9_1 Geothermal - Hydrothermal

Recap:

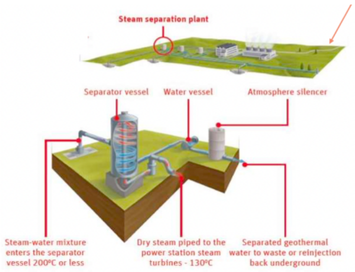
1. Geothermal Resource Characterizations by:
   a. Environment/Geological Habit
   b. Geophysics
   c. Drilling - for exploration and production
2. Designed to reduce risk of projects - drilling is one of the most significant costs

Movies*:* (IGA): https://www.youtube.com/watch?v=ZjtmFfBTBBg
(Indonesia): https://www.youtube.com/watch?v=WBpjzBg1nRw

Resources: WG10

Motivation:

1. Motivation [10%] Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?



Quality of resource defined by Thermal_power = Mass_rate * c * delta_T
How is hot water/steam recovered. And once recovered - used to generate power?

Scientific Questions:

2. Scientific Questions to be Answered/Outline [10%] What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

Hydrothermal

1. Plant layout
2. Recovery from wells
3. Friction losses in wellbores
4. Thermodynamics of energy conversion
   A. Single-flash production
   B. Double-flash production
   C. Binary production

Introduction

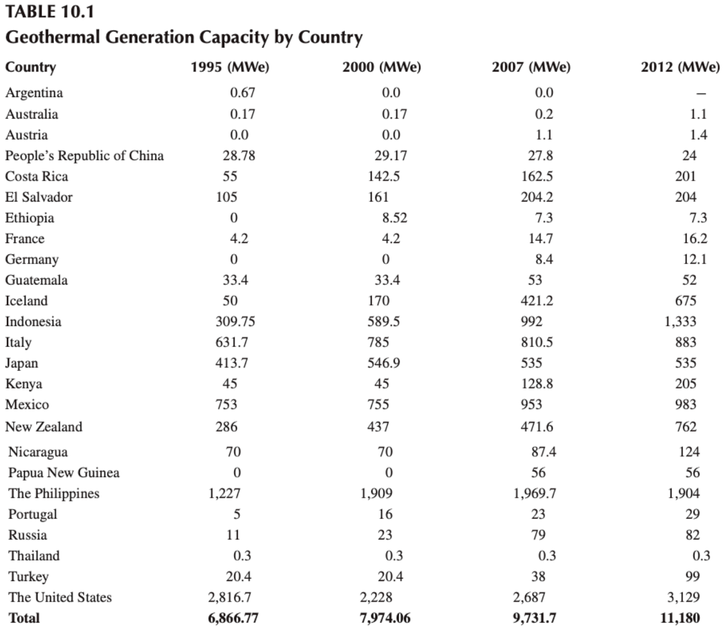
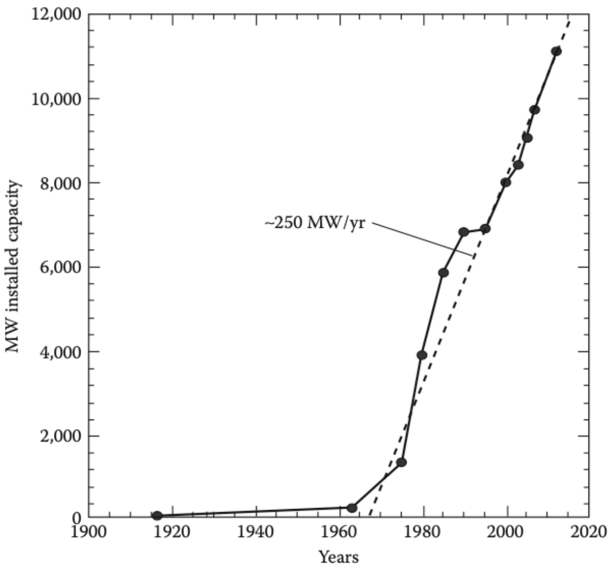
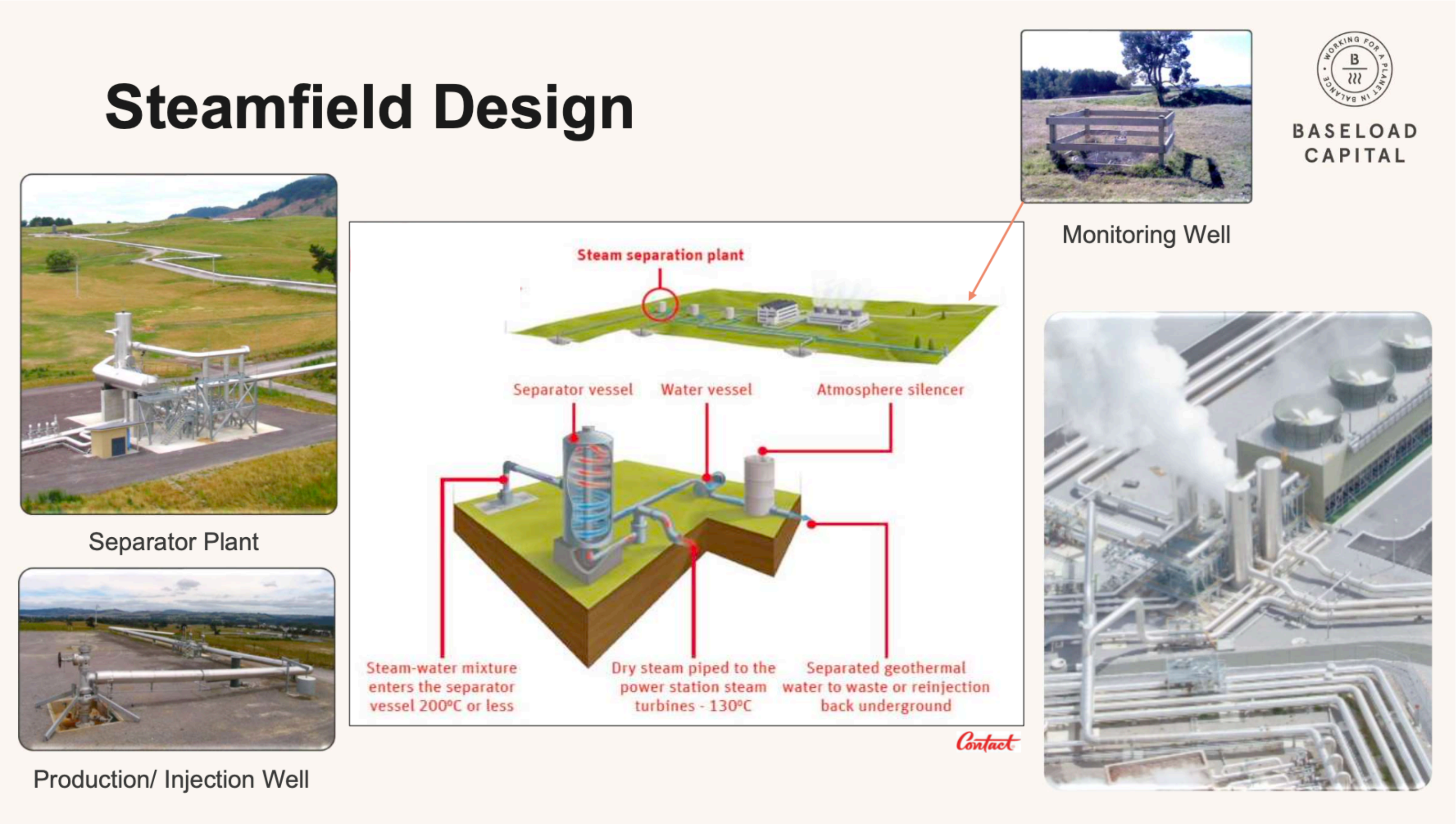


