

U.S. DEPARTMENT OF ENERGY



Geothermal Energy from Oil + Gas
Demonstrated Engineering

WELL MODELLING APPLIED TO GEOTHERMAL RESOURCE EVALUATION

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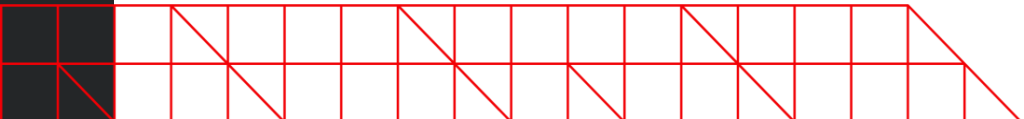
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Overview of Geothermal Reservoir Modelling

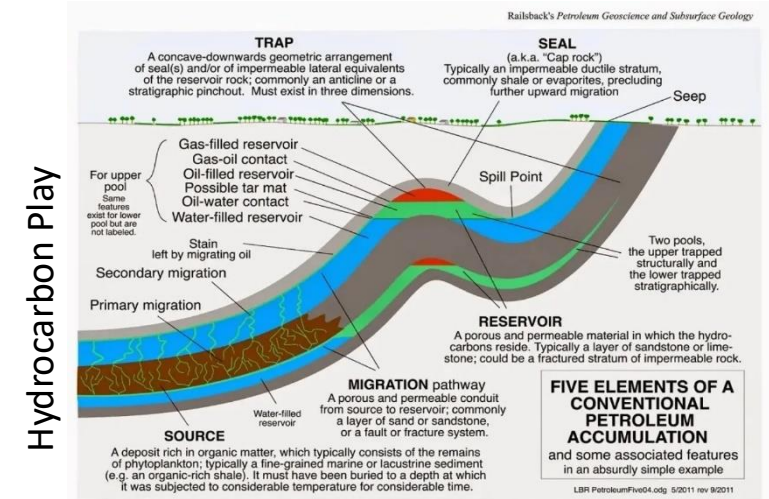
Overview of Geothermal Reservoir Modelling

Geologic Perspective On Geothermal Play Systems

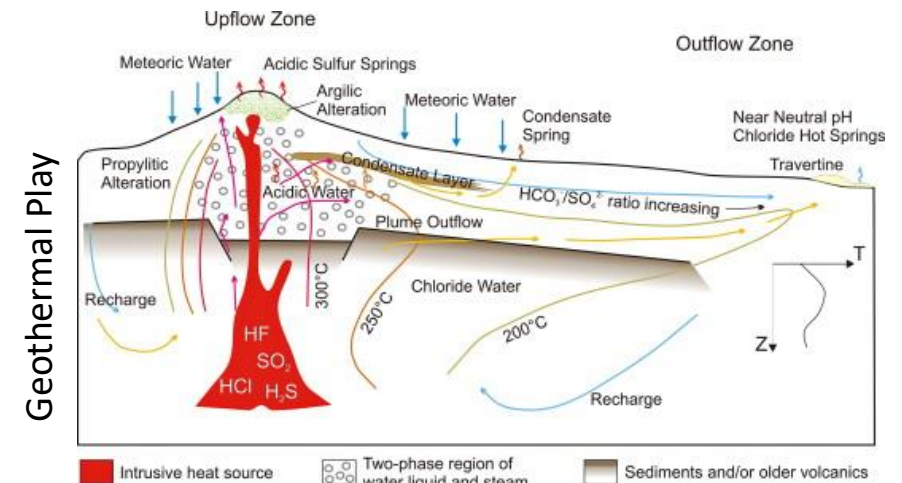
A **geothermal play systems** in contrast to the straightforward definition of hydrocarbon play systems, which are clearly defined by their source rock, reservoir and trap, geothermal play systems are lacking such a clear set of geological features.

Instead, geothermal play systems appear in diverse geologic environments and theoretically all over the world.

For geothermal resource utilization, important factors are how much heat is stored at a drillable depth and if this heat is producible at an economic rate for a specific project.



<https://www.geologyin.com/2014/08/petroleum-system.html>



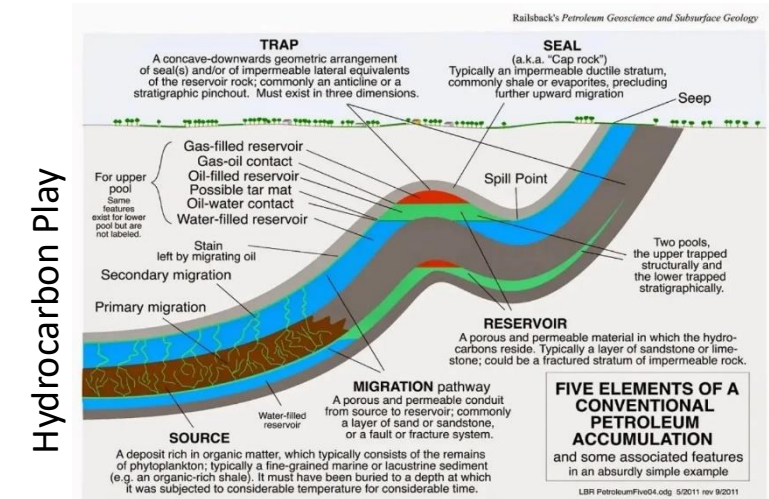
Inga S. Moeck 2014

Overview of Geothermal Reservoir Modelling

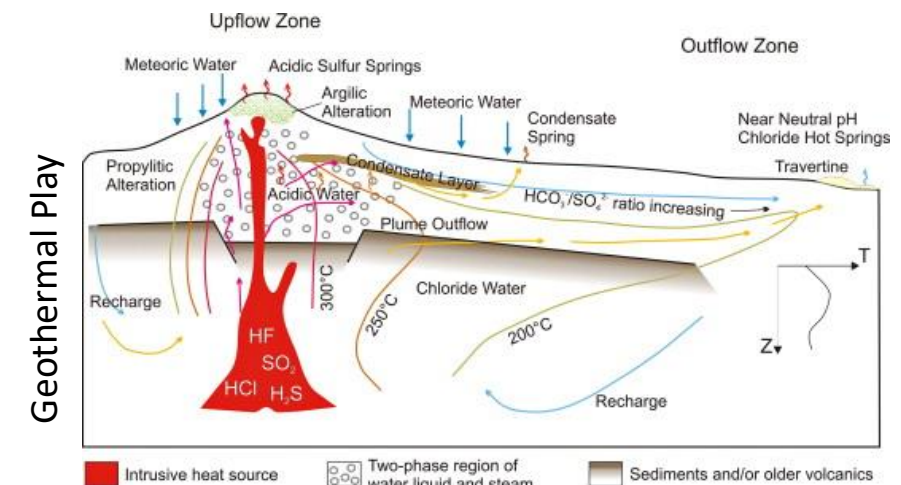
Geologic Perspective On Geothermal Play Systems

A **conceptual model** on how a number of geological factors might generate a recoverable geothermal resource at a specific structural position in a certain geologic setting. The characteristics of individual geothermal systems are a function of site-specific variables:

- The nature and depth of the heat source;
- The dominant heat transfer mechanism;
- Permeability and porosity distribution;
- Rock mechanical properties;
- Fluid/rock chemistry;
- Fluid recharge rates/sources.
- Identify the play type → focussed exploration strategy



<https://www.geologyin.com/2014/08/petroleum-system.html>



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Overview of Geothermal Reservoir Modelling

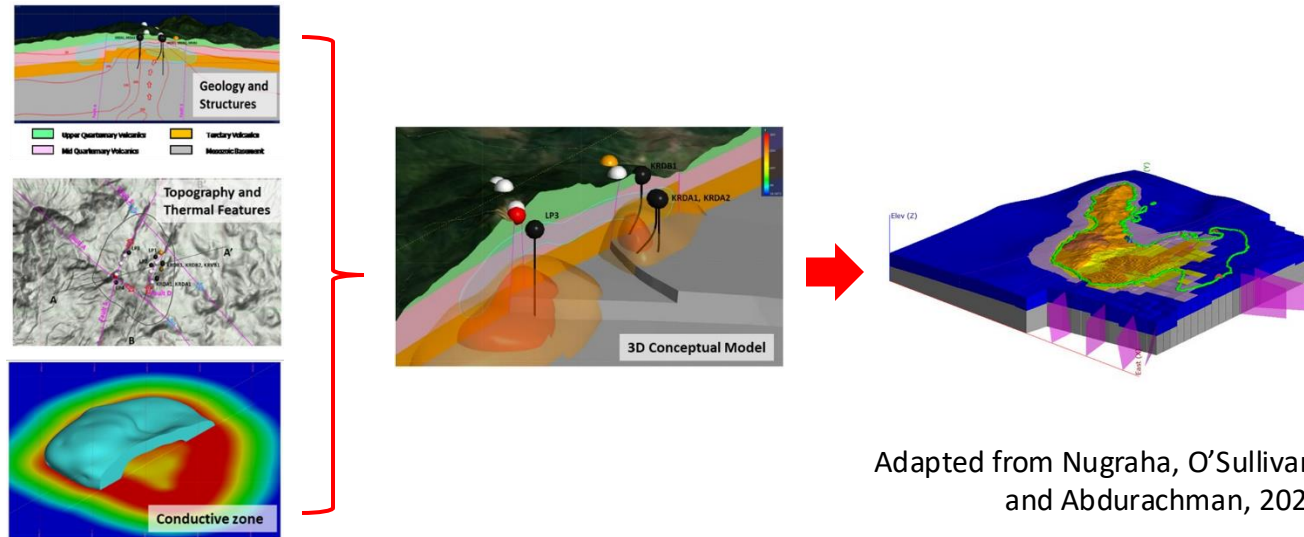
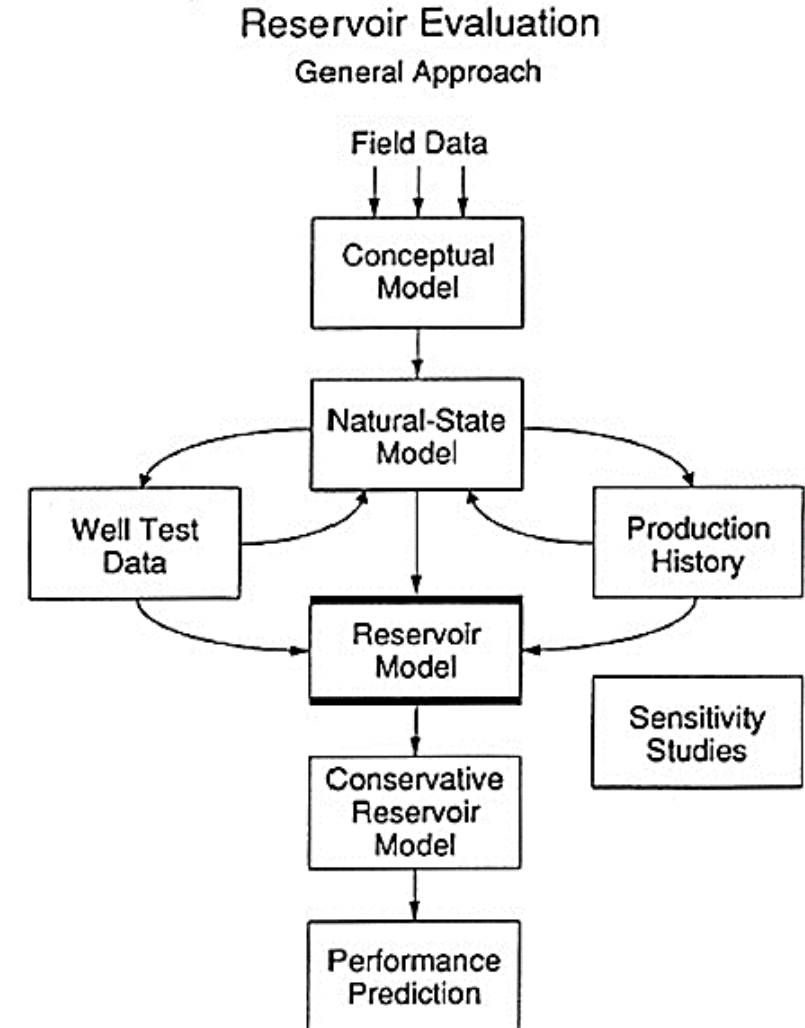
Types of geothermal reservoirs Play Systems

Type	Subtype	Geologic Setting	Heat Source	Dominant Heat Transport Mechanism
CV-1: Magmatic	CV-1a: Extrusive	Magmatic Arcs, Mid Oceanic Ridges, Hot Spots	Active Volcanism, Shallow Magma Chamber	Magmatic-hydrothermal Circulation
	CV-1b: Intrusive	Magmatic Arcs, Mid Oceanic Ridges, Hot Spots	Active Volcanism, Shallow Magma Chamber	Magmatic-hydrothermal Circulation, Fault Controlled
CV-2: Plutonic	CV-2a: Recent or Active Volcanism	Convergent Margins with Recent Plutonism (<3 Ma), Young Orogens, Post-orogenic Phase	Young Intrusion+Extension, Felsic Pluton	Magmatic-hydrothermal Circulation, Fault Controlled
	CV-2b: Inactive Volcanism	Convergent Margins with Recent Plutonism (<3 Ma), Young Orogens, Post-orogenic Phase	Young Intrusion+Extension, Felsic Pluton, Heat Producing Element in Rock	Hydrothermal Circulation, Fault Controlled
CV-3: Extensional Domain		Metamorphic Core Complexes, Back-arc Extension, Pull-apart Basins, Intracontinental Rifts	Thinned Crust+Elevated Heatflow, Recent Extensional Domains	Fault Controlled, Hydrothermal Circulation
CD-1: Intracratonic Basin		Intracratonic/Rift Basins, Passive Margin Basins	Lithospheric Thinning and Subsidence	Litho/Biofacies Controlled
CD-2: Orogenic Belt		Foreland Basins within Fold-and-thrust Belts	Crustal Loading and Subsidence Adjacent to Thickened Crust	Fault/Fracture Controlled, Litho/Biofacies Controlled
CD-3: Crystalline Rock - Basement		Intrusion in Flat Terrain	Heat Producing Element in Rock, Hot Intrusive Rock	Hot Dry Rock, Fault/Fracture Controlled

Overview of Geothermal Reservoir Modelling

General approach to reservoir evaluation

- Data collection
- Building a conceptual model
- “Natural state” numerical modelling (Initialization)
- Production modelling



Overview of Geothermal Reservoir Modelling

General approach to reservoir evaluation

DATA SOURCES

Geological data

- Data from surface outcrops (structure, lithology)
- Borehole data (stratigraphy, hydrothermal alterations)

Geochemical data

- Chemical composition
- Geothermometers

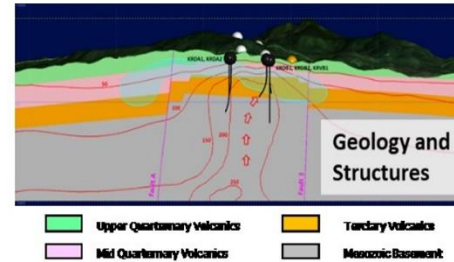
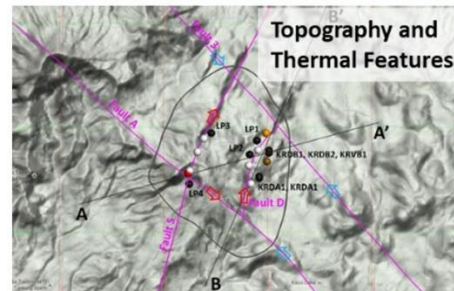
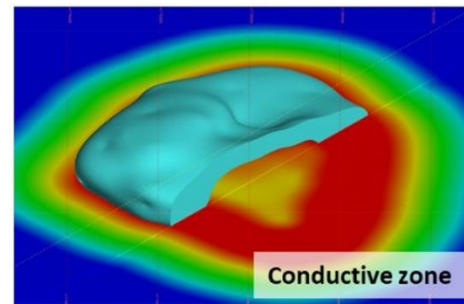
Heat and mass flow measurements

Temperature and discharge of springs, geysers and fumaroles

Temperature gradient measurements in shallow boreholes

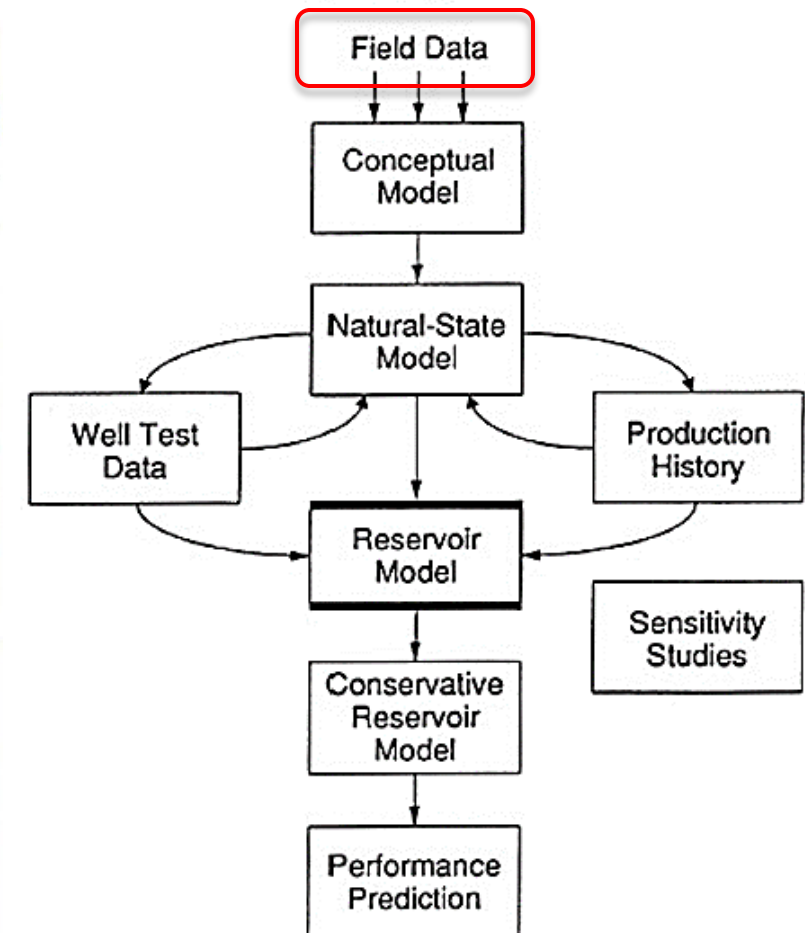
Geophysical data

- Surface geophysical data: Resistivity, gravity, seismics, self-potential
- Down-hole data: well logs, T and P profiles, flow rates, flowing enthalpies



