

**GEOHERMAL TRAINING
BINARY BOTTOMING POWER PLANTS FOR THE
INCREASE IN EFFICIENCY OF THE SINGLE-FLASH
GEOHERMAL POWER PLANTS AND
IMPLEMENTATION OF SCALING MANAGEMENT**

12th July 2023



WHO'S STEAM?

- We are an **Italian consultancy company** with a 36-year history in **geothermal** and **environmental sectors**
- Our experts will become your team for **geology, geochemistry, geophysics and engineering**
- We support our customers with end-to-end services:
 - Resource assessment and management
 - Drilling engineering and supervision
 - Feasibility studies and environmental assessments
 - Engineering and construction management
 - O&M support and capacity building





steam

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NATIONS

20+

FEASIBILITY STUDIES

30+

RESOURCE ASSESSMENTS

40+

WELLS COMMISSIONED

10+

DRILLING
SUPERVISIONS

80+

KMs OF GATHERING
SYSTEMS ENGINEERED

220+

PLANT MWs SUPERVISED

375+

PLANT MWs ENGINEERED



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**MINERAL EXTRACTION
FROM GEOTHERMAL BRINE**



**OWN. ENG. FLASH PLANTS
540 MW OLKARIA I, IV, I**



**105+80 MW MENENGA I +
OLKARIA I-U6 WELLS+FCRS**



**SOSIAN – O.ENG. FLASH +
BINARY 35 MW MENENGA I**

+ PROJECTS IN ETHIOPIA, UGANDA, DJIBOUTI, AND MOZAMBIQUE

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YEAR: 2015-2023

CAPACITY: 35 to 160 MW each

TECHNOLOGY: Binary, flash and combined

ACTIVITIES:

- Project management and feasibility
- Plant concept selection and design
- Technical specifications for the equipment
- Procurement management (EPC/supply)
- Design review during project execution
- HazOp and risk assessment
- Off-site technical support to erection, installation, commissioning and testing
- Site assistance during erection, installation, commissioning and testing
- Commissioning and testing of wells and gathering system

TRAINING PROGRAM TODAY

1. Power plant configurations
 1. Flash systems
 2. Binary and combined systems
 3. Efficiency of a bottoming cycle combined with a single-flash geothermal steam turbine
2. Silica scaling
 1. Why silica scaling
 2. How to manage it
3. Silica scaling management in combined cycles