TABLE 10.1
Geothermal Generation Capacity by Country

Country	1995 (MWe)	2000 (MWe)	2007 (MWe)	2012 (MWe)
Argentina	0.67	0.0	0.0	–
Australia	0.17	0.17	0.2	1.1
Austria	0.0	0.0	1.1	1.4
People's Republic of China	28.78	29.17	27.8	24
Costa Rica	55	142.5	162.5	201
El Salvador	105	161	204.2	204
Ethiopia	0	8.52	7.3	7.3
France	4.2	4.2	14.7	16.2
Germany	0	0	8.4	12.1
Guatemala	33.4	33.4	53	52
Iceland	50	170	421.2	675
Indonesia	309.75	589.5	992	1,333
Italy	631.7	785	810.5	883
Japan	413.7	546.9	535	535
Kenya	45	45	128.8	205
Mexico	753	755	953	983
New Zealand	286	437	471.6	762
Nicaragua	70	70	87.4	124
Papua New Guinea	0	0	56	56
The Philippines	1,227	1,909	1,969.7	1,904
Portugal	5	16	23	29
Russia	11	23	79	82
Thailand	0.3	0.3	0.3	0.3
Turkey	20.4	20.4	38	99
The United States	2,816.7	2,228	2,687	3,129
Total	**6,866.77**	**7,974.06**	**9,731.7**	**11,180**



1. Plant Layout



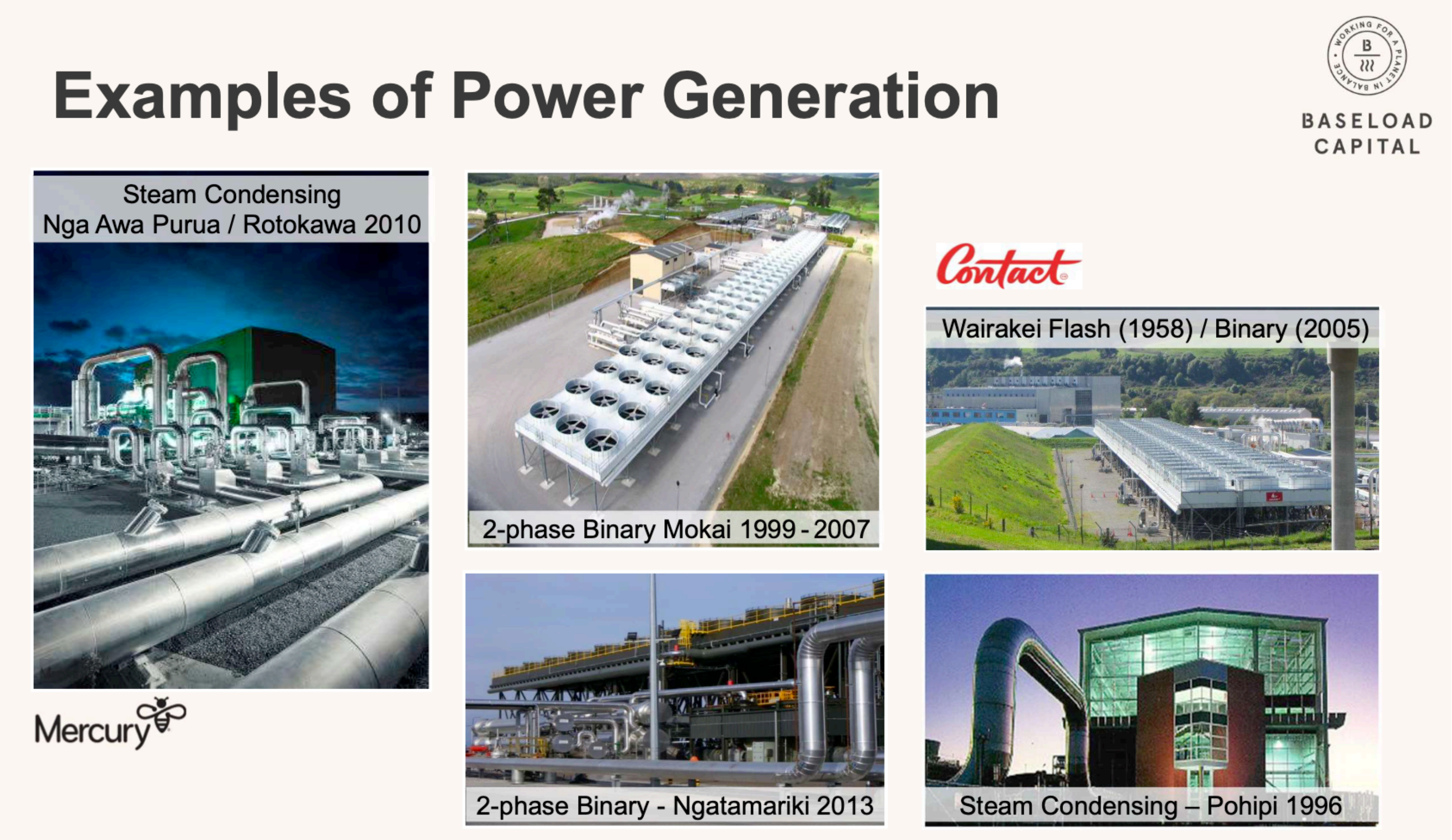
Steamfield Design

BASELOAD CAPITAL

Separator Plant

Production/ Injection Well

Monitoring Well



Examples of Power Generation

BASELOAD CAPITAL

Steam Condensing
Nga Awa Purua / Rotokawa 2010

Mercury

2-phase Binary Mokai 1999 - 2007

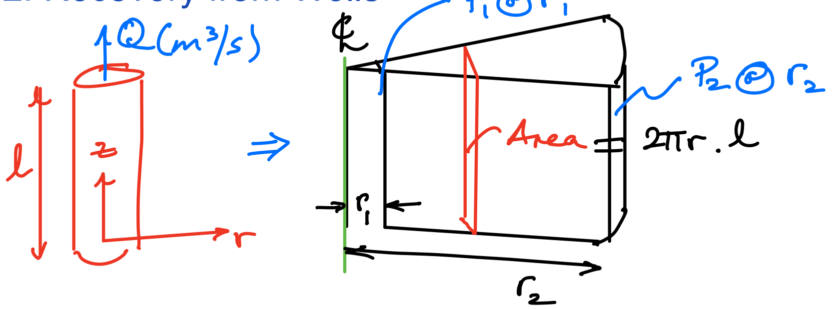
2-phase Binary - Ngatamariki 2013

Contact

Wairakei Flash (1958) / Binary (2005)