Adapted from Nugraha, O'Sullivan, and Abdurachman, 2022

Reservoir Evaluation General Approach



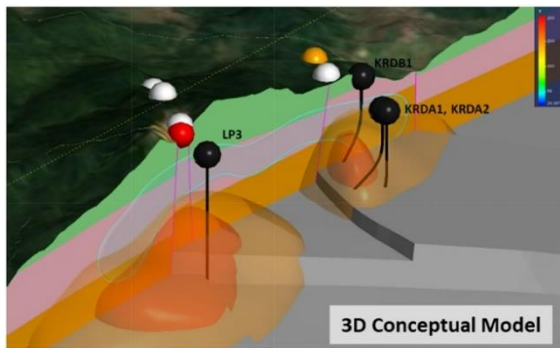
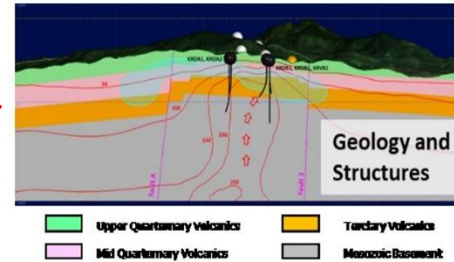
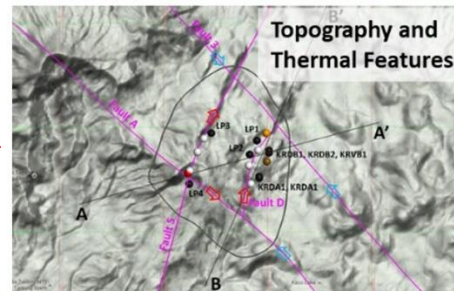
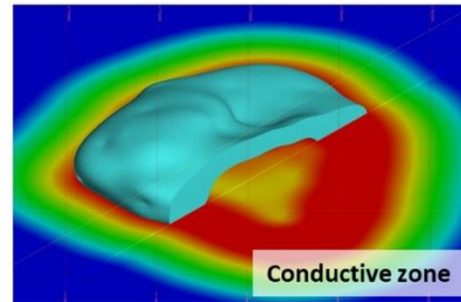
Bodvarsson and Witherspoon, 1989

Overview of Geothermal Reservoir Modelling

General approach to reservoir evaluation

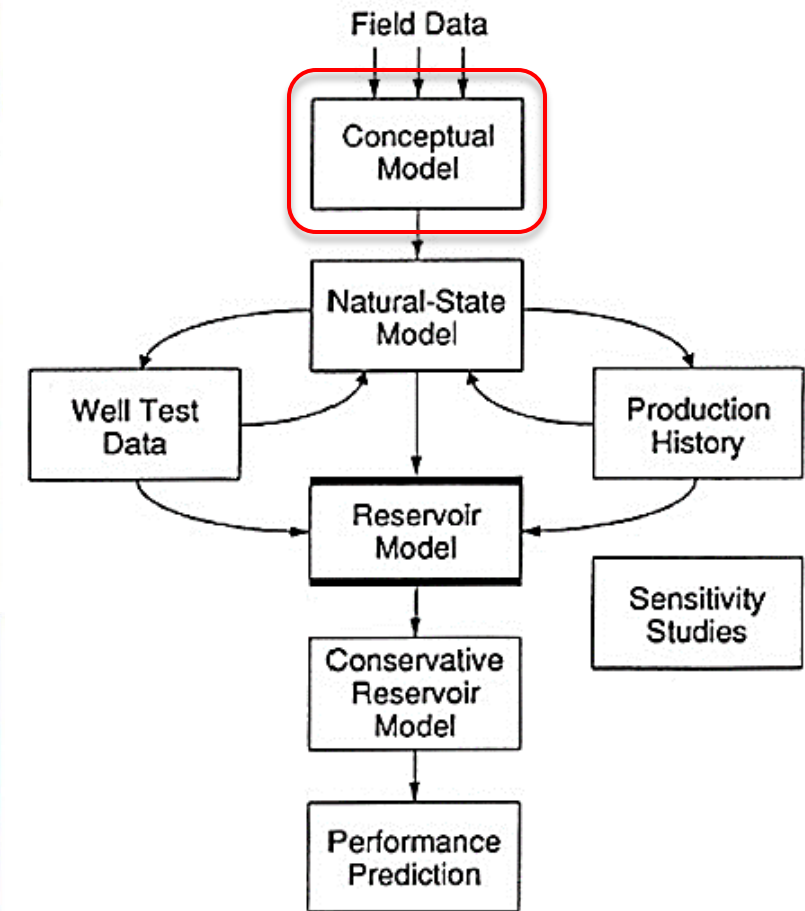
Components of a conceptual model

- Reservoir geometry
- Distribution of hydraulic and thermal properties
- Directions of fluid movement
- Location of inflow/outflow zones, and hydraulic boundaries
- Location of heat inputs and outputs
- Temperatures
- Two-phase zones



Adapted from Nugraha, O'Sullivan, and Abdurachman, 2022

Reservoir Evaluation General Approach



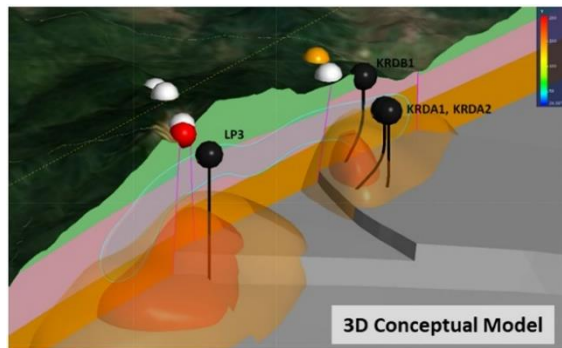
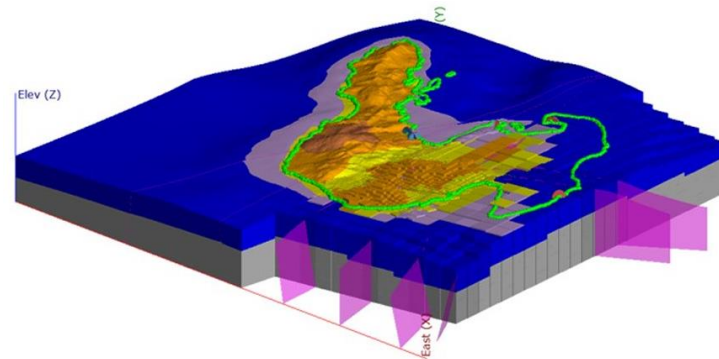
Bodvarsson and Witherspoon, 1989

Overview of Geothermal Reservoir Modelling

General approach to reservoir evaluation

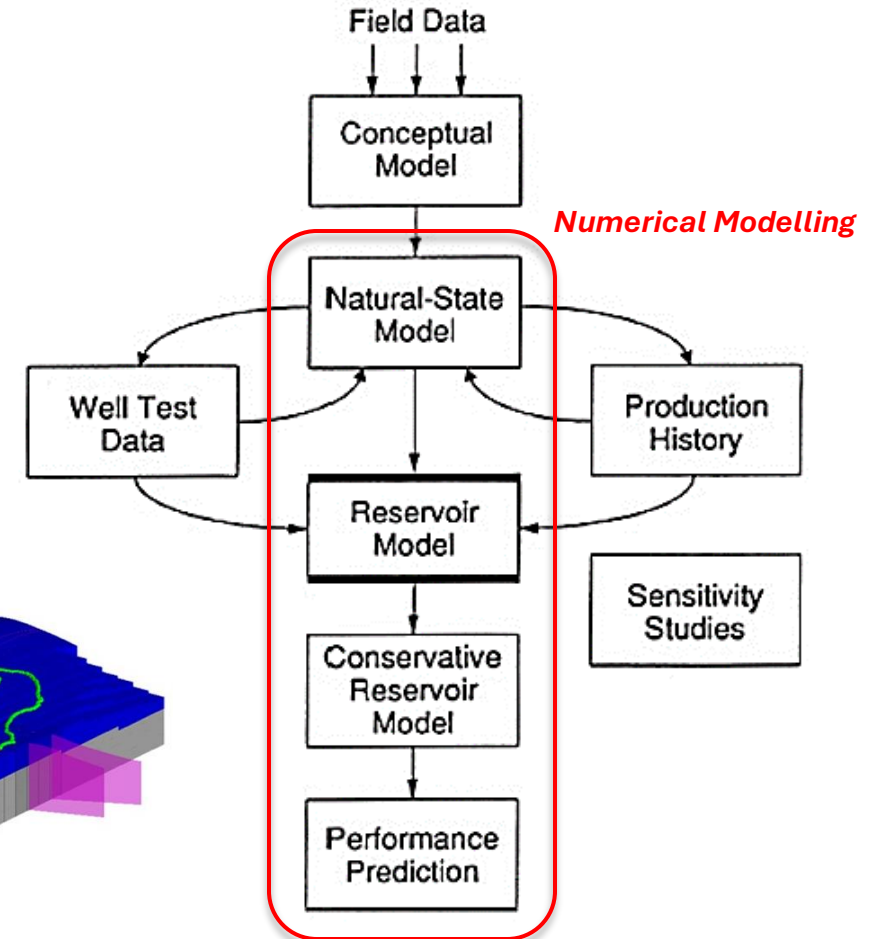
The purpose of Numerical Modelling

- To understand the physical functioning of a system
- To estimate generating capacity
- To design/optimize geothermal utilization system
- To predict the behaviour of the system (temperature, pressure) during extraction
- To estimate chemical changes during production
- To predict environmental impacts
- To help evaluating different conceptual models of the field
- To assess the economic feasibility
- To enhance safety measures



Adapted from Nugraha, O'Sullivan,
and Abdurachman, 2022

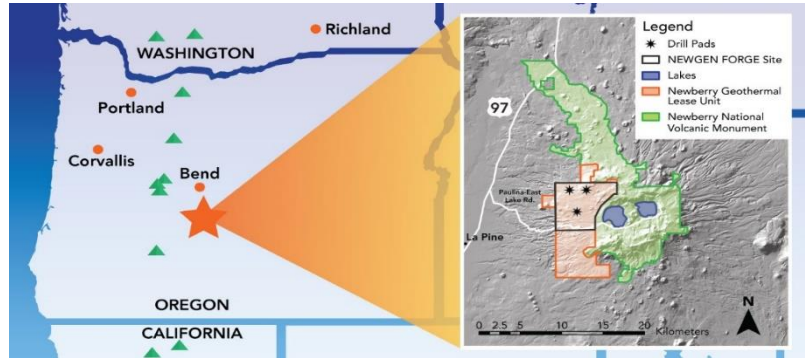
Reservoir Evaluation General Approach



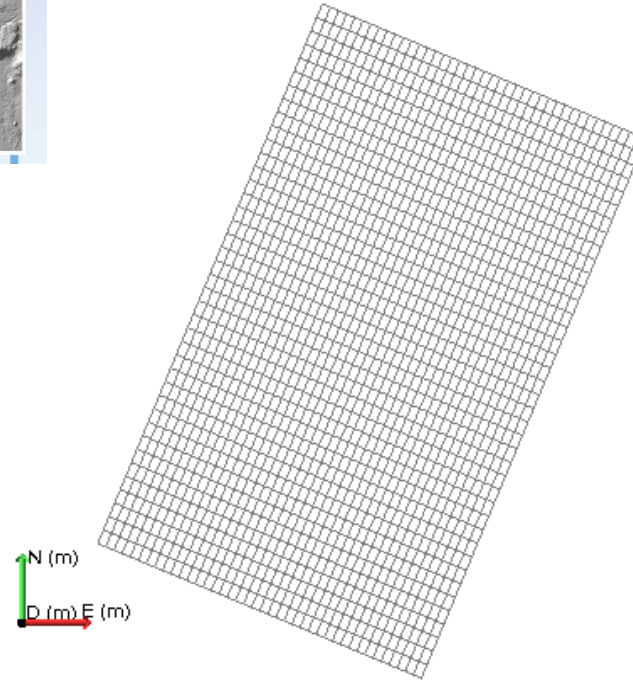
Bodvarsson and Witherspoon, 1989

Overview of Geothermal Reservoir Modelling

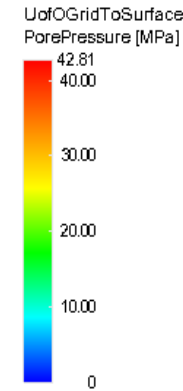
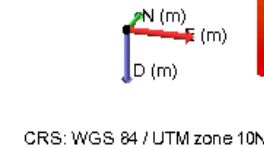
Simplified Geomodel – Case Example



- Modeling area 3000 m x 5000 m
- Vertical extent 5500 m
- Cell size 75x125x75m
- Pressure
- Temperature
- Porosity
- Permeability
- Available information



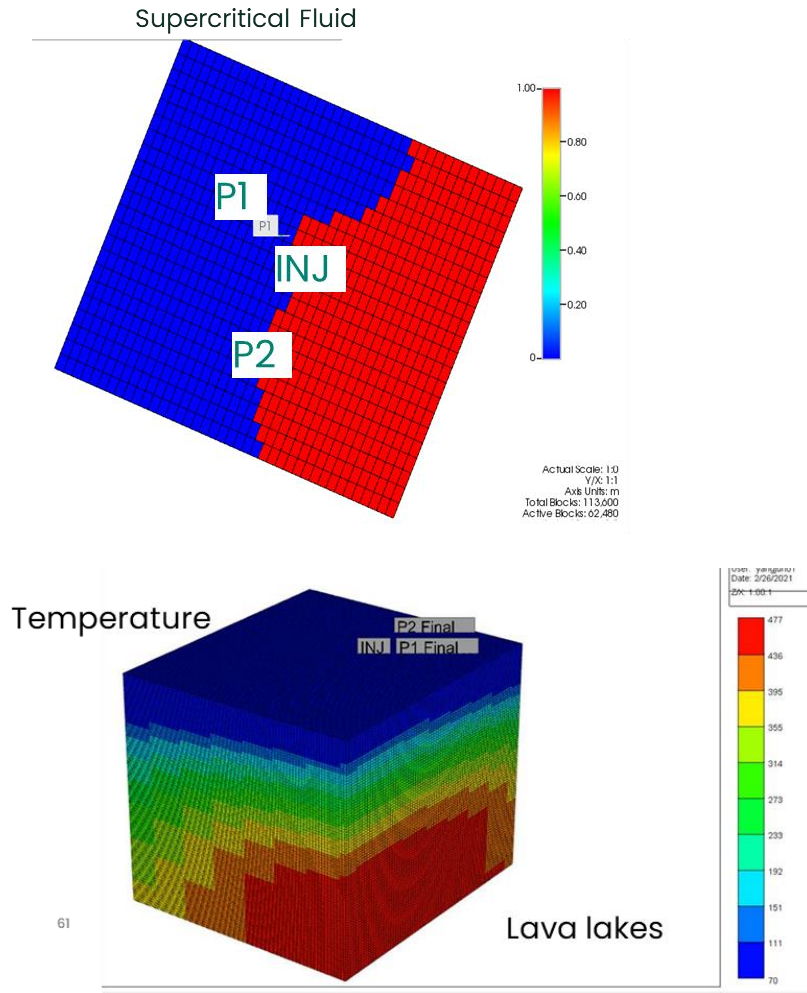
CRS: WGS 84 / UTM zone 10N



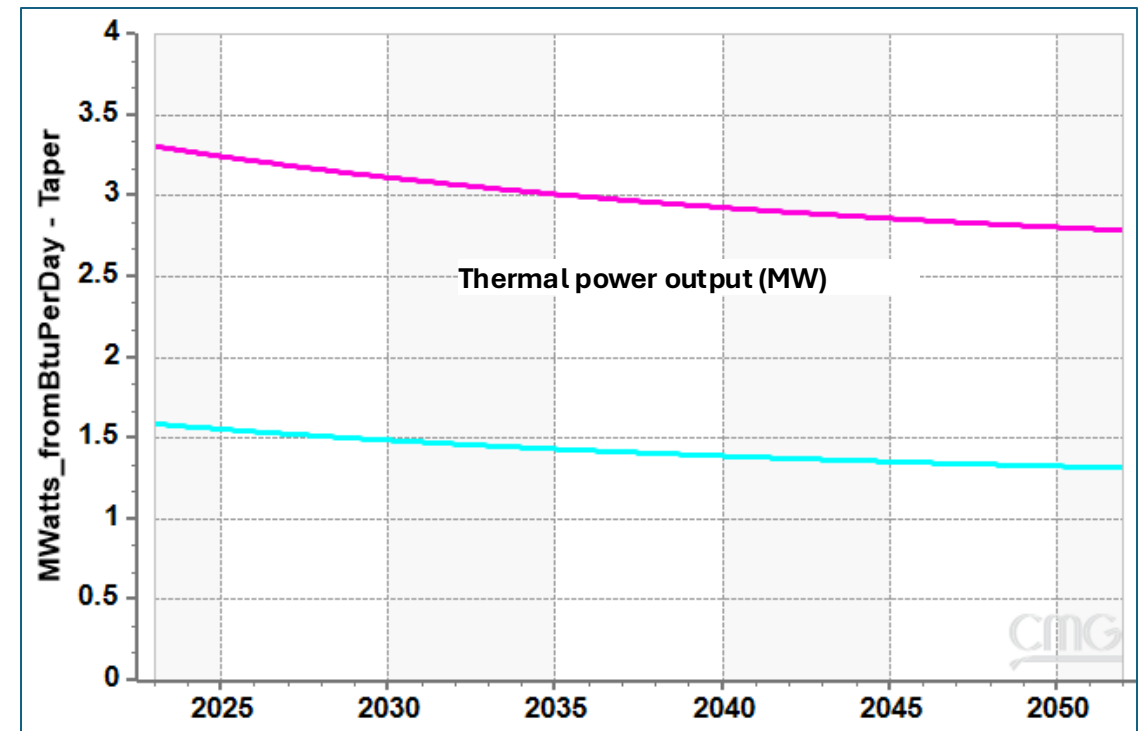
CRS: WGS 84 / UTM zone 10N

Overview of Geothermal Reservoir Modelling

Temperature gradient to create a realistic model



Outcomes & Value Delivery

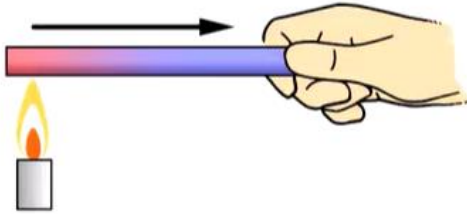


Initial condition determines the coexistence of superheated water and supercritical water

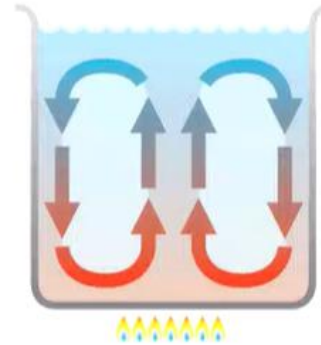
Temperature Modelling in the Well

Temperature Modelling in the Well

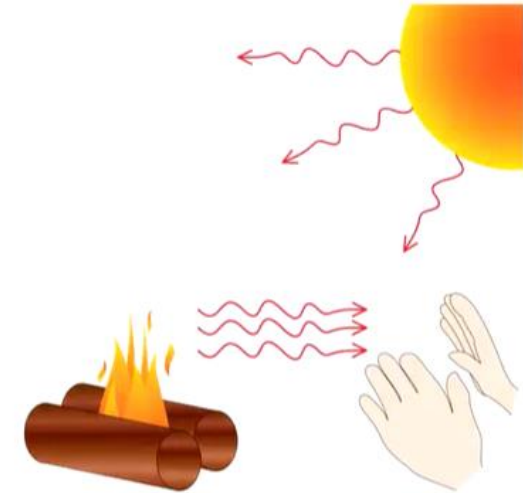
Heat Transfer Processes



CONDUCTION



CONVECTION

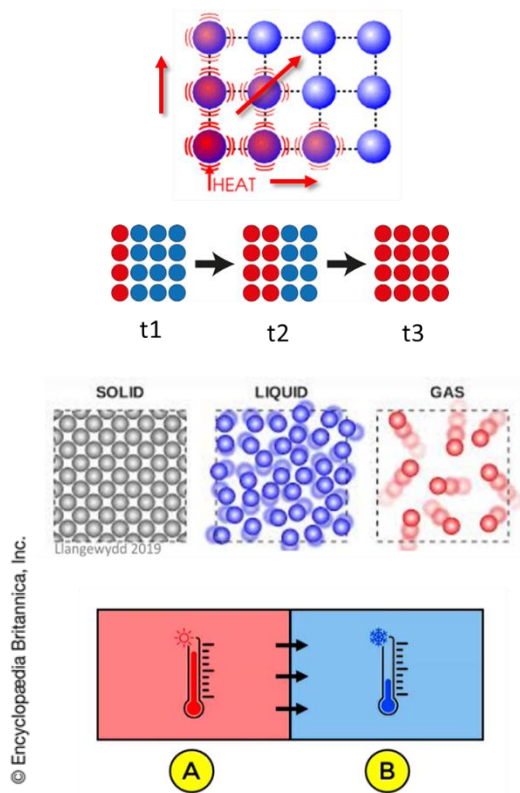


RADIATION

Temperature Modelling in the Well

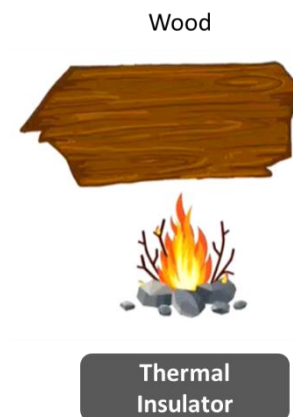
Heat Conduction

The transfer of heat by **direct contact** between the molecules of a body or substance.



