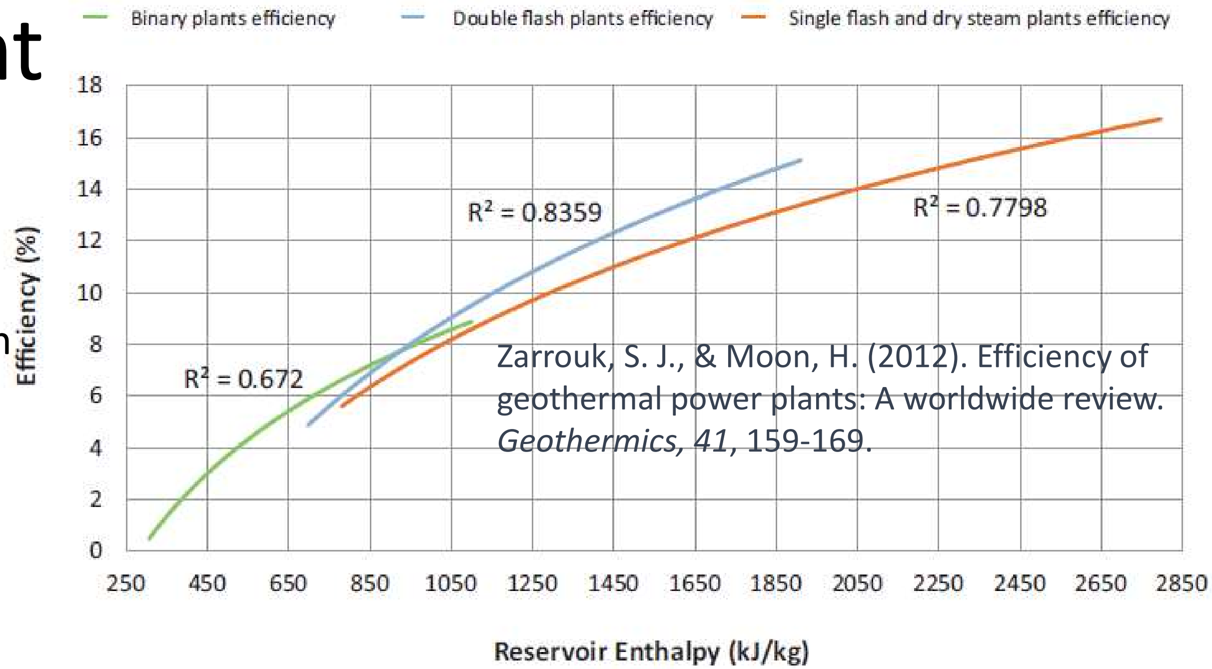
PW	Production well	WV	Wellhead valve	S	Silencer
HPS	High pressure separator	LPS	Low pressure separator	BCV	Ball check valve
TV	Throttle valve	MR	Moisture remover	C	condenser
CSV	Control / stop valve	T/G	Turbine / generator	SE/C	Steam ejector/condenser
CT	Cooling tower	CWP	Cooling water pump	CP	Condensate pump
RP	Reinjection pump	RW	Reinjection well	P	Pump
MW	Make-up water				

- Single Flash Power Plant

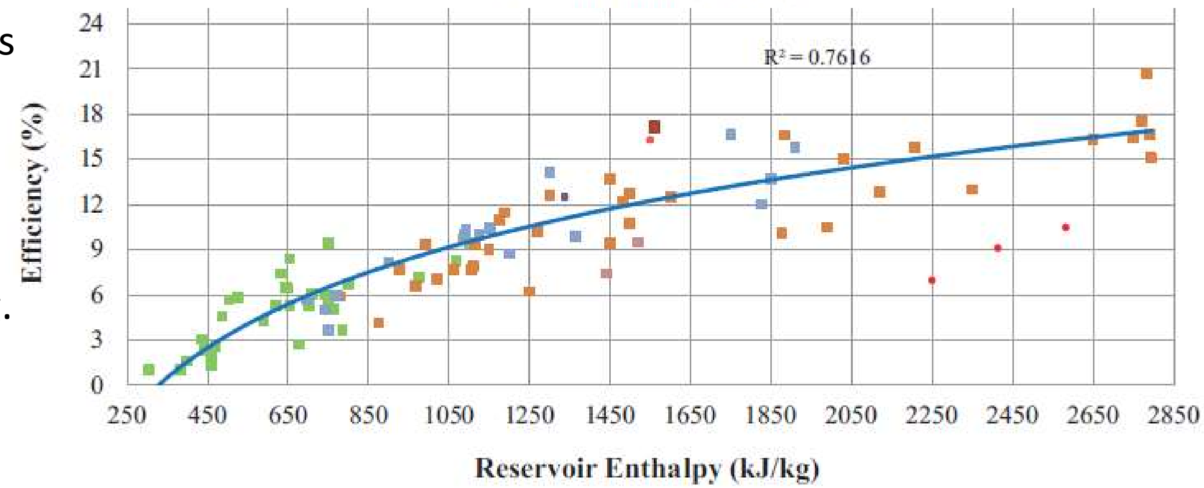
Double Flash Power Plant

Power Plant Efficiency

- The conversion efficiency of geothermal power developments is generally lower than that of all conventional thermal power plants.
- The overall conversion efficiency is affected by many parameters
- The highest reported conversion efficiency is approximately 21%
- The use of binary plants in low-enthalpy resources has allowed the use of energy from fluid with enthalpy as low as 306 kJ/kg.



Zarrouk, S. J., & Moon, H. (2012). Efficiency of geothermal power plants: A worldwide review. *Geothermics*, *41*, 159-169.



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