Steam Condensing – Pohipi 1996

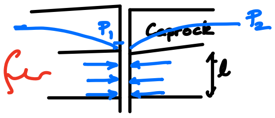
2. Recovery from Wells



Darcy's law: $q = -\frac{k}{\mu}\frac{dp}{dr}$

Area = $2\pi r . l$

Assumed radial flow – confined aquifer



$$Q = A . q = 2\pi r l . \times \frac{k}{\mu}\frac{dp}{dr}$$

$$Q\int_{r_1}^{r_2}\frac{dr}{r} = 2\pi l . \frac{k}{\mu} . \int_{P_1}^{P_2} dp$$

$$Q(\ln r_2 - \ln r_1) = 2\pi l . \frac{k}{\mu}(P_2 - P_1)$$

$$\boxed{Q = 2\pi l \frac{k}{\mu}\frac{(P_2 - P_1)}{\ln(r_2/r_1)}}$$

Choose some numbers:

Hydrothermal – $k \sim 10^{-15}\ m^2$ (mD)

μ @ 200°c ~ 10^{-4} Pa.s

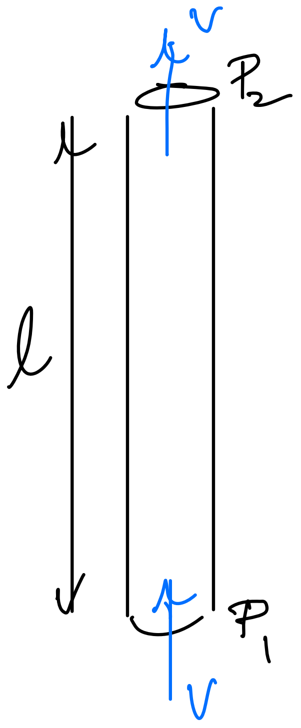
$l \sim 1000$ m

ΔP_{max} ~ depth to base of caprock × γ_{water}

r_2 ~ well spacing/2

r_1 ~ 0.1 m = 4" radius.

3. Friction losses in wellbores



$$v = \frac{Q}{A}$$

$$l = (z_2 - z_1)$$

$$\frac{P_1}{\gamma} + z_1 + \cancel{\frac{v^2}{2g}} + h_p = \frac{P_2}{\gamma} + z_2 + \cancel{\frac{v^2}{2g}} + \sum h_L$$

$$\frac{(P_1 - P_2)}{\gamma} + (z_1 - z_2) + h_p = \sum h_L$$

$$h_p = \frac{W}{g\underbrace{\rho Q}_{\dot{m}}} \; ; \qquad h_L = f \cdot \frac{l}{D} \cdot \frac{v^2}{2g}$$