Thermal Conductivity

Material	Thermal Conductivity - k - W/(m K)
Air, atmosphere (gas)	0.024
Aluminum	205
Balsa wood	0.048
Brass	109
Carbon dioxide (gas)	0.0146
Copper	401
Diamond	1000
Fiberglass	0.04
Glass	1.05
Gold	310
Hardwoods (oak, maple...)	0.16
Iron	80
Lead	35
Mercury, liquid	8.3
Paper	0.05
Silver	429
Softwoods (fir, pine ...)	0.12
Steel, Carbon 1%	43
Stainless Steel	16
Vacuum	0
Water	0.58
Zinc Zn	116

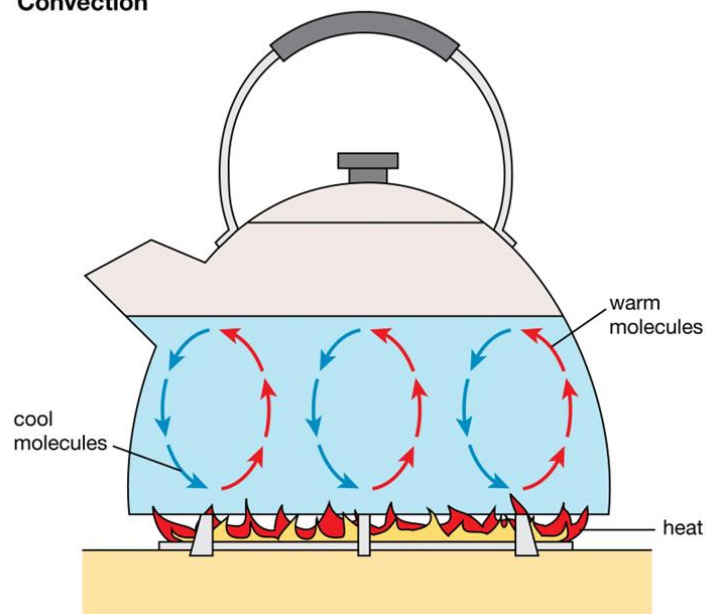


Temperature Modelling in the Well

Heat Convection

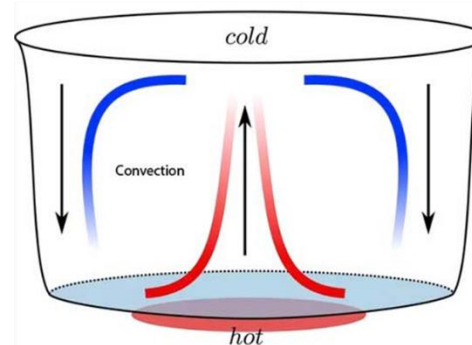
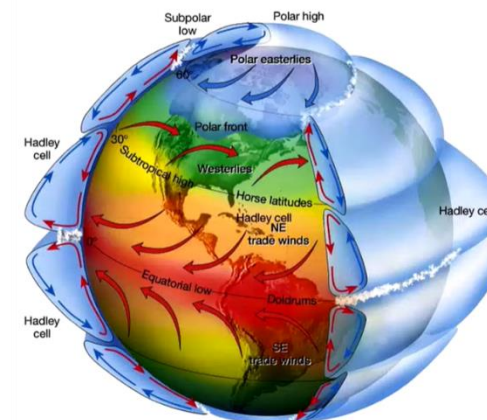
Convective heat transfer is the transfer of heat between two bodies by currents of moving gas or fluid. This convection can be **Natural** or **Forced**.

Convection



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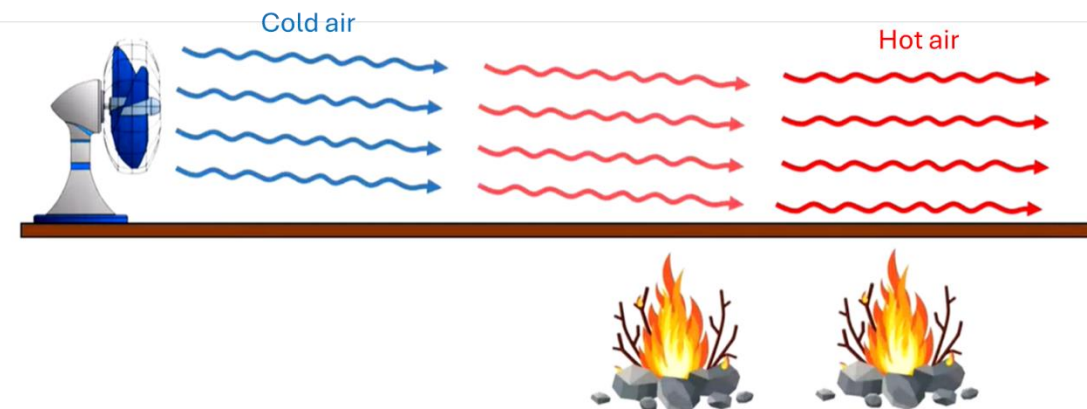
Natural Convection



<https://www.prodiffs.com/article/difference-between-natural-and-forced-convection>

Forced Convection

Fan



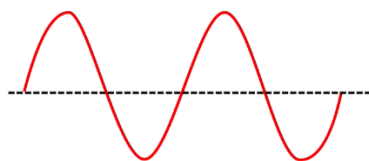
Modified from OpenStax

Temperature Modelling in the Well

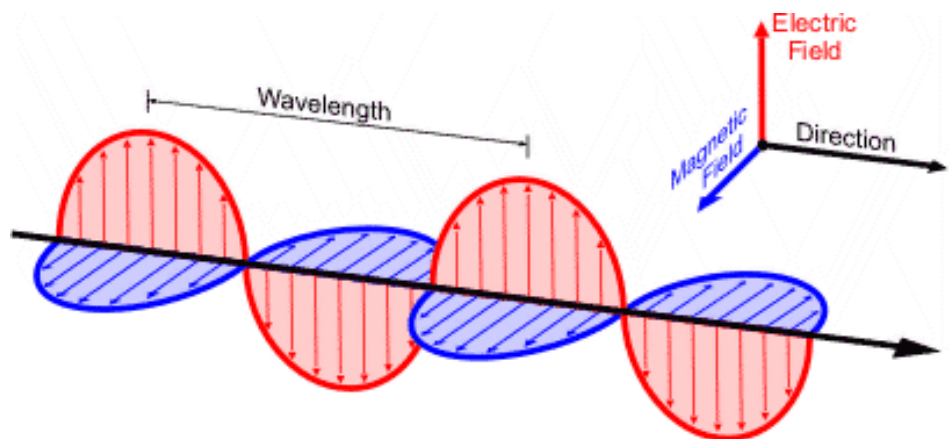
Heat Radiation

It is heat that is transmitted by means of electromagnetic waves.

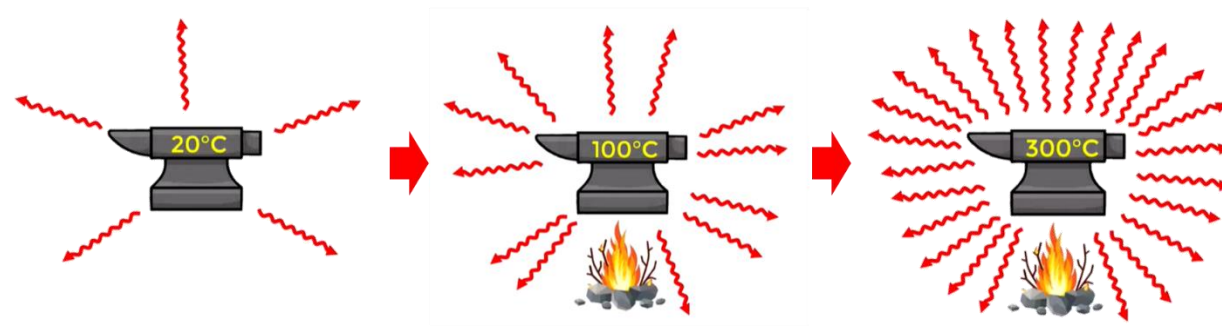
Electromagnetic Wave



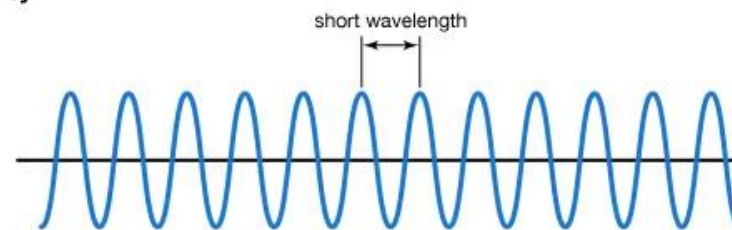
All bodies emit radiation



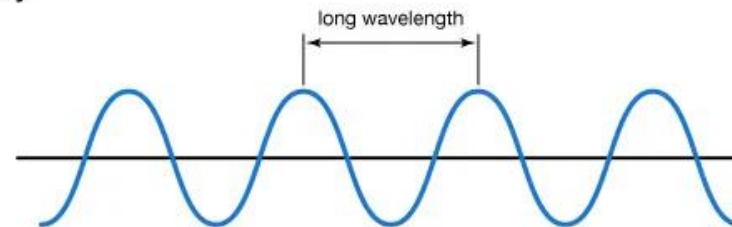
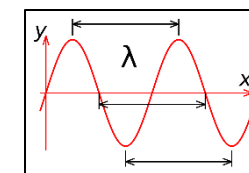
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High frequency



Low frequency



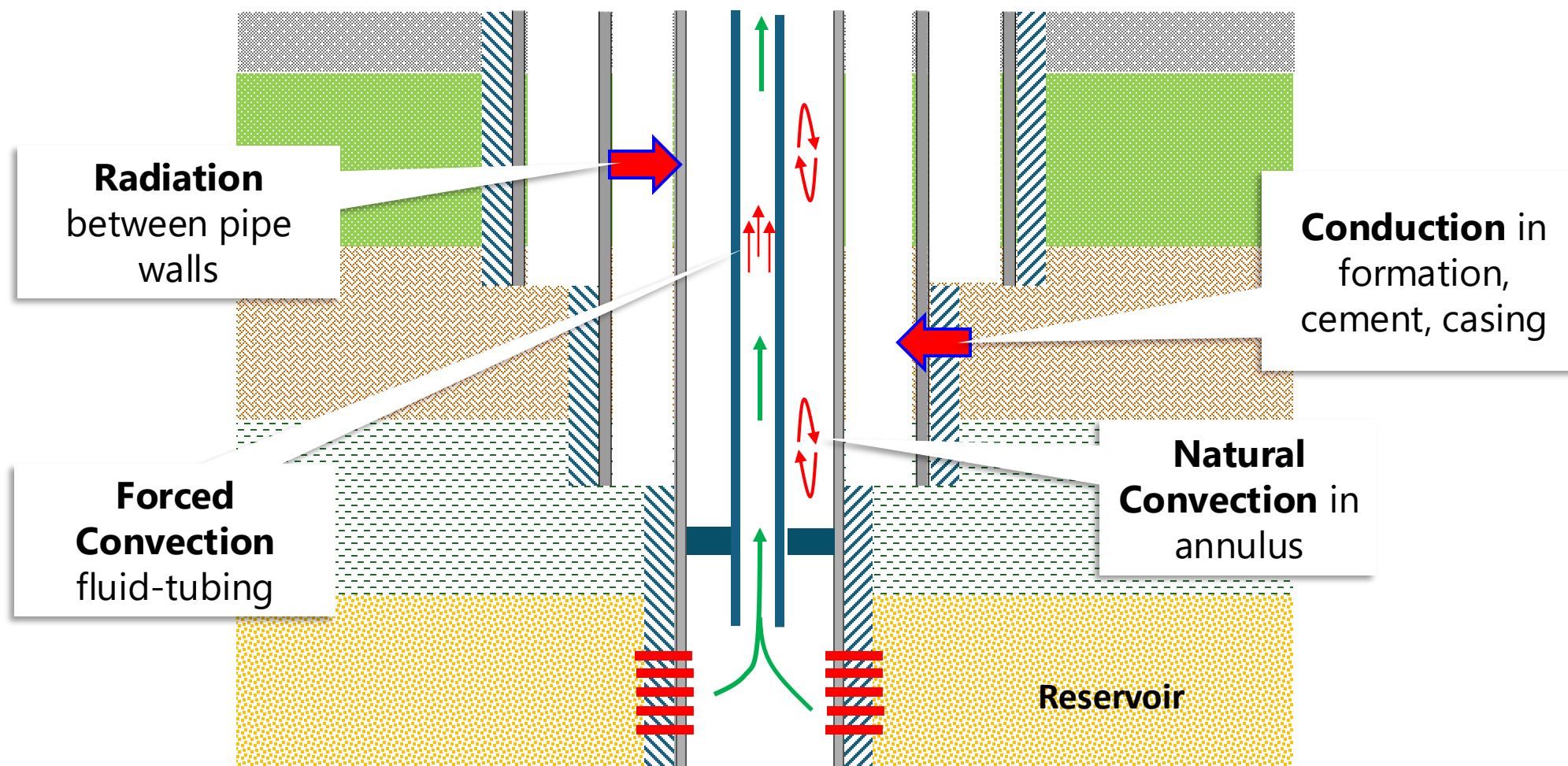
Temperature Modelling in the Well

Basic models

Heat Transfer Process	Model	Equation
Conduction	Fourier's Law of Heat Conduction.	$q_{cond}^* = -kA \frac{dT}{dx}$
Convection	Newton's Law of Heating and Cooling	$q_{conv}^* = h(T_s - T_\infty)$
Radiation	Wien's law	$\lambda_{max} = \frac{b}{T}$

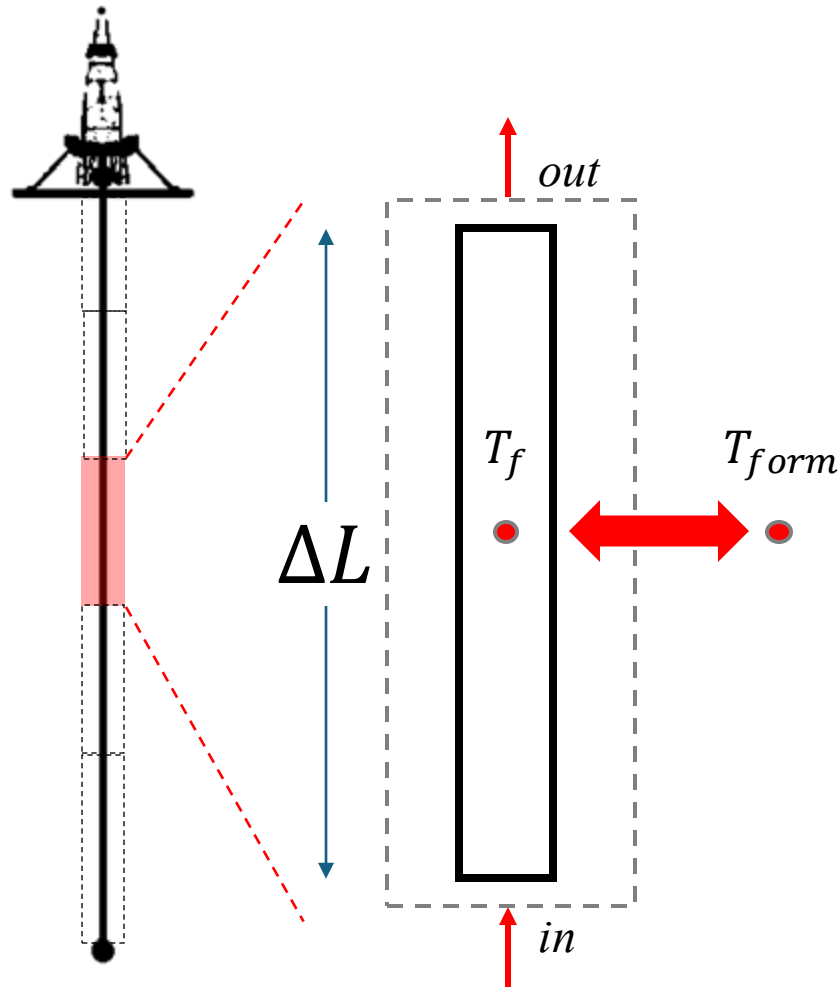
Temperature Modelling in the Well

Heat Transfer Mechanisms in a Geothermal Well



Temperature Modelling in the Well

Well Model



Conservation equation:

$$\dot{Q} + \dot{W} = \dot{m}(E_{out} - E_{in})$$

This energy (specific) is usually split in:

- Internal (u) - enthalpy
- Potential ($z \cdot g$)
- Kinetic ($V^2/2$)

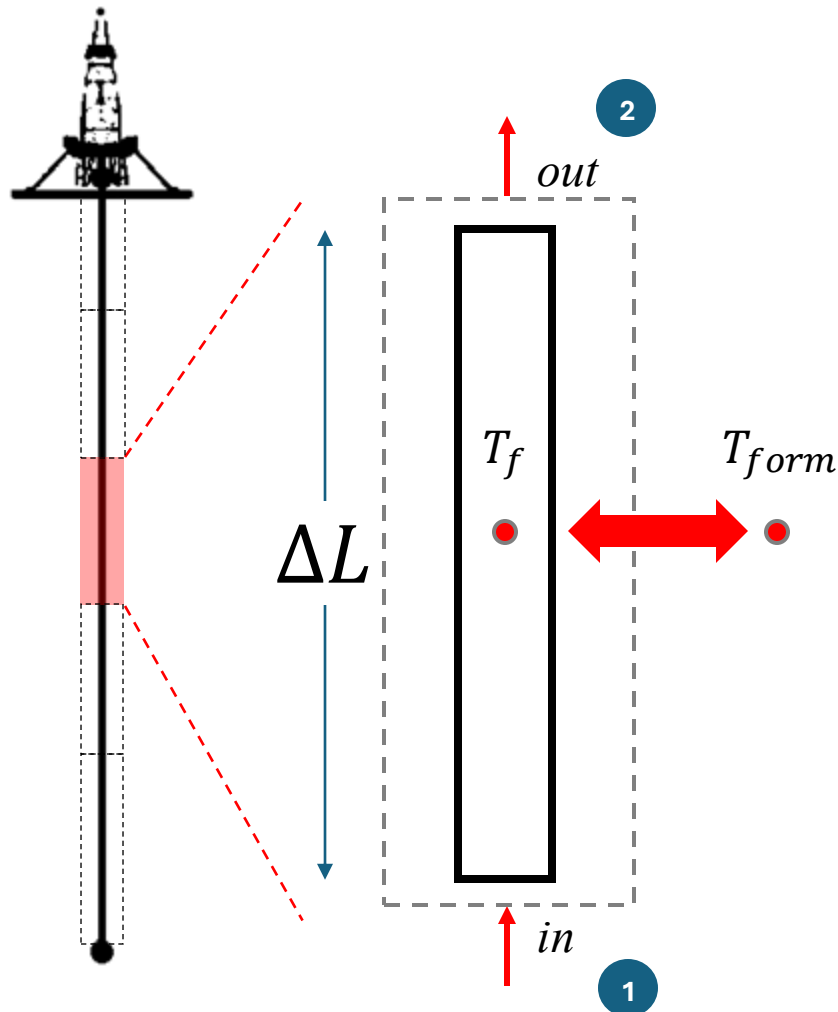
There is no work exchange with the surroundings.

$$\dot{Q} = \dot{m} \left(\left(h_{out} + z_{out} \cdot g + \frac{V_{out}^2}{2} \right) - \left(h_{in} + z_{in} \cdot g + \frac{V_{in}^2}{2} \right) \right)$$

$$\dot{Q} = \dot{m} \left(\Delta h + \Delta z \cdot g + \frac{V_{out}^2}{2} - \frac{V_{in}^2}{2} \right)$$

Temperature Modelling in the Well

Well Model



$$\dot{Q} = \dot{m} \left(\Delta h + \Delta z \cdot g + \frac{V_{out}^2}{2} - \frac{V_{in}^2}{2} \right)$$

$$\Delta L \rightarrow 0$$

$$\frac{d\dot{Q}}{dL} = \dot{m} \left(\frac{dh}{dL} + \frac{dz}{dL} \cdot g + V \frac{dV}{dL} \right)$$

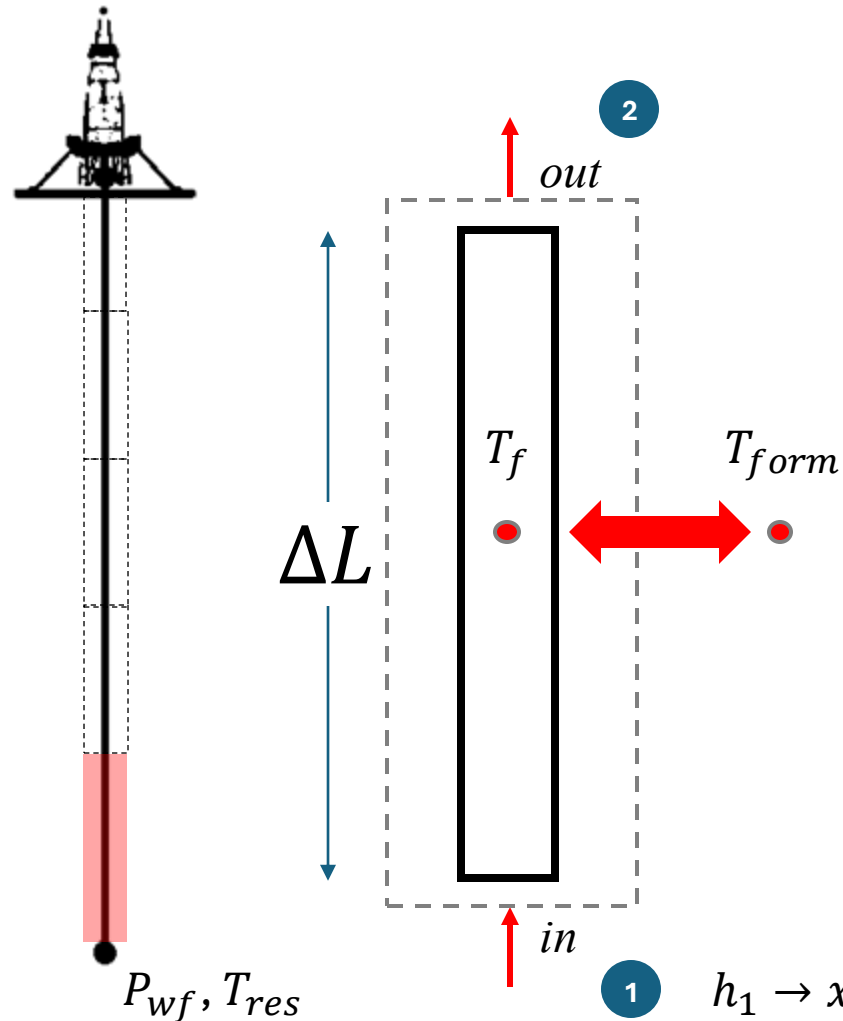
$$V \frac{dV}{dL} \rightarrow 0 \quad \text{Non-compressible liquid, the kinetic energy becomes zero}$$

$$\frac{d\dot{Q}}{dL} = \dot{m} \left(\frac{dh}{dL} + \frac{dz}{dL} \cdot g \right)$$

$$\dot{Q} = \dot{m}(h_2 - h_1 + \Delta z \cdot g)$$

Temperature Modelling in the Well

Well Model



$$\dot{Q} = \dot{m}(h_2 - h_1 + \Delta z \cdot g)$$

Knows/unknowns

$$\dot{Q} = \dot{m}(h_2 - h_1 + \Delta z \cdot g)$$

$$h_1 \rightarrow P_{wf}, T_{res}$$

$$\Delta z \rightarrow \Delta L$$

$$\dot{m} \rightarrow \text{reservoir model}$$

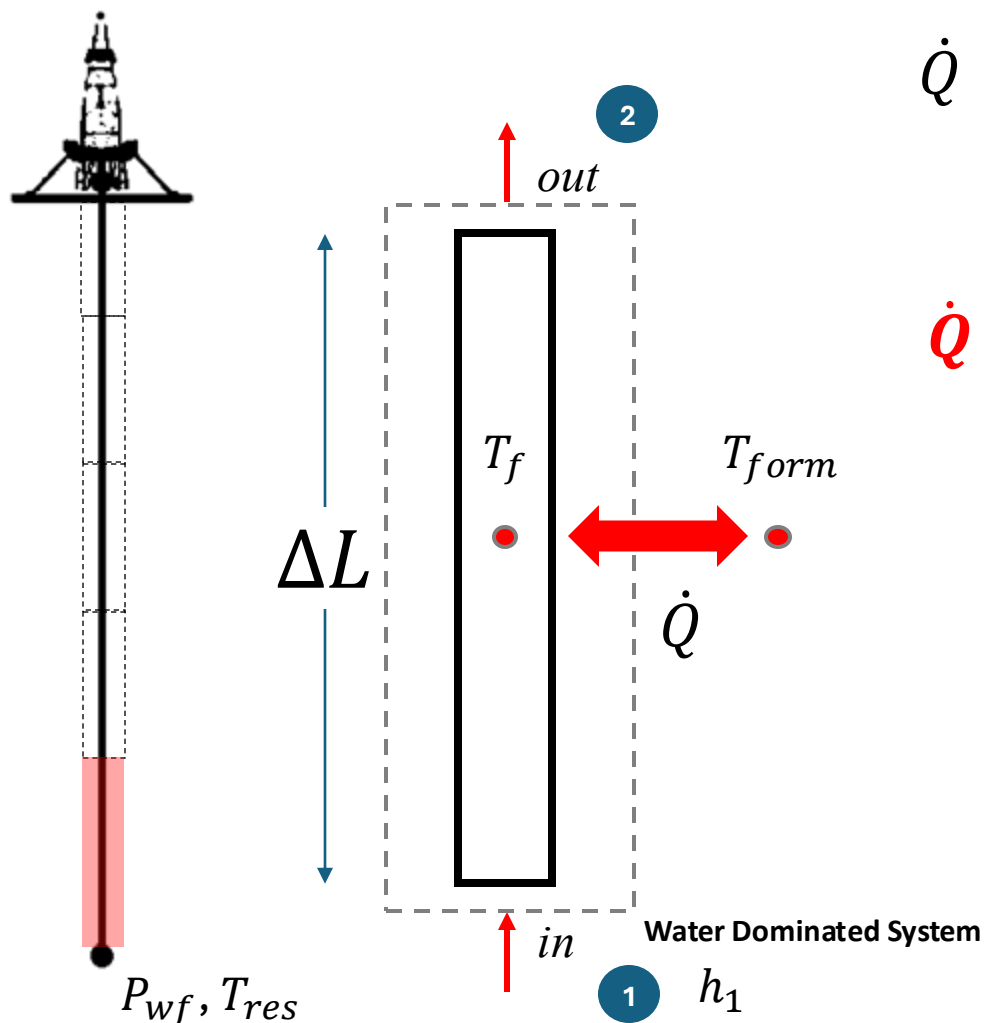
$$P(z) \rightarrow \text{know}$$

$$\left\{ \begin{array}{l} h_1 = x_g \cdot h_g + x_o \cdot h_o + x_w \cdot h_w \\ x_{phase} = \frac{\dot{m}_{phase}}{\dot{m}_{total}} \\ h_1 = x_g \cdot h_g + x_o \cdot h_o + x_w \cdot h_w \end{array} \right.$$

**Water
Dominated
System**

Temperature Modelling in the Well

Well Model



$$\dot{Q} = \dot{m}(h_2 - h_1 + \Delta z \cdot g) \rightarrow \dot{m}(\Delta h + \Delta z \cdot g)$$

Knows/unknowns

$$\dot{Q} = \dot{m}(h_2 - h_1 + \Delta z \cdot g)$$

$$h_1 \rightarrow P_{wf}, T_{res}$$

$$\Delta z \rightarrow \Delta L$$

$$\dot{m} \rightarrow \text{reservoir model}$$

$$P(z) \rightarrow \text{know}$$

$$\dot{Q} \rightarrow T_f, T_{form} \rightarrow T_f \approx T_1$$

$$(1): h_2 = \frac{\dot{Q}}{\dot{m}} + h_1 - \Delta z \cdot g$$

$$(2): \text{With } P_2 \text{ and assuming } T_2 \rightarrow h_2$$

$$\Delta h = C_p \Delta T$$

Liquids

$$C_p = f(P, T)$$

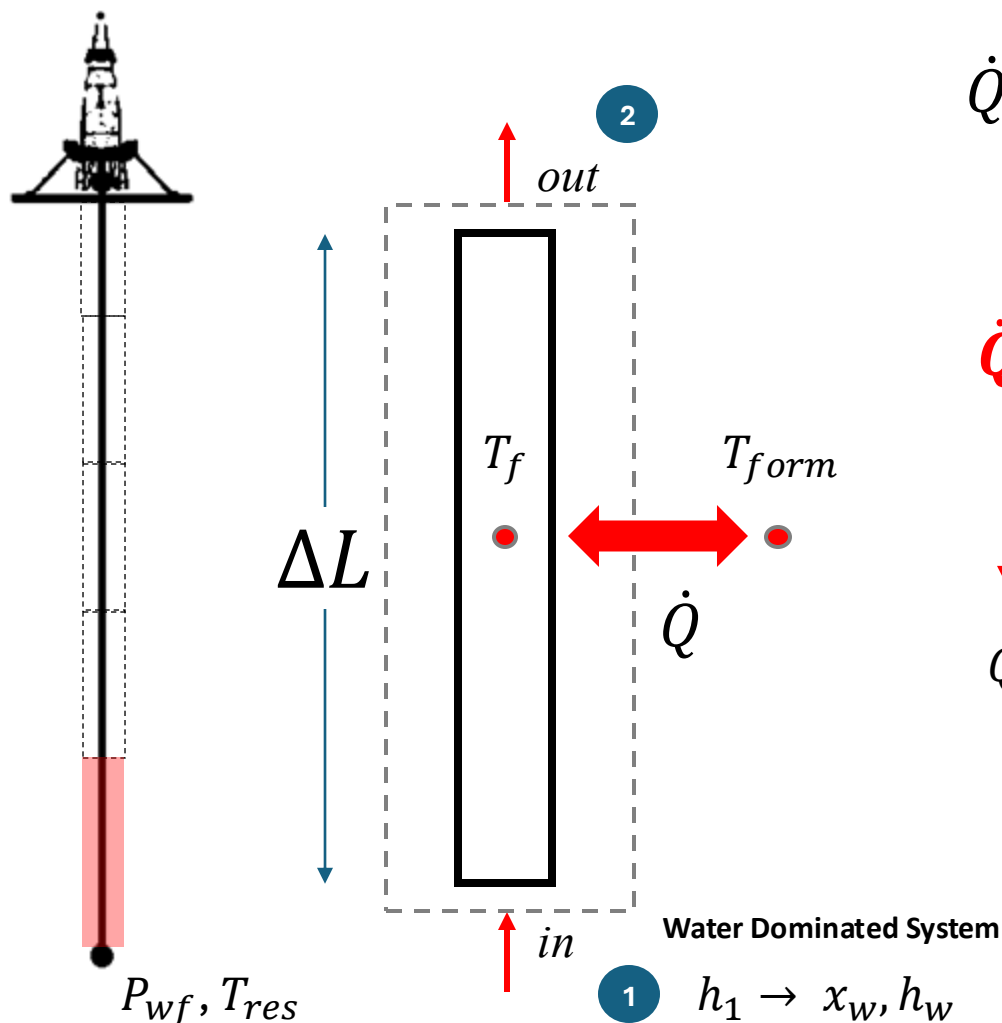
Gases

Iterative process:

$$h_2^{(1)} \approx h_2^{(2)}$$

Temperature Modelling in the Well

Well Model



$$\dot{Q} = \dot{m}(C_p \Delta T + \Delta z \cdot g) \quad \text{Liquid phase}$$

Knows/unknowns

$$\dot{Q} = \dot{m}(C_p \Delta T + \Delta z \cdot g)$$

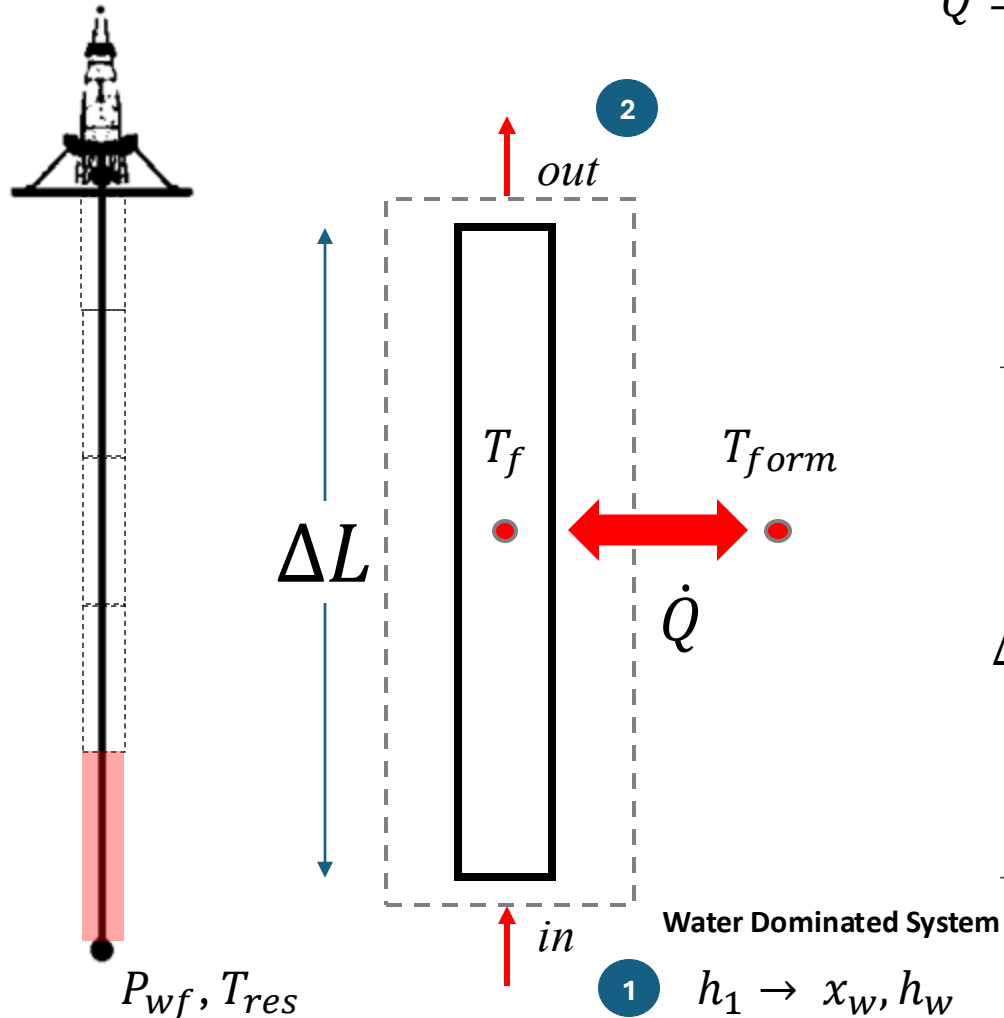
$$\Delta T = T_1 - T_2$$

$$\dot{Q} = UA(T_{surroundings} - T_{fluid,avg})$$

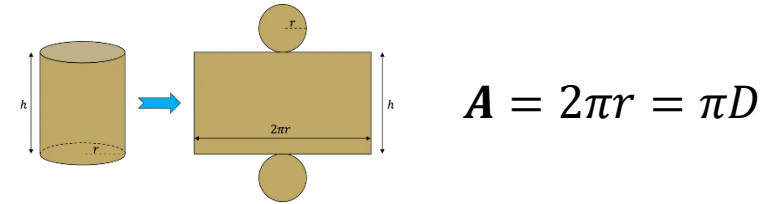
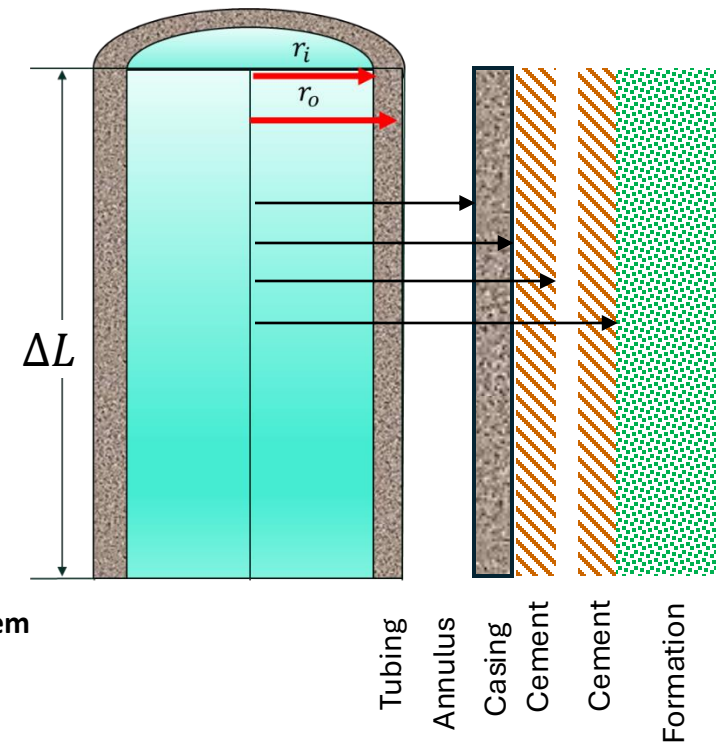
- Conduction
- Forced Convection
- Free Convection
- Radiation