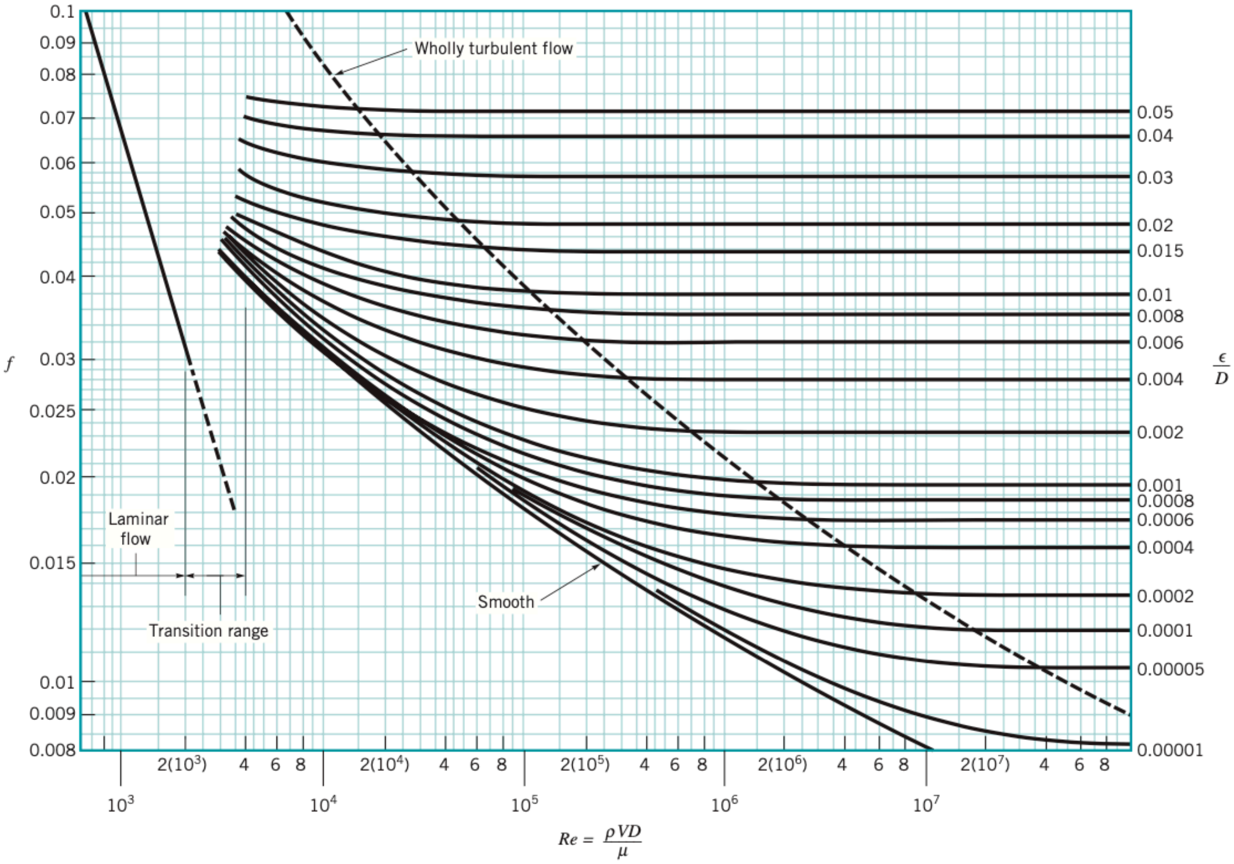
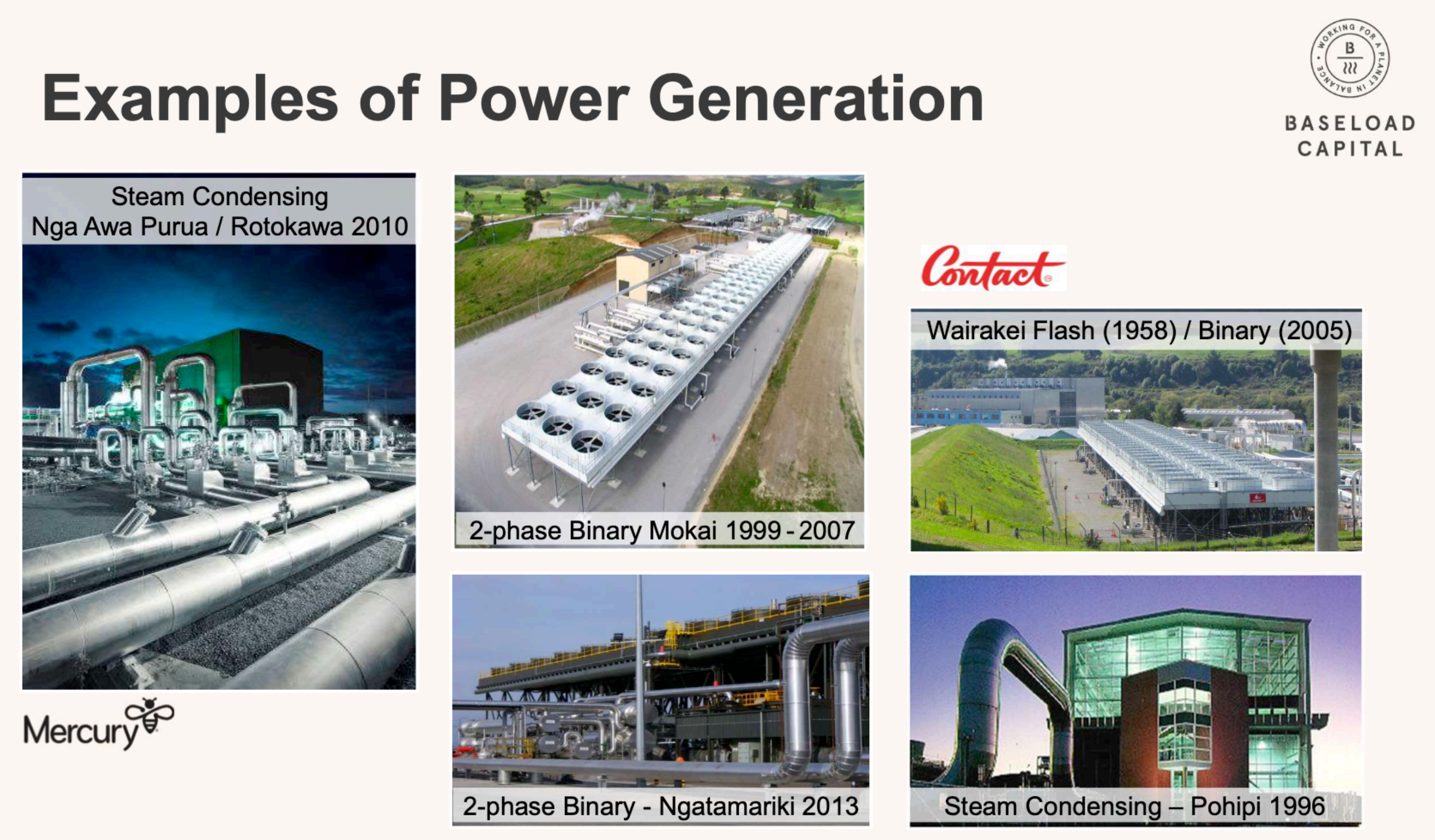


FIGURE 8.20 Friction factor as a function of Reynolds number and relative roughness for round pipes—the Moody chart. (Data from Ref. 7 with permission.)



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2-phase Binary - Ngatamariki 2013

Steam Condensing – Pohipi 1996

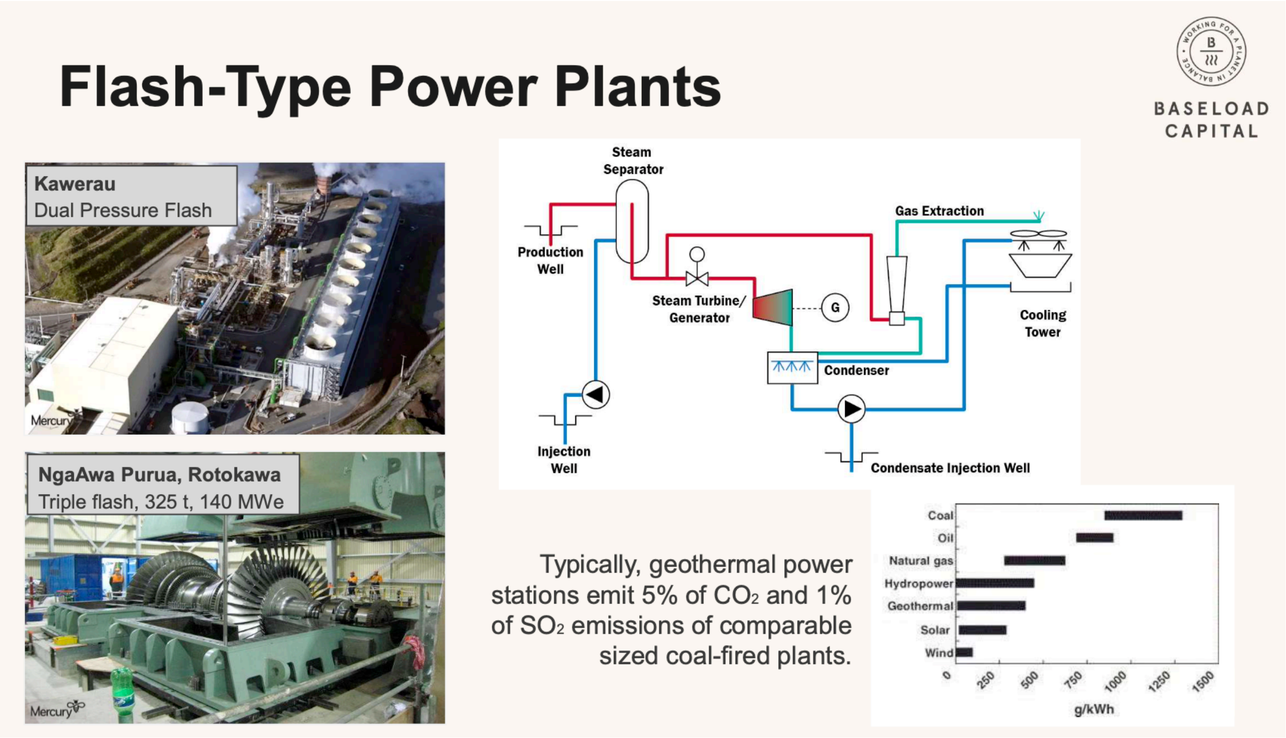
IN GENERAL

f(0.85; steam content)

$$P_{\text{electrical}} = Eff_{\text{generator}} \times Eff_{\text{turbine}} \times P_{\text{thermal}}$$