Temperature Modelling in the Well

Well Model



$$\dot{Q} = UA(T_{surroundings} - T_{f,avg})$$



Overall heat transfer coefficient

$$U = f(r)$$

Conduction: k_{av}

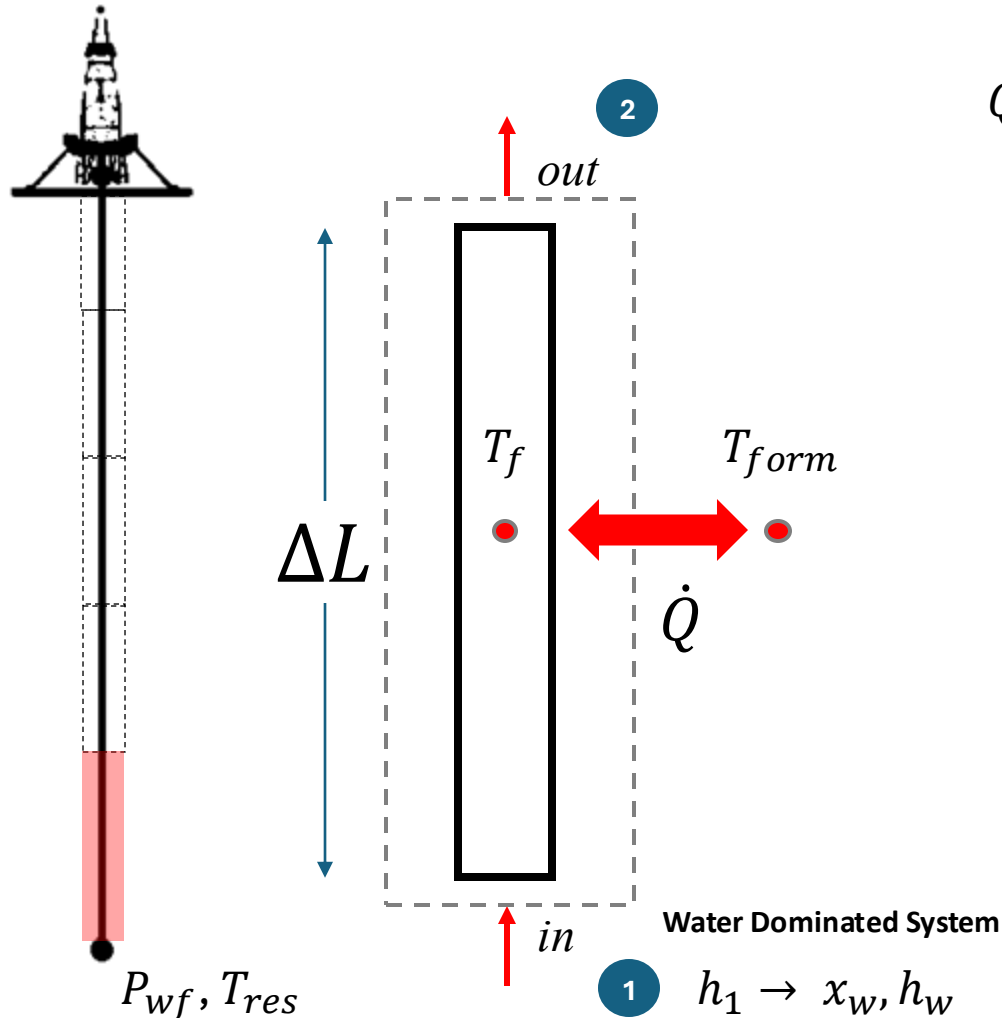
Forced: $f(Re, Pr)$

Natural: $f(Gr, Pr)$

Radiation: σ

Temperature Modelling in the Well

Well Model



$$\dot{Q} = UA(T_{surroundings} - T_{f,avg})$$

Conduction:

$$\frac{d\dot{Q}}{dL} = -2\pi k_{av} \frac{(T_i - T_o)}{\ln(r_o/r_i)}$$

Steady State

Convection/Radiation:

$$\frac{d\dot{Q}}{dL} = -2\pi r_i h_i (T_f - T_i)$$

Forced: $f(Re, Pr)$

Natural: $f(Gr, Pr)$

Radiation: σ

Temperature Modelling in the Well

Well Model

$$\dot{Q} = UA(T_{surroundings} - T_{f,avg})$$

Conduction:

$$\frac{d\dot{Q}}{dL} = -2\pi k_{av} \frac{(T_i - T_o)}{\ln(r_o/r_i)}$$

Convection/Radiation:

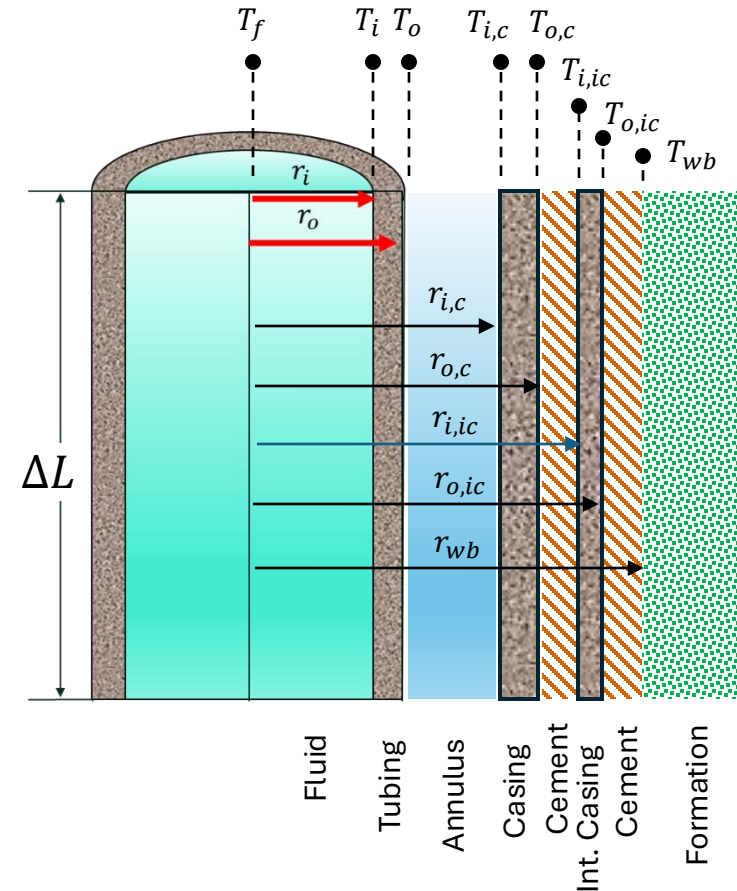
$$\frac{d\dot{Q}}{dL} = -2\pi r_i h_i (T_f - T_i)$$



Forced: $f(Re, Pr)$

Natural: $f(Gr, Pr)$

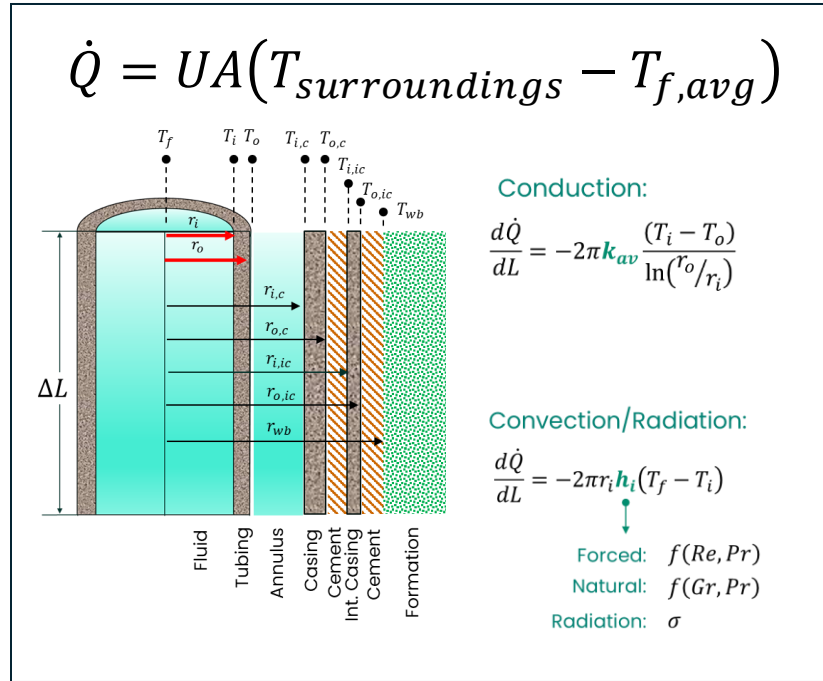
Radiation: σ



$$\frac{d\dot{Q}}{dL} = \left. \frac{d\dot{Q}}{dL} \right|^{conv,tub} + \left. \frac{d\dot{Q}}{dL} \right|^{cond,tub} + \left. \frac{d\dot{Q}}{dL} \right|^{conv,ann} + \left. \frac{d\dot{Q}}{dL} \right|^{cond,cas} + \left. \frac{d\dot{Q}}{dL} \right|^{cond,cem} + \left. \frac{d\dot{Q}}{dL} \right|^{cond,int.cas}$$

Temperature Modelling in the Well

Well Model



$$\frac{d\dot{Q}}{dL} = \frac{d\dot{Q}}{dL} \Big|^{conv,tub} + \frac{d\dot{Q}}{dL} \Big|^{cond,tub} + \frac{d\dot{Q}}{dL} \Big|^{conv,ann} + \frac{d\dot{Q}}{dL} \Big|^{cond,cas} + \frac{d\dot{Q}}{dL} \Big|^{cond,cem} + \frac{d\dot{Q}}{dL} \Big|^{cond,int.cas}$$



$$\begin{aligned} \frac{d\dot{Q}}{dL} &= \frac{d\dot{Q}}{dL} \Big|^{conv,tub} + \frac{d\dot{Q}}{dL} \Big|^{cond,tub} + \frac{d\dot{Q}}{dL} \Big|^{conv,ann} + \frac{d\dot{Q}}{dL} \Big|^{cond,cas} + \frac{d\dot{Q}}{dL} \Big|^{cond,cem} + \frac{d\dot{Q}}{dL} \Big|^{cond,int.cas} \\ &= -2\pi r_i h_i (T_f - T_i) - 2\pi k_{tub} \frac{(T_i - T_o)}{\ln(r_o/r_i)} - 2\pi r_o h_{ann} (T_o - T_{i,c}) - 2\pi k_{cas} \frac{(T_{i,c} - T_{o,c})}{\ln(r_{o,c}/r_{i,c})} - 2\pi k_{cem} \frac{(T_{o,c} - T_{i,ic})}{\ln(r_{i,ic}/r_{o,c})} \\ &\quad - 2\pi k_{int.cas} \frac{(T_{i,ic} - T_{o,ic})}{\ln(r_{o,ic}/r_{i,ic})} - 2\pi k_{cem} \frac{(T_{o,ic} - T_{wb})}{\ln(r_{wb}/r_{o,ic})} \end{aligned}$$



$$-\frac{d\dot{Q}}{dL} \left[\frac{1}{2\pi r_i h_i} + \frac{1}{\frac{\ln(r_o/r_i)}{2\pi k_{tub}}} + \frac{1}{2\pi r_o h_{ann}} + \frac{1}{\frac{\ln(r_{o,c}/r_{i,c})}{2\pi k_{cas}}} + \frac{1}{\frac{\ln(r_{i,ic}/r_{o,c})}{2\pi k_{cem}}} + \frac{1}{\frac{\ln(r_{o,ic}/r_{i,ic})}{2\pi k_{int.cas}}} + \frac{1}{\frac{\ln(r_{wb}/r_{o,ic})}{2\pi k_{cem}}} \right] = (T_f - T_{wb})$$

If the inner radius will be used as reference, we can divide by the inner perimeter of the inner tubing:

$$-\frac{d\dot{Q}}{dL} \frac{1}{2\pi r_i} \left[\frac{1}{h_i} + \frac{r_i \ln(r_o/r_i)}{k_{tub}} + \frac{r_i}{r_o h_{ann}} + \frac{r_i \ln(r_{o,c}/r_{i,c})}{k_{cas}} + \frac{r_i \ln(r_{i,ic}/r_{o,c})}{k_{cem}} + \frac{r_i \ln(r_{o,ic}/r_{i,ic})}{k_{int.cas}} + \frac{r_i \ln(r_{wb}/r_{o,ic})}{k_{cem}} \right] = (T_f - T_{wb})$$

Overall heat transfer coefficient
W/m² -K or BTU/ft² -h-°F

Temperature Modelling in the Well

Well Model

Overall heat transfer coefficient:

$$U = \left[\frac{1}{h_i} + \frac{r_i \ln(r_o/r_i)}{k_{tub}} + \frac{r_i}{r_o h_{ann}} + \frac{r_i \ln(r_{o,c}/r_{i,c})}{k_{cas}} + \frac{r_i \ln(r_{i,ic}/r_{o,c})}{k_{cem}} + \frac{r_i \ln(r_{o,ic}/r_{i,ic})}{k_{int.cas}} + \frac{r_i \ln(r_{wb}/r_{o,ic})}{k_{cem}} \right]^{-1}$$

Dry Rock Properties

	Cp	Conductivity	Specific Gravity
	BTU/lb/deg F	BTU/hr/ft/deg F	
Sandstone	0.183	1.06	2.64
Shale	0.224	0.7	2.4
Limestone	0.202	0.54	2.71
Dolomite	0.219	1.0	2.87
Halite	0.219	2.8	2.17
Anhydrite	0.265	0.75	2.96
Gypsum	0.259	0.75	2.32
Lignite	0.3	2.0	1.5
Volcanics	0.2	1.6	2.65

Thermal properties Database (modified from PROSPER manual)

Rock In Situ Fluids

	Cp	Conductivity
	BTU/lb/deg F	BTU/hr/ft/deg F
Water (Low salinity)	1.0	0.35
Water (High Salinity)	1.02	0.345
Heavy Oil	1.04	0.34
Medium Oil	0.49	0.083
Light Oil	0.5	0.0815
Gas	0.26	0.0215

Downhole Equipment

	Conduction Heat Transfer Coefficient	Emmissivity
	BTU/ft/hr/deg F	
Mild Steel Tubing	26	0.65
Plactic Coated Tubing	20	0.65
Stainless Steel (13%)	18	0.4
Stainless Steel (15%)	15	0.3
Line Pipe	27	0.9
Plactic Coated Pipe	20	0.9
Flexible	0.3	0.95
Bitumen	0.6	0.95
Foam	0.02	0.8
Concrete	0.1	0.9

Temperature Modelling in the Well

Well Model

$$\dot{Q} = UA(T_{surroundings} - T_{f,avg})$$

$$\dot{Q} = \dot{m}(C_p \Delta T + \Delta z \cdot g)$$

$$\frac{dT}{dx} = \frac{U\pi D}{\dot{m}C_p} (T_{surroundings} - T_{f,avg})$$

Ramey's equation:

$$T_f = Az + B - \frac{A}{L_R} + \left(T_o + \frac{A}{L_R} - B \right) e^{zL_R}$$

T_f : Injection Bottomhole temperature

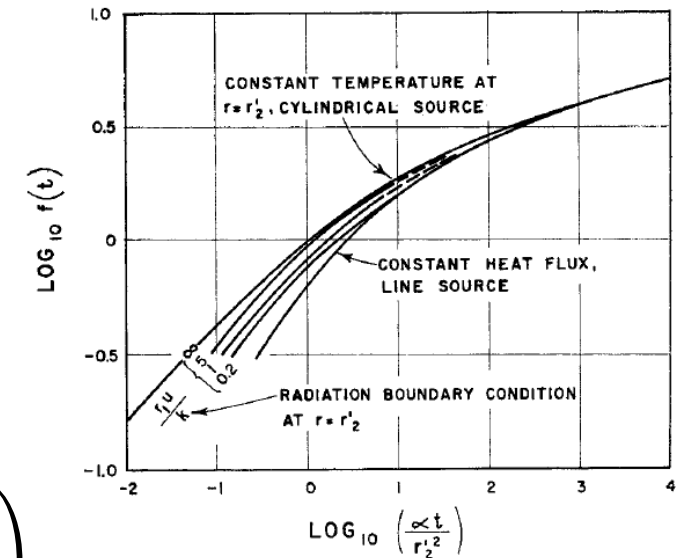
$Az + B$: Linear geothermal gradient

z : true vertical depth

T_o : Injection temperature at surface

L_R : Relaxation coefficient

$$L_R = \frac{2\pi}{C_p \dot{m}} \left(\frac{r_i U k}{k + r_i U T_D} \right)$$



Wellbore Heat Transmission, H.J. Ramey Jr. 1962

Temperature Modelling in the Well

Integrated System

Surface Model

(ORC power block)