~ 0.90 Kinetic → Electrical

A. Single-flash production

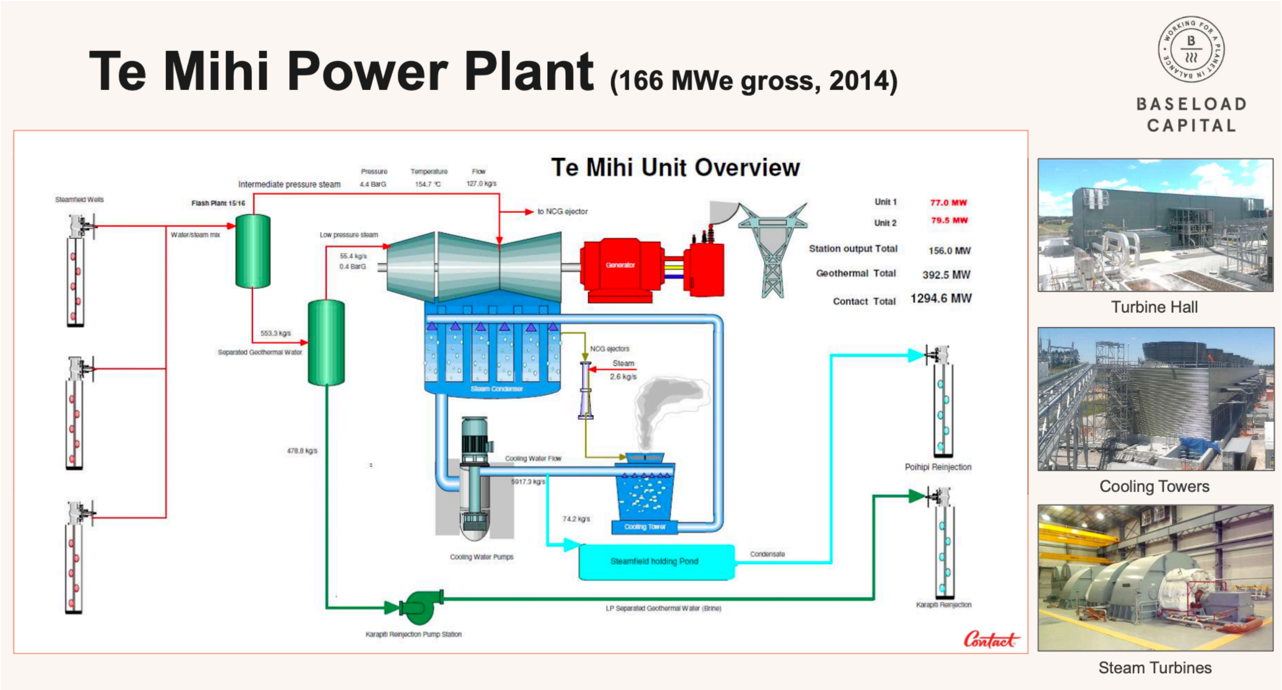


Flash-Type Power Plants

Kawerau
Dual Pressure Flash

NgaAwa Purua, Rotokawa
Triple flash, 325 t, 140 MWe

Typically, geothermal power stations emit 5% of CO_2 and 1% of SO_2 emissions of comparable sized coal-fired plants.



Te Mihi Power Plant (166 MWe gross, 2014)

Te Mihi Unit Overview

Unit 1 77.0 MW
Unit 2 79.5 MW
Station output Total 156.0 MW
Geothermal Total 392.5 MW
Contact Total 1294.6 MW

Turbine Hall

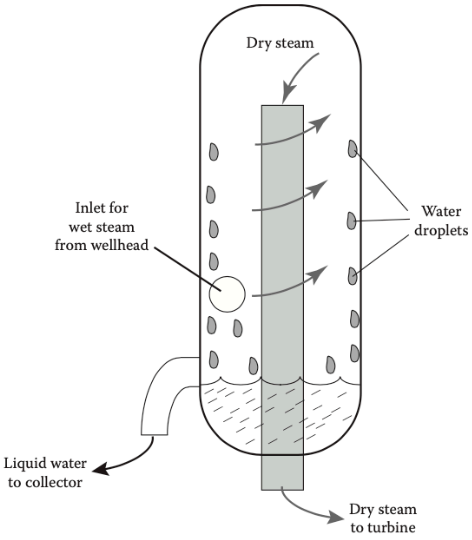
Cooling Towers

Steam Turbines

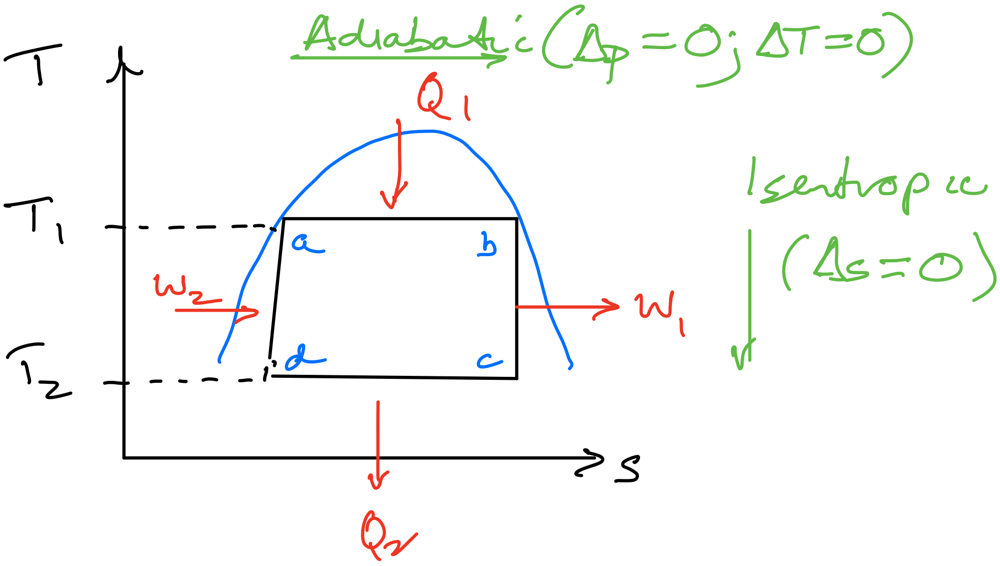
Physics of energy conversion

Turbine: $Eff_{turbin} \sim 0.85 \times \left(\frac{1+x_s}{2}\right)$

x_s = steam fraction: $\frac{100\% \rightarrow 1.0 \checkmark}{0\% \rightarrow 0.0}$



CARNOT CYCLE



Adiabatic $(\Delta p = 0;\ \Delta T = 0)$

Isentropic $(\Delta s = 0)$

① $$\boxed{\eta_c = 1 - \frac{T_2}{T_1}}$$

② $\underline{Q + W = \Delta h}$ $\begin{cases} Q = h_b - h_a & (W=0) \\ W = h_b - h_c & (Q=0) \end{cases}$

③ $h = (1-x)\, h_l + x\, h_g$

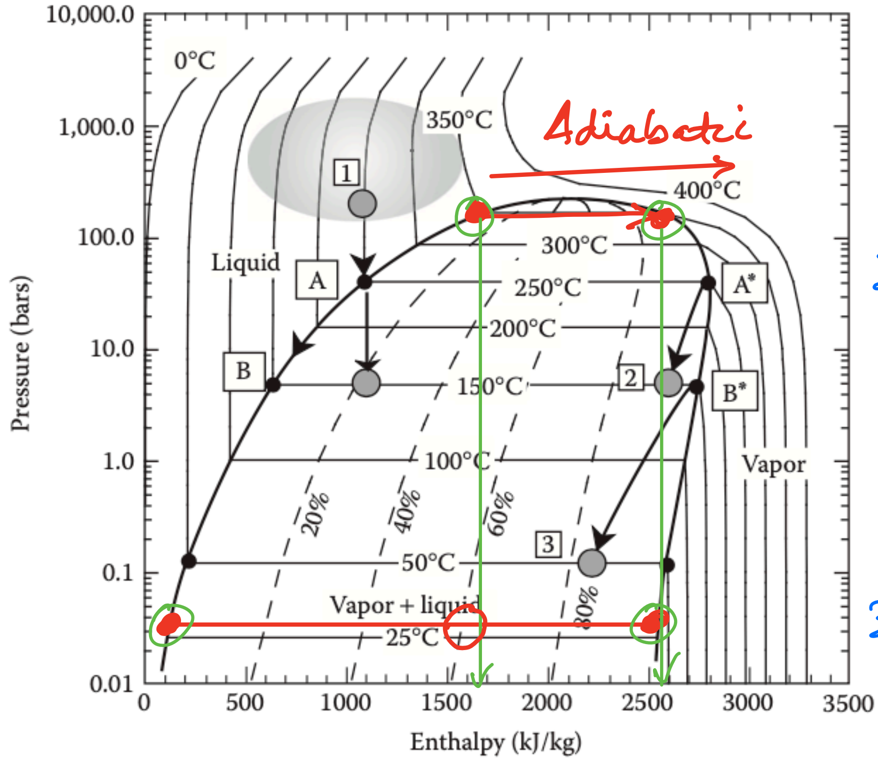
$s = (1-x)\, s_l + x\, s_g$

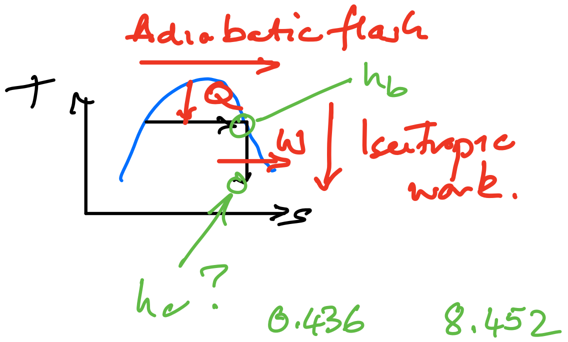
CONSIDER: Reservoir ⓐ: $T = 352°c$, $p = 170$ bar

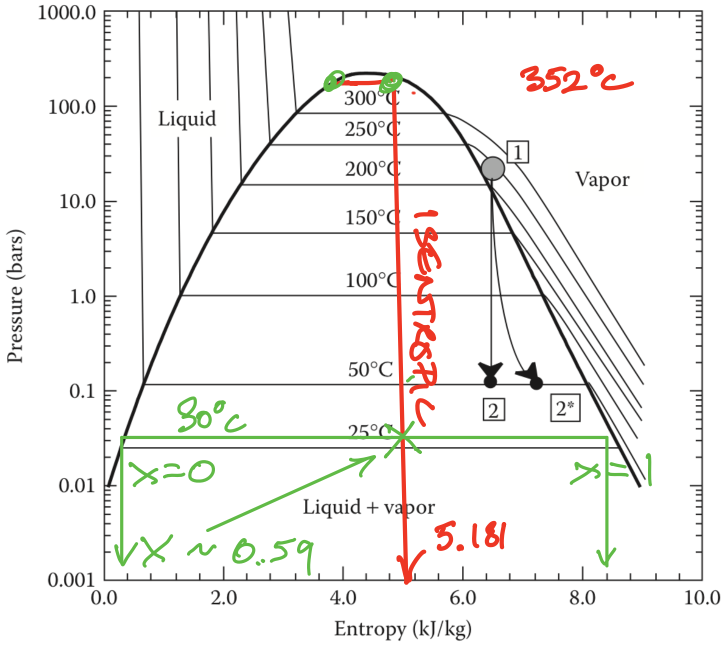
Discharge ⓒ: $T = 30°c$; $p = 0.04$b

$$\eta_c = 1 - \frac{273+30}{273+352} \cong 0.52$$

T	h_l (kJ/kg)	h_g (kJ/kg)
352°c	1690	2548 $= h_b$
30°c	126	2556







$$S_c = (1-x)\,S_l + x\,S_g$$

S_c = 5.181; S_l = 0.436; S_g = 8.452; ?

$$\boxed{x \sim 0.59}$$

$$\therefore\ h_c = (1-x)\,h_l + x\,h_g$$

$$\boxed{h_c \sim 1560 \text{ kJ/kg}}$$

$$W = h_b - h_c = 2548 - 1560 \simeq 988 \text{ kJ/kg}.$$

EFFICIENCY CONSTRAINTS

$$\text{POWER}_{\text{ELEC}} = \eta_{\text{generator}} \times \eta_{\text{turbine}} \times \text{POWER}_{\text{THERM}}$$

$$\eta_{\text{TURBINE}} \simeq 0.85 \times \left(\frac{1+\cancelto{0.59}{X}}{2}\right)$$

$$\simeq 0.85 \times 0.8 = 0.68 \sim \underline{\underline{0.7}}$$

$$\eta_{\text{GENERATOR}} \sim 90-100\%.$$

Viable well for payback is 100 kg/s.