Bulk System

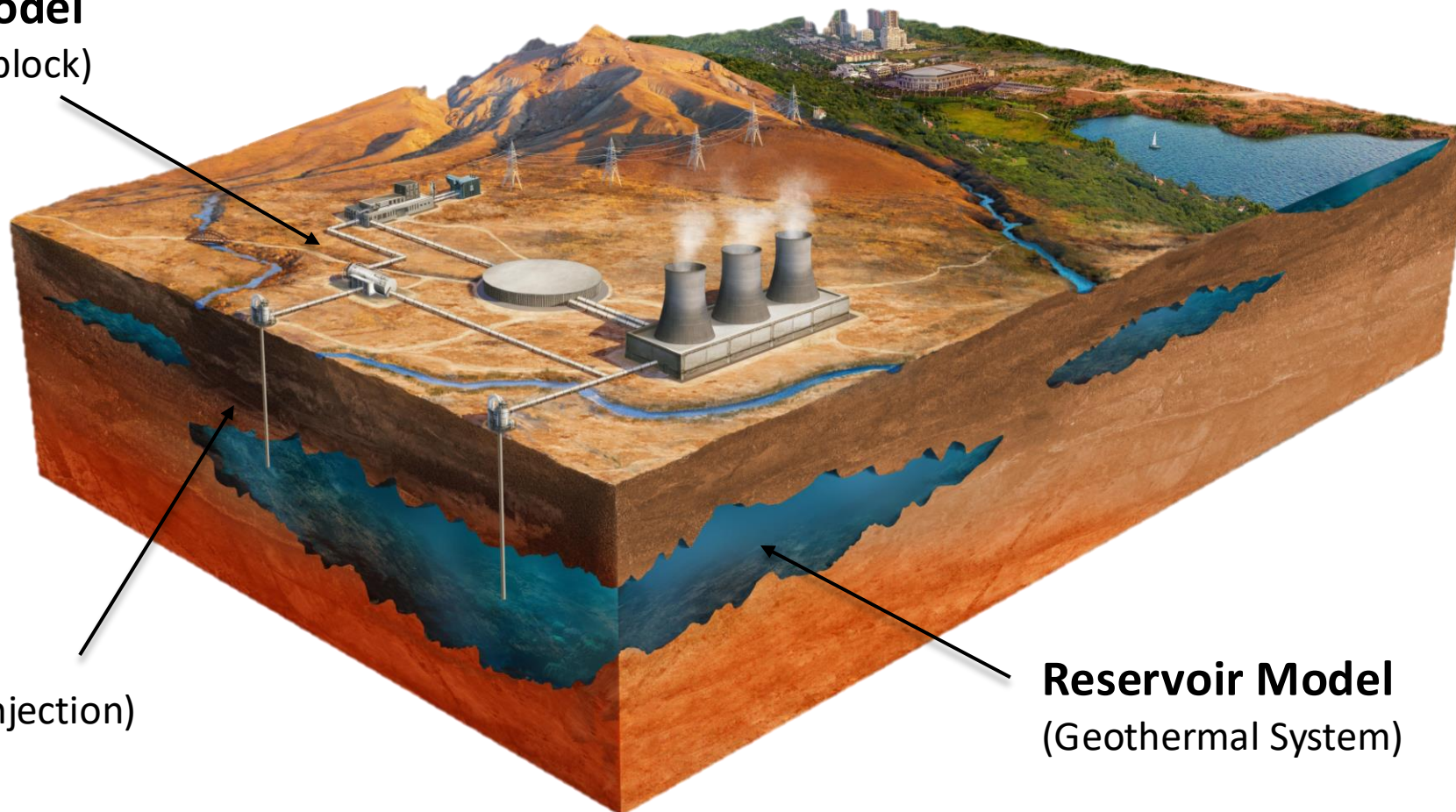
(Grid Connection, Electricity, Heating)

Well Model

(Production/Injection)

Reservoir Model

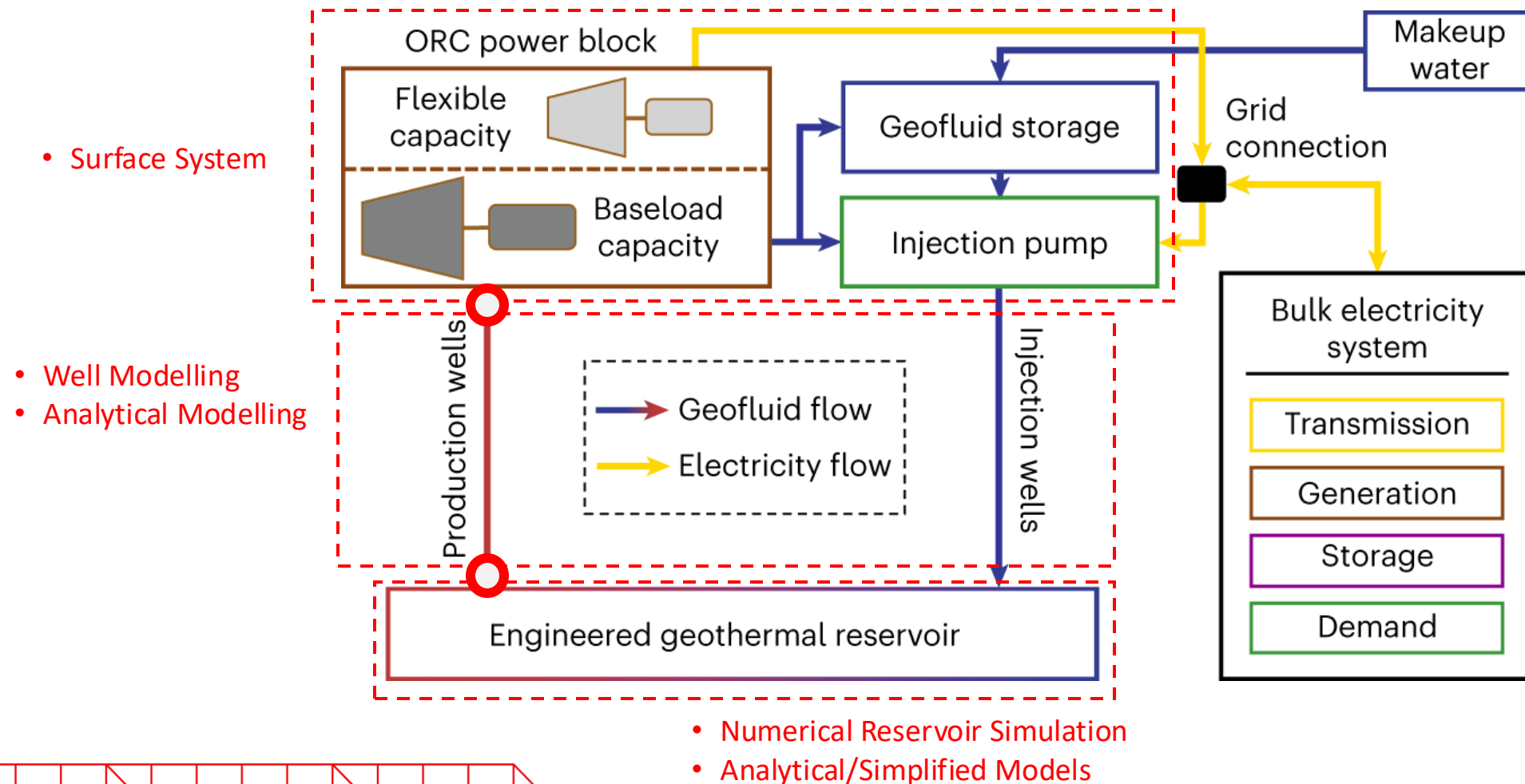
(Geothermal System)



Temperature Modelling in the Well

Integrated System

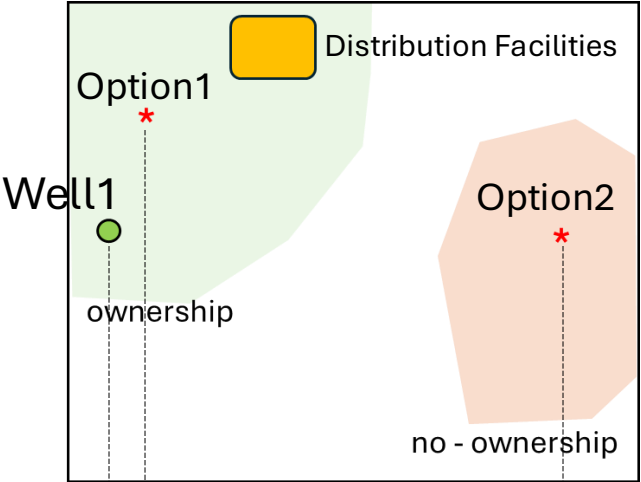
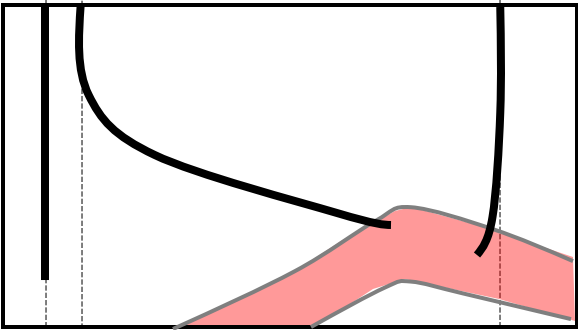
The role of flexible geothermal power in decarbonized electricity systems – Nature Energy – Jan. 2024



Example Cases

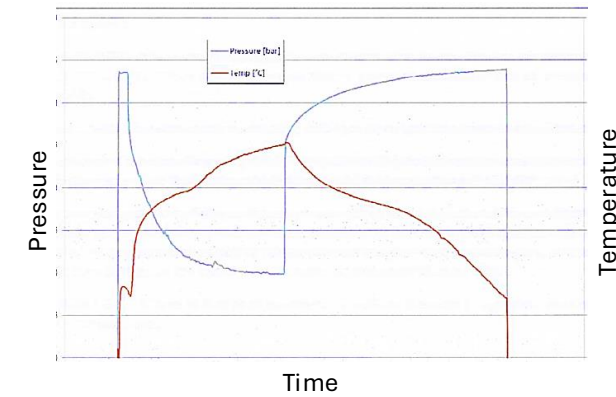
Case 1

Trajectory Comparisons

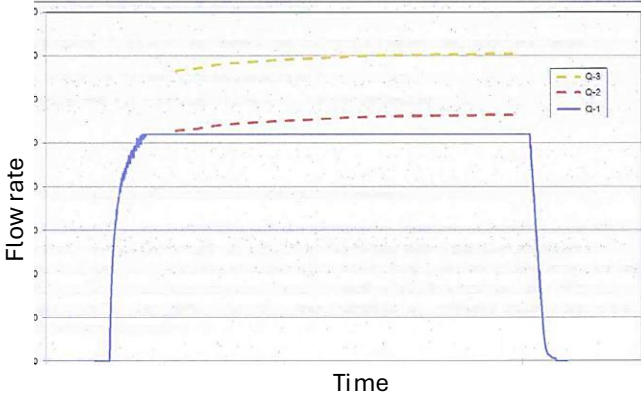


Well1

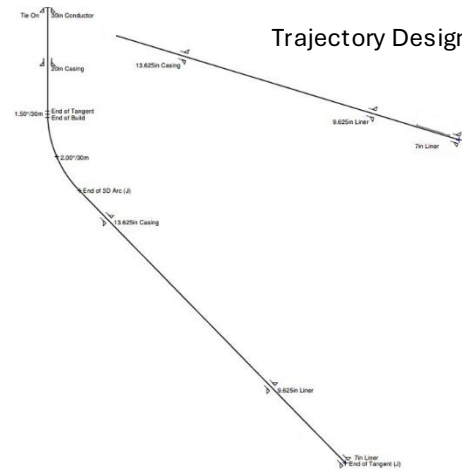
Record of Pressure and Temperature



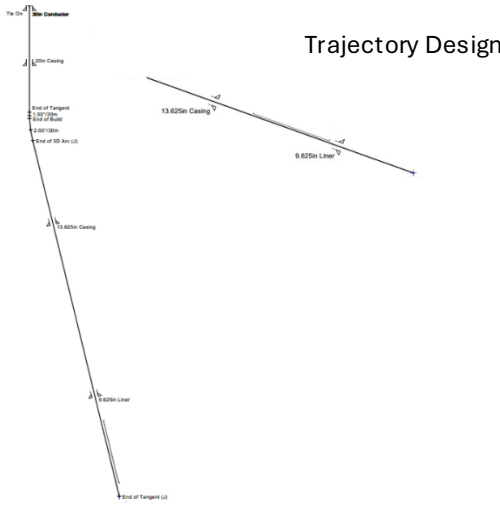
Record of Flow Rate Data



Option 1

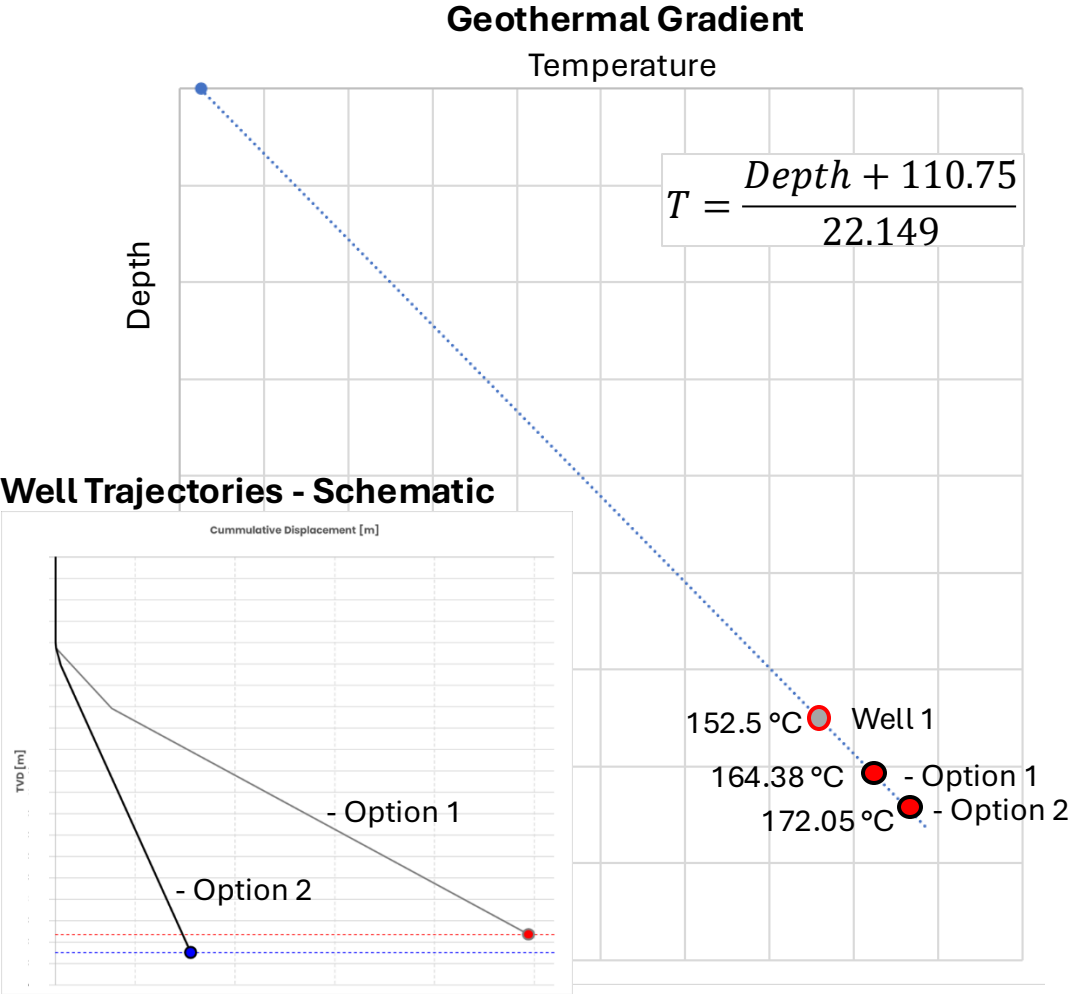


Option 2



Case 1

Trajectory Comparisons



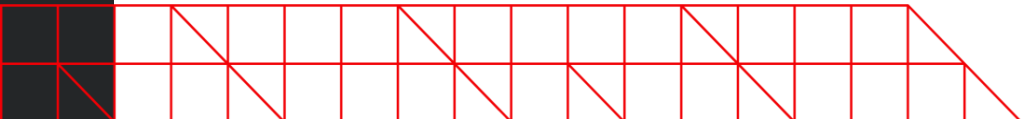
INPUT	Values	Reference
Well Head Pressure	2 bars	BH
Overall Heat Transfer Coefficient	[2 - 10] BTU/hr-ft2-F	2 BTU/hr-ft2-F – excellent internal/external insulated conditions with low conductivity of cement.
		8 BTU/hr-ft2-F - average internal/external insulated conditions high conductivity of cement.
		10 BTU/hr-ft2-F - internal/external uninsulated conditions with poor conductivity of cement
Flow Rate	[50 - 70] L/s	Reference values from records in Well 1

Summary of Results

Q	U	Option 1			Option 2		
		Tres	TWH	% thermal	Tres	TWH	% thermal
L/s	STB/D	degC	degC	loss	degC	degC	loss
50	26396.3	8	164.4	130.9	172.05	138.63	19
60	31675.6	8	164.4	135.01	172.05	143.52	17
70	36954.8	8	164.4	138.7	172.05	147.17	14
50	26396.3	2	164.4	154.66	172.05	162.71	5
60	31675.6	2	164.4	156.22	172.05	164.22	5
70	36954.8	2	164.4	157.6	172.05	165.31	4
50	26396.3	10	164.4	123.2	172.05	131.74	23
60	31675.6	10	164.4	128.9	172.05	137.45	20
70	36954.8	10	164.4	133.22	172.05	141.75	18

Case 2

Selection of the reservoir with the greatest potential

[illegible]

Case 2

Selection of the reservoir with the greatest potential

Analysis:



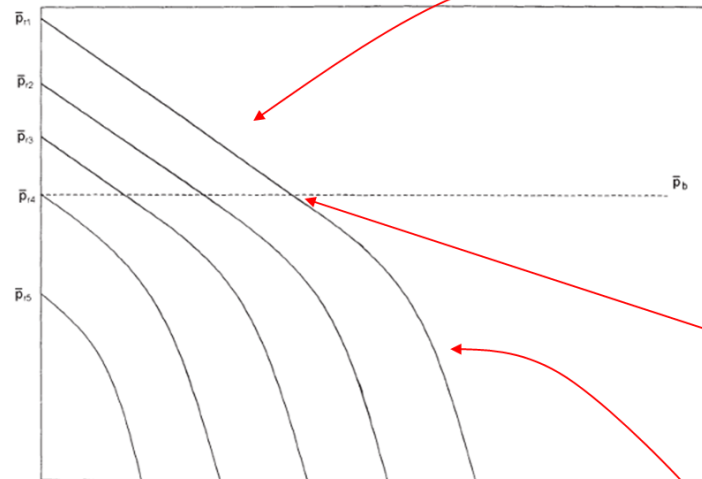
Darcy's Law:

$$q = -\frac{k}{\mu L} \Delta p$$

- Porosity
- Permeability
- Fluid properties
- Rock Properties

P_{wf}, T_{res}

Effect of Reservoir Pressure



Darcy based on IPR: $P_{wf} (P_{wf} > P_b)$

$$Q = J(P_R - P_{wf}) = J\Delta p$$

$$J = \frac{2\pi k_o h}{\mu_o B_o \ln\left(\frac{r_e}{r_w}\right)}$$

h – thickness (m);

r_e – drainage radius (m);

r_w – wellbore radius (m).