100 kg/s   352°C → 30°C

$$\text{POWER}_{\text{THERMAL}} = 988\ \text{kJ/kg} \times 100\ \text{kg/s}$$

$$= 100{,}000\ \text{kJ/s}$$

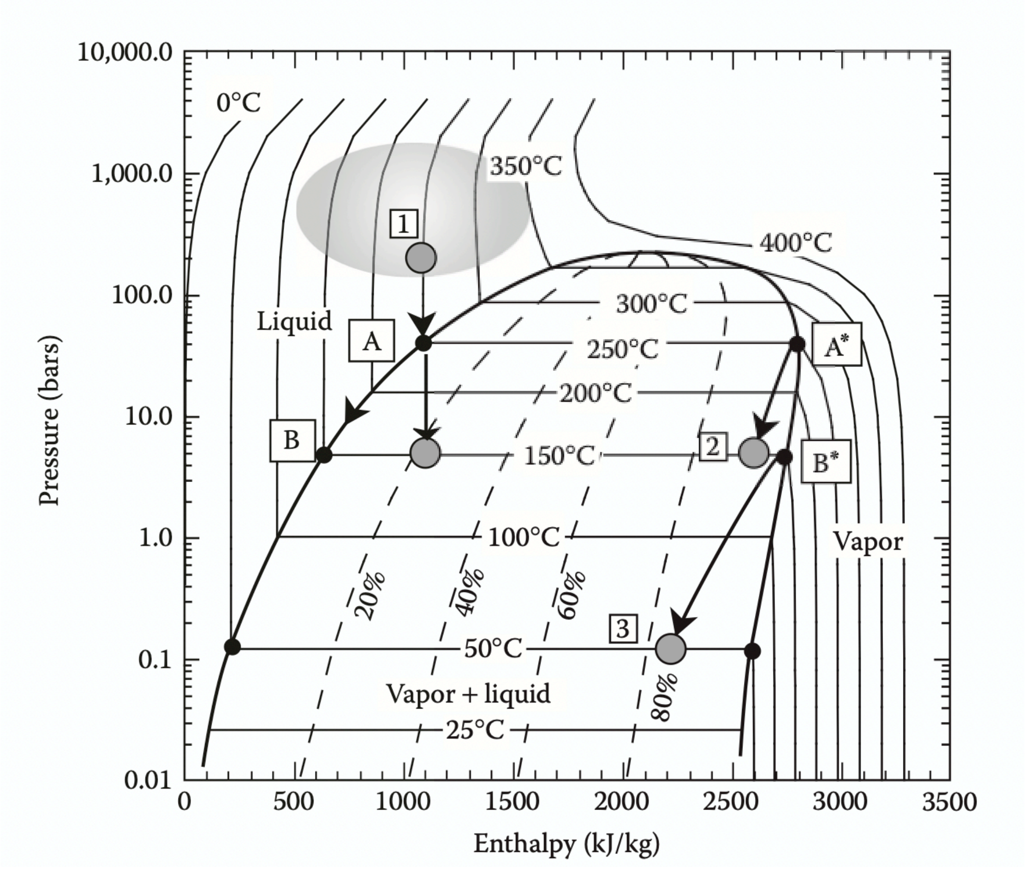
$$= 100\ \text{MW}_{\text{TERMAL}}$$

@ 60% efficiency → 60 MW.

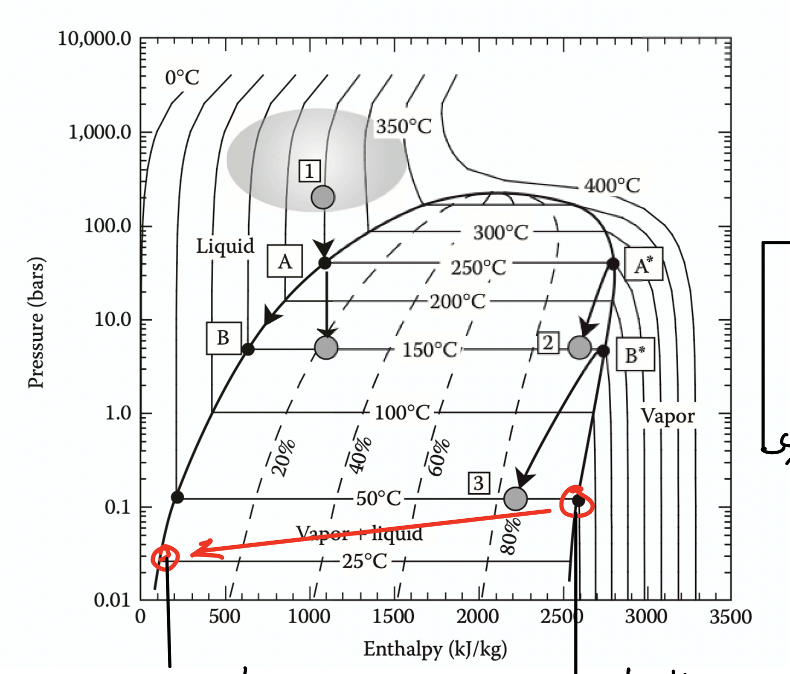
Possible ΔT → 30°C is higher than expected.

∴ track along $X \simeq 60\%$ steam @ higher $T_c \uparrow$

B. Dual-flash plants



Condensing water for reinjection



105 kJ/kg

2592 kJ/kg

2592 − 105 ~ 2487.

Turbine exit 50°C

Cool to 25°C

$$\Delta H_{inj} = \dot{M}_{inj} \times 2487\, kJ/kg$$

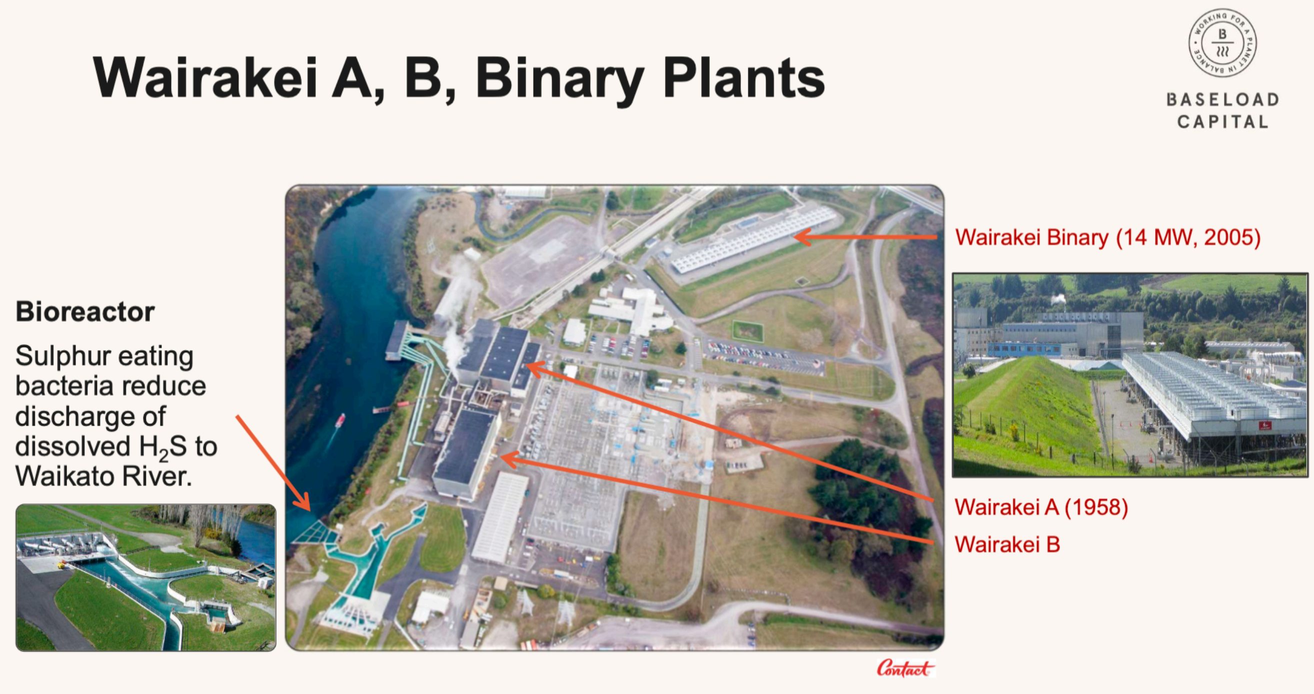
$$\Delta H_{condnt} = \dot{M}_c c \Delta T$$