Stabilized test data point (Q and P_{wf}):

$$Q_{max} = \frac{Q}{1 - 0,2\left(\frac{P_{wf}}{P_R}\right) - 0,8\left(\frac{P_{wf}}{P_R}\right)^2}$$

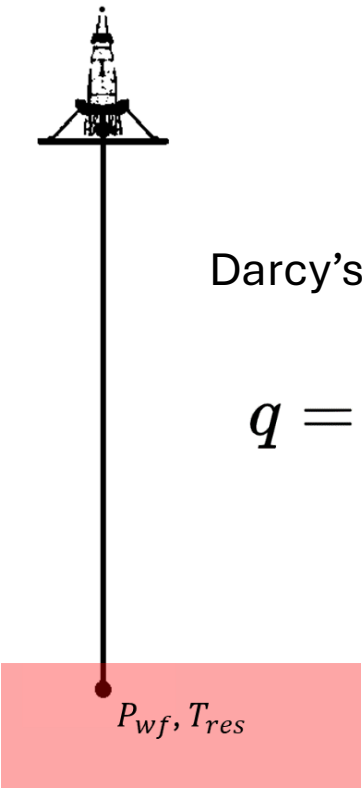
Vogel's equation: $P_{wf} (P_{wf} < P_b)$

$$Q = Q_{max} \left[1 - 0,2\left(\frac{P_{wf}}{P_R}\right) - 0,8\left(\frac{P_{wf}}{P_R}\right)^2 \right]$$

Case 2

Selection of the reservoir with the greatest potential

Analysis:

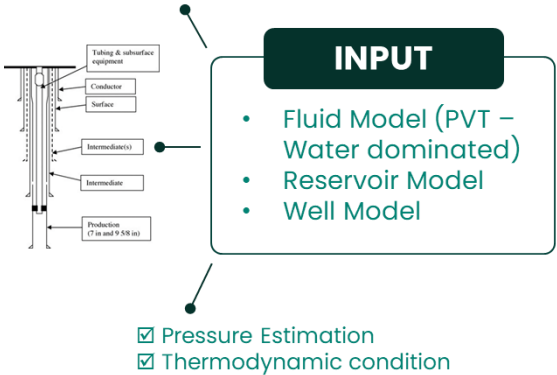


Darcy's Law:

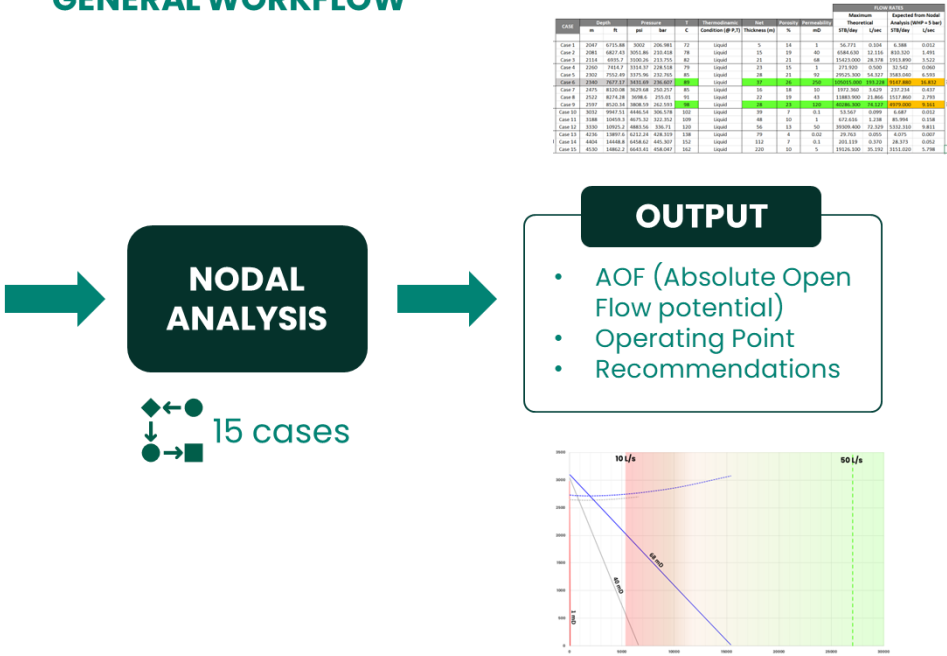
$$q = -\frac{k}{\mu L} \Delta p$$

- Porosity
- Permeability
- Fluid properties
- Rock Properties

	Min	Base	Max	Min	Base	Max	Min	Base	Max	Min	Base	Max	Min	Base	Max
Well Depth, m	2247	2081	214	2250	2082	2147	2475	2082	2147	3532	2188	2330	4230	4404	4530
Temperature, °C	22	78	82	79	88	89	85	88	90	102	109	120	138	182	192
Net thickness, m	5	18	21	22	28	37	10	22	28	30	48	58	79	102	200
Porosity	14	19	21	15	21	26	18	19	23	7	10	13	4	7	10
Permeability, mD	<1	40	68	1	82	200	10	43	120	<0.1	1	50	0.02	0.3	5



GENERAL WORKFLOW



Case 2

Selection of the reservoir with the greatest potential

Analysis:



Darcy's Law:

$$q = -\frac{k}{\mu L} \Delta p$$

P_{wf}, T_{res}

- Porosity
- Permeability
- Fluid properties
- Rock Properties

Res. 1

Res. 2

Res. 3

Res. 4

Res. 5

CASE	Depth		Pressure		T °C	Thermodynamic Condition (@ P,T)	Net Thickness (m)	Porosity %	Permeability mD
	m	ft	psi	bar					
Case 1	2047	6715.879	3001.998	206.9806	72	Liquid	5	14	1
Case 2	2081	6827.428	3051.86	210.4184	78	Liquid	15	19	40
Case 3	2114	6935.696	3100.256	213.7552	82	Liquid	21	21	68
Case 4	2260	7414.698	3314.37	228.5179	79	Liquid	23	15	1
Case 5	2302	7552.494	3375.965	232.7647	85	Liquid	28	21	92
Case 6	2340	7677.166	3431.693	236.607	89	Liquid	37	26	250
Case 7	2475	8120.079	3629.675	250.2574	85	Liquid	16	18	10
Case 8	2522	8274.278	3698.602	255.0098	91	Liquid	22	19	43
Case 9	2597	8520.341	3808.593	262.5933	98	Liquid	28	23	120
Case 10	3032	9947.507	4446.536	306.578	102	Liquid	39	7	0.1
Case 11	3188	10459.32	4675.315	322.3518	109	Liquid	48	10	1
Case 12	3330	10925.2	4883.563	336.71	120	Liquid	56	13	50
Case 13	4236	13897.64	6212.244	428.3193	138	Liquid	79	4	0.02
Case 14	4404	14448.82	6458.622	445.3065	152	Liquid	112	7	0.1
Case 15	4530	14862.21	6643.406	458.0469	162	Liquid	220	10	5

* Pressure Gradient: 0.443 psi/ft for Fresh Water, 0.465 psi/ft with 100000 ppm

Case 2

Selection of the reservoir with the greatest potential

Analysis:



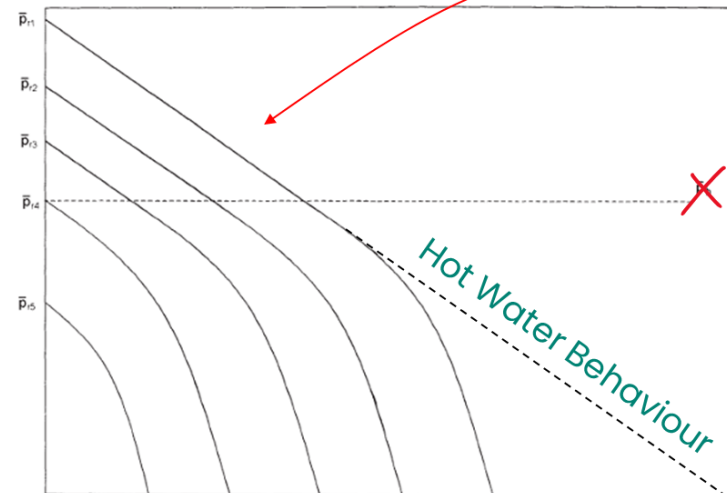
Darcy's Law:

$$q = -\frac{k}{\mu L} \Delta p$$

P_{wf}, T_{res}

- Porosity
- Permeability
- Fluid properties
- Rock Properties

Effect of Reservoir Pressure



Darcy based on IPR: $P_{wf} (P_{wf} > P_b)$

$$Q = J(P_R - P_{wf}) = J\Delta p$$

$$J = \frac{2\pi k_o h}{\mu_o \cdot B_o \cdot \ln\left(\frac{r_e}{r_w}\right)}$$

h – thickness (m);

r_e – drainage radius (m);

r_w – wellbore radius (m).

Reservoir Model:

- Permeability, Thickness, Porosity: as the case
- Drainage Area: 250 acres (exploratory wells)*
- Wellbore radius: 4.25 inches

Well Model:

- Tubing: 4 1/2 inches
- Casing: 7 inches
- Well Head Pressure: 5 bar
- Depth: as the case

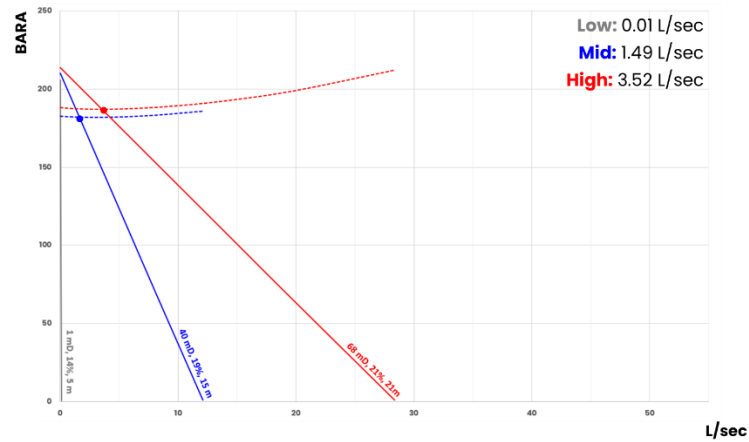
Fluid Model:

- PVT: Water dominated, same for all cases

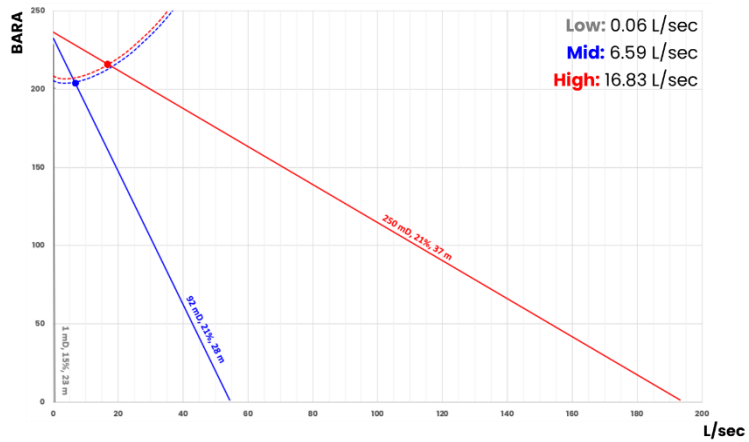
Case 2

Selection of the reservoir with the greatest potential

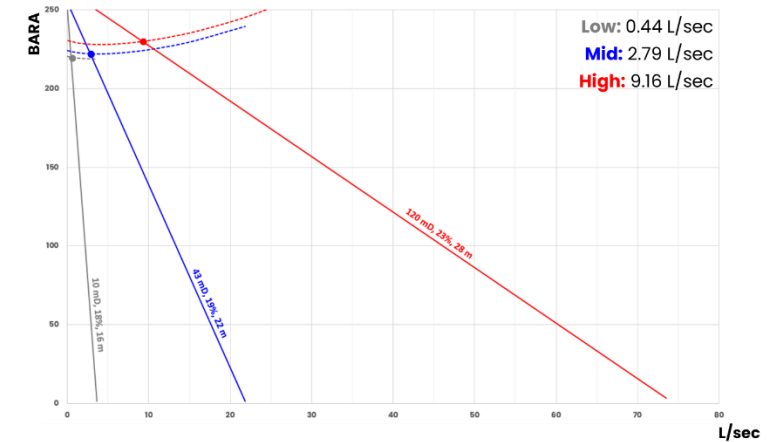
Reservoir 1



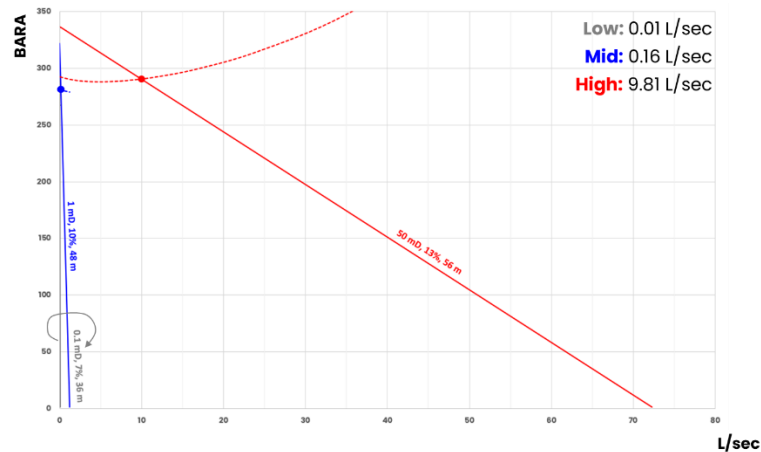
Reservoir 2



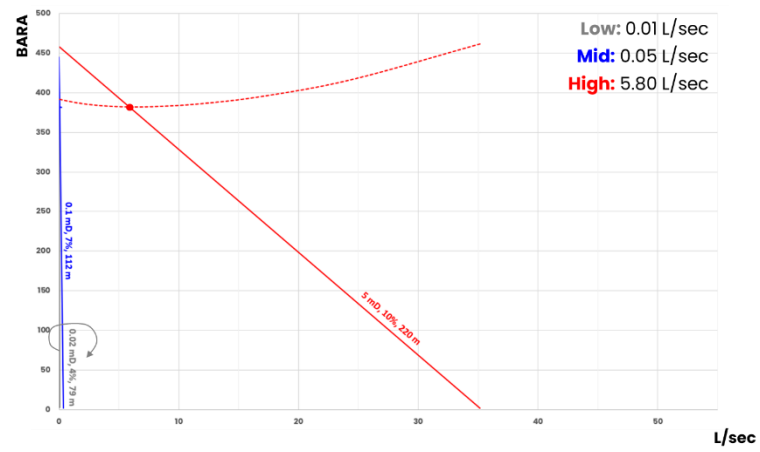
Reservoir 3



Reservoir 4



Reservoir 5



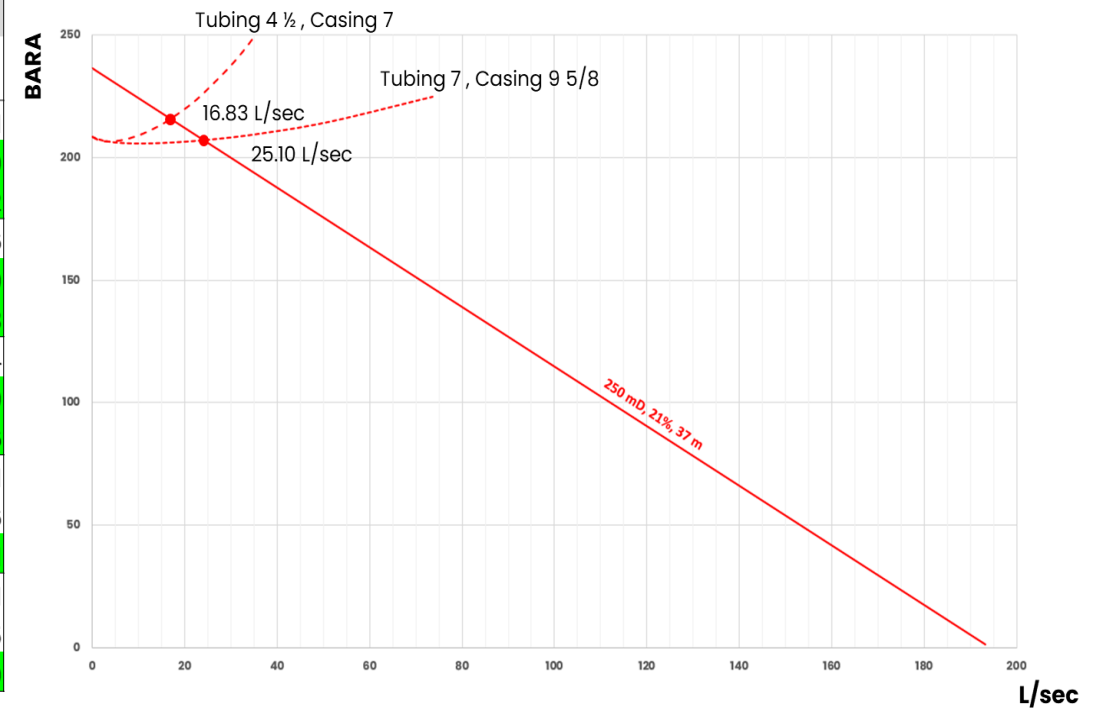
Case 2

Selection of the reservoir with the greatest potential

Flow Rates Estimation

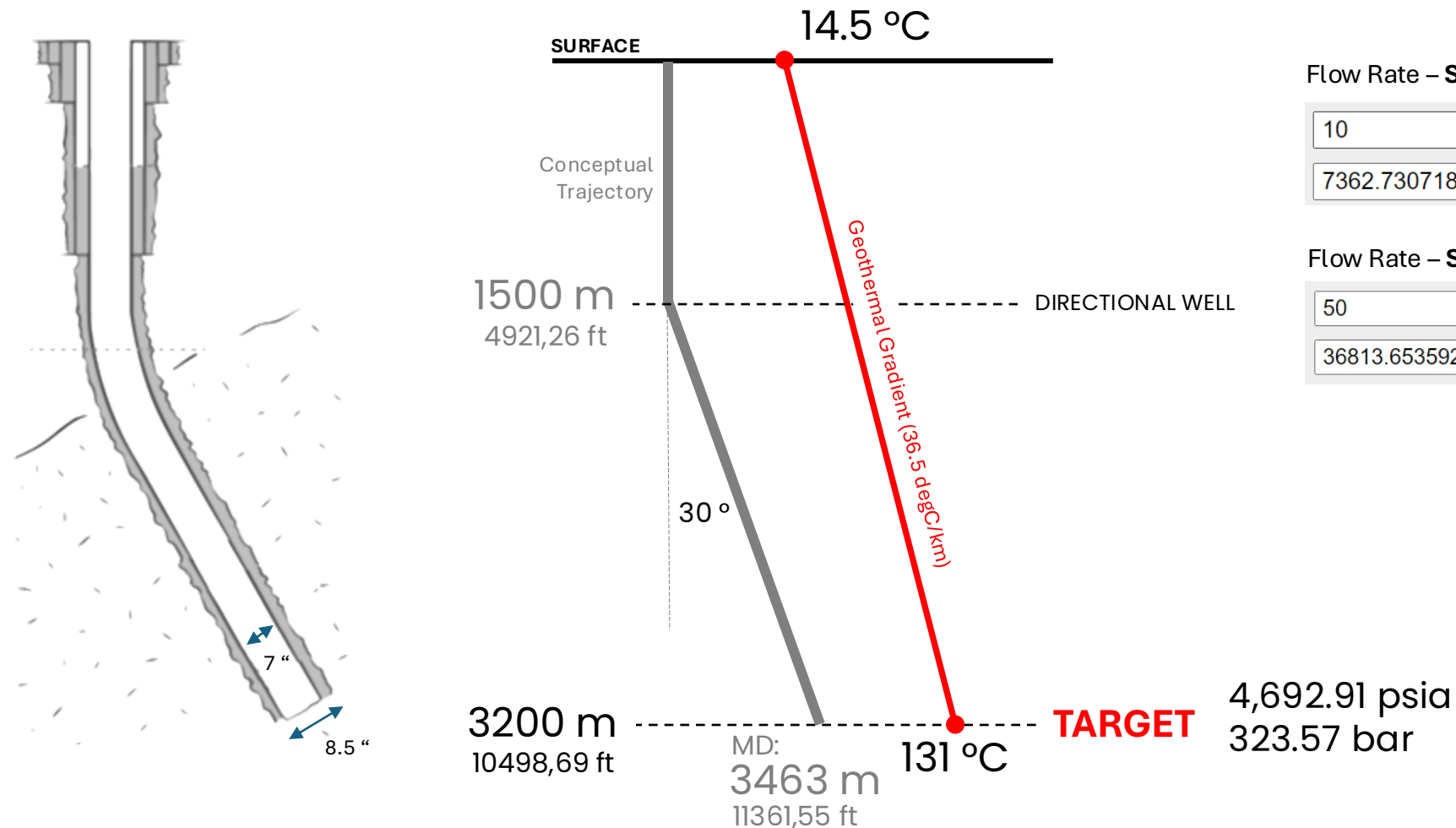
							FLOW RATES		
	CASE	Depth m	Pressure bar	T °C	Net Thickness (m)	Porosity %	Permeability mD	AOF	Operating
								Potential L/sec	Point L/sec
Res. 1	Case 1	2047	206.98	72	5	14	1	0.10	0.01
	Case 2	2081	210.42	78	15	19	40	12.12	1.49
	Case 3	2114	213.76	82	21	21	68	28.38	3.52
Res. 2	Case 4	2260	228.52	79	23	15	1	0.50	0.06
	Case 5	2302	232.76	85	28	21	92	54.33	6.59
	Case 6	2340	236.61	89	37	26	250	193.23	16.83
Res. 3	Case 7	2475	250.26	85	16	18	10	3.63	0.44
	Case 8	2522	255.01	91	22	19	43	21.87	2.79
	Case 9	2597	262.59	98	28	23	120	74.13	9.16
Res. 4	Case 10	3032	306.58	102	39	7	0.1	0.10	0.01
	Case 11	3188	322.35	109	48	10	1	1.24	0.16
	Case 12	3330	336.71	120	56	13	50	72.33	9.81
Res. 5	Case 13	4236	428.32	138	79	4	0.02	0.05	0.01
	Case 14	4404	445.31	152	112	7	0.1	0.37	0.05
	Case 15	4530	458.05	162	220	10	5	35.19	5.80

Flow Rates Estimation Considering different Casing and Tubing Size



Case 3

Thermal Losses and Power Output



Flow Rate – Scenario 1

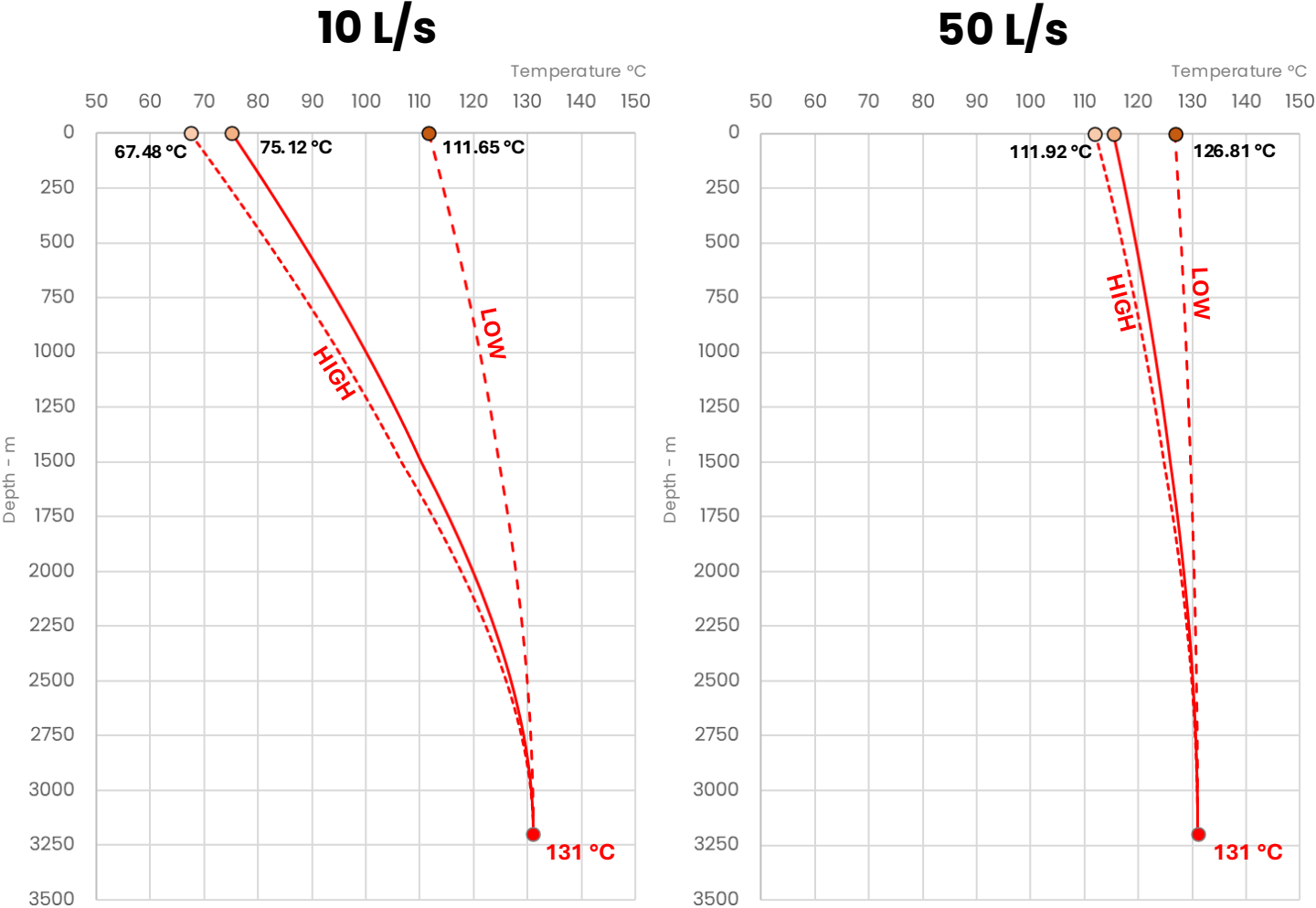
<input type="text" value="10"/>	L/s
<input type="text" value="7362.7307184743995"/>	barrel per day

Flow Rate – Scenario 2

<input type="text" value="50"/>	L/s
<input type="text" value="36813.653592372"/>	barrel per day

Case 3

Thermal Losses and Power Output



Well Head Temperature (WHT) - °C

	Scenario 1: 10 L/s	Scenario 2: 50 L/s
LOW	67.48	111.92
AVRG.	75.12	115.37
HIGH	111.65	126.81

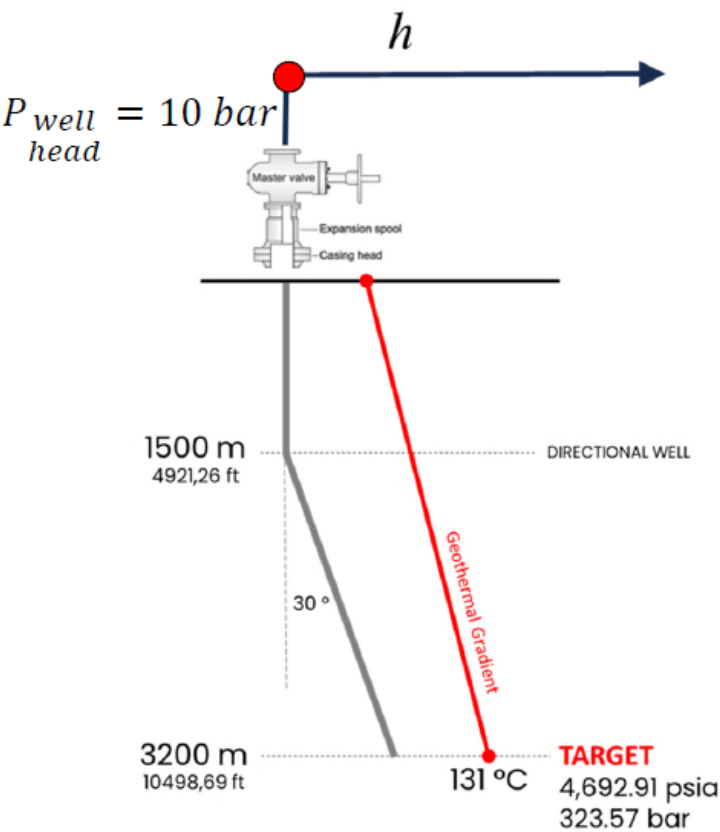
HIGH: 2 BTU/hr-ft2-F – excellent internal/external insulated conditions with low conductivity of cement.

AVERAGE: 8 BTU/hr-ft2-F - average internal/external insulated conditions high conductivity of cement.

LOW: 10 BTU/hr-ft2-F - internal/external uninsulated conditions with poor conductivity of cement

Case 3

Thermal Losses and Power Output



$$E_{rate} = \rho_F * Q * h$$

E_{rate} - Energy Rate (thermal)
@ Well Head
 ρ_F - Fluid Density
 Q - Flow Rate
 h - Enthalpy @ Well Head

	Scenario 1: 10 L/s			Scenario 2: 50 L/s		
	T °C	h (BTU/lb)	MWt	T °C	h (BTU/lb)	MWt
LOW	67.48	121.81	2.82	111.92	202.14	23.43
AVRG.	75.12	135.55	3.14	115.37	208.41	24.16
HIGH	111.65	201.64	4.68	126.81	229.26	26.58

MWt – MW thermal

Case 3

Thermal Losses and Power Output

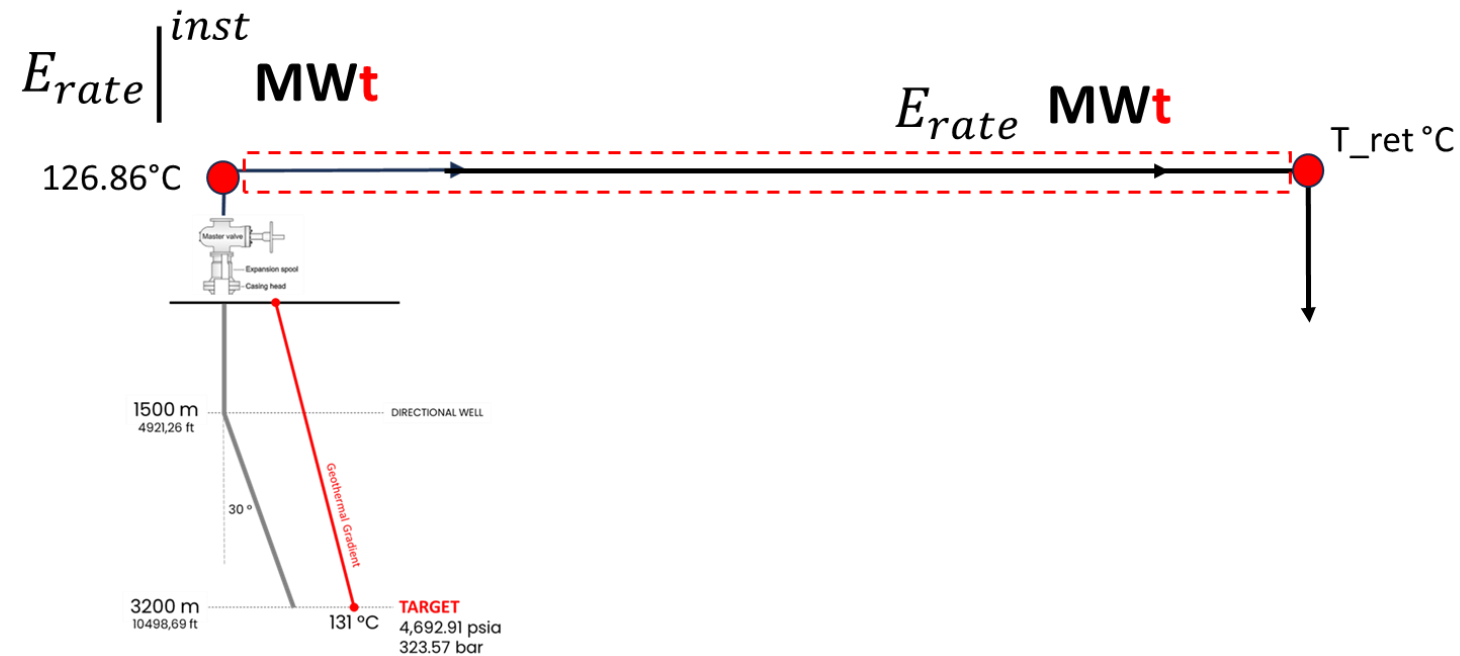
$$\begin{aligned} E_{rate} &= \rho_F * c_F * Q * (T_i - T_o) \text{ MWt} \\ \text{Thermal} & \\ \text{Rate} & \\ &= \rho_F * Q * (hi - ho) \text{ MWt} \end{aligned}$$



Case 3

Thermal Losses and Power Output

$$\begin{aligned} E_{rate}^{Thermal} &= \rho_F * c_F * Q * (T_i - T_o) \text{ MWt} \\ &= \rho_F * Q * (hi - ho) \text{ MWt} \end{aligned}$$

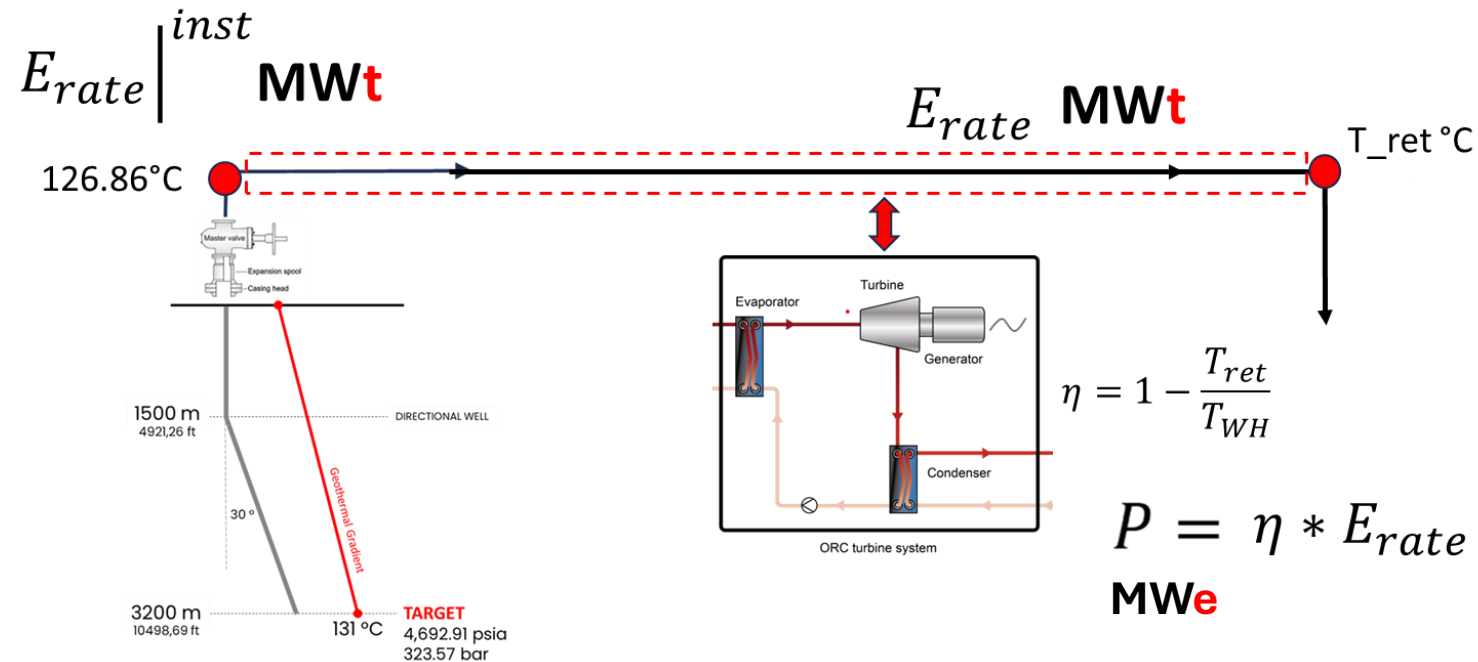


Case 3

Thermal Losses and Power Output

$$E_{rate}^{Thermal} = \rho_F * c_F * Q * (T_i - T_o) \text{ MWt}$$

$$= \rho_F * Q * (h_i - h_o) \text{ MWt}$$



Well Simplified Model

- Steady state
- Water Dominated system ($h_1 = x_w \cdot h_w$), single phase (liquid)
- Incompressible fluid
- U assumed/calculated
- No phase changes along the tubing
- Reservoir – Darcy Model

Q&A

FEEDBACK

GEODE Series - Webinar: Well Modelling Applied to Geothermal Resource Evaluation

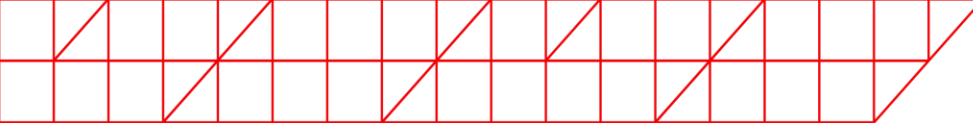


U.S. DEPARTMENT OF ENERGY



Geothermal Energy from Oil + Gas
Demonstrated Engineering





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