?

4.2 kJ/kg.K

25°C

C. Binary plants



Wairakei A, B, Binary Plants

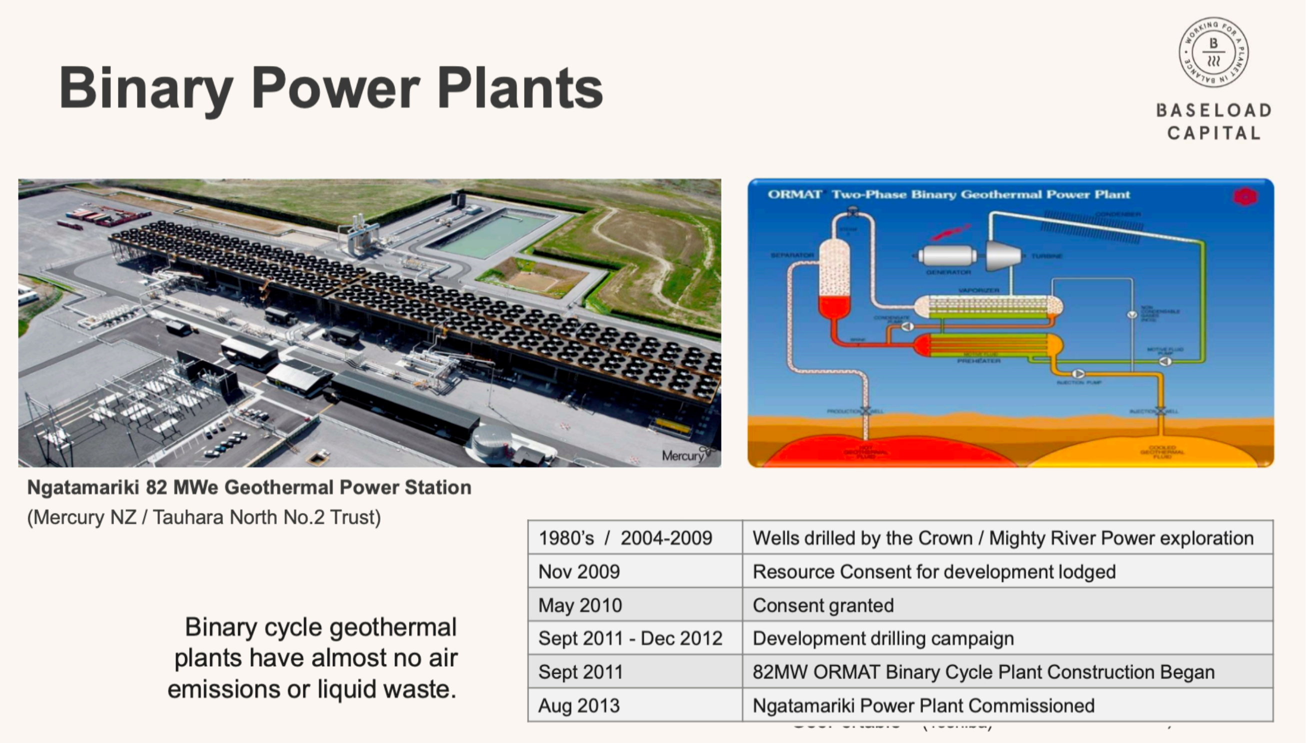
Bioreactor

Sulphur eating bacteria reduce discharge of dissolved H_2S to Waikato River.

Wairakei Binary (14 MW, 2005)

Wairakei A (1958)

Wairakei B



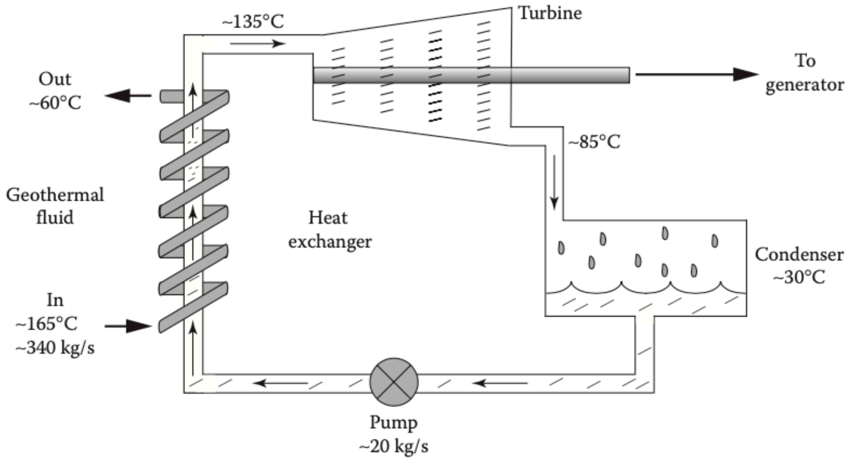
Binary Power Plants

Ngatamariki 82 MWe Geothermal Power Station

(Mercury NZ / Tauhara North No.2 Trust)

Binary cycle geothermal plants have almost no air emissions or liquid waste.

1980's / 2004-2009	Wells drilled by the Crown / Mighty River Power exploration
Nov 2009	Resource Consent for development lodged
May 2010	Consent granted
Sept 2011 - Dec 2012	Development drilling campaign
Sept 2011	82MW ORMAT Binary Cycle Plant Construction Began
Aug 2013	Ngatamariki Power Plant Commissioned



ISOPENTANE FLASH

BP ~ 28°C

C ~ 2.3 kJ/kg.°c

Heat of vap ~ 344 kJ/kg.

∴ Heat input to condense

$$\Delta H = c \dot{M} \Delta T$$

$$= 2.3 \frac{kJ}{kg.K} \cdot 20 \frac{kg}{s} \cdot 50°c$$

~ 2.3 MW @ 100% Efficn