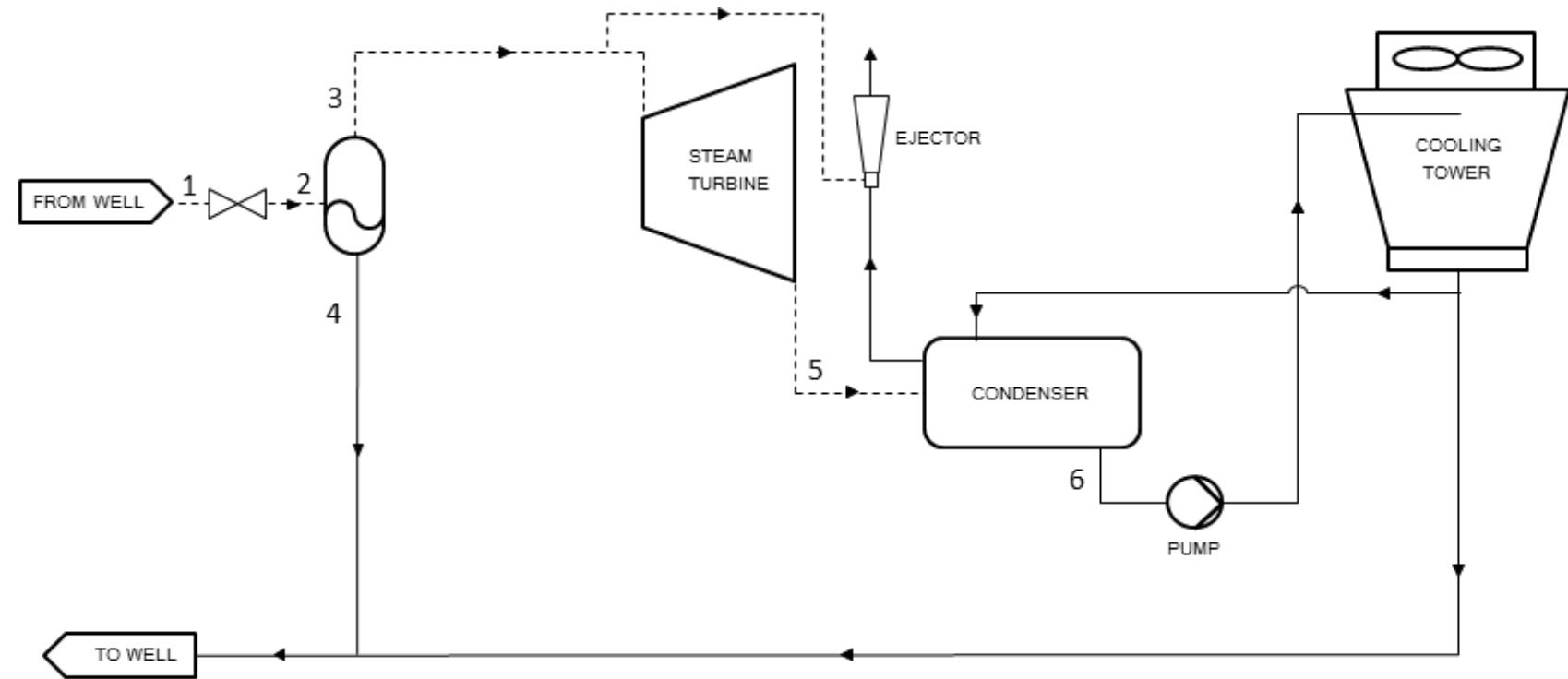
1. POWER PLANT CONFIGURATIONS



steam
geothermal energy

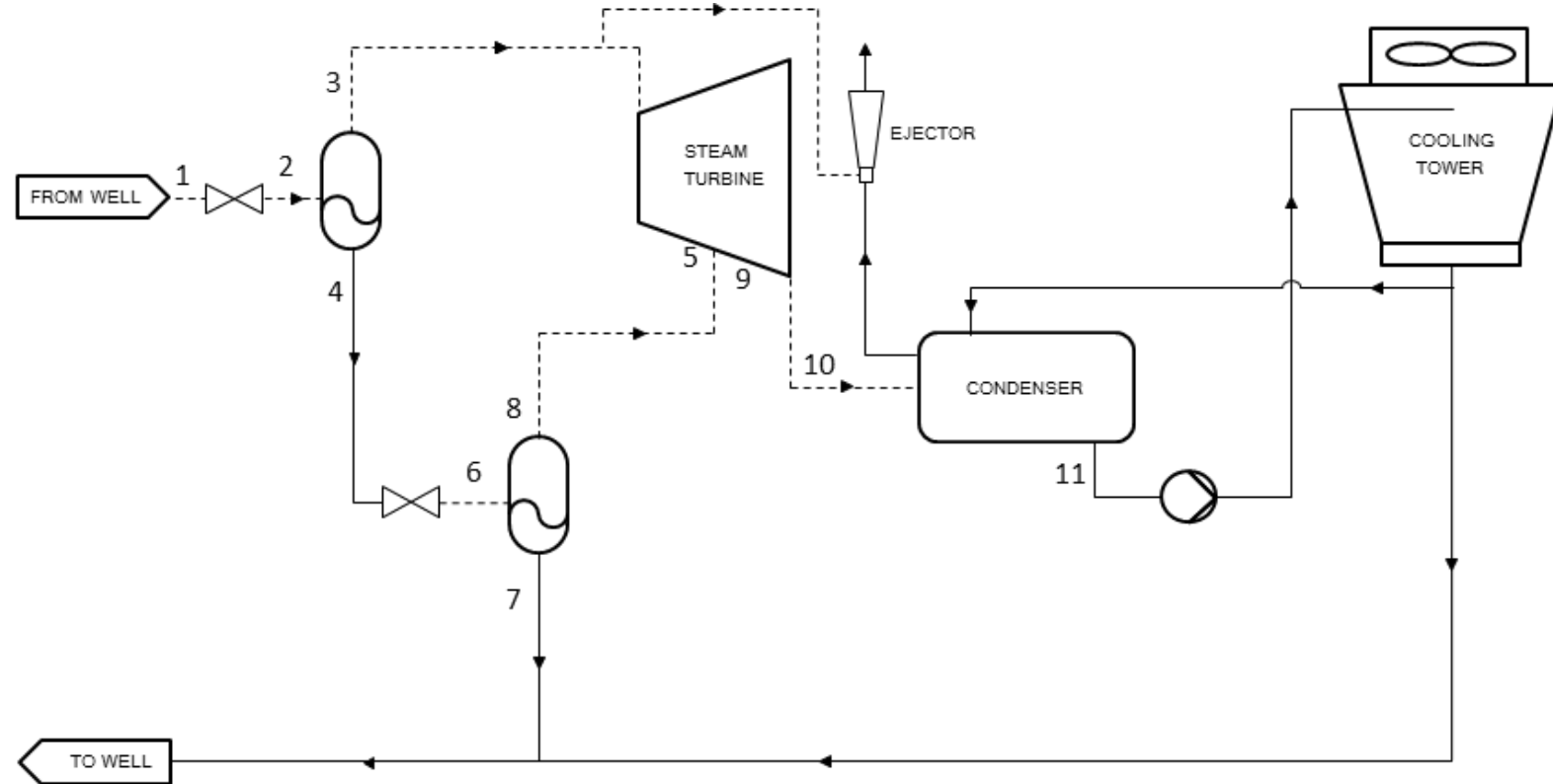
1.1 FLASH SYSTEMS – SINGLE FLASH

In case the reservoir is liquid-dominated, a separation of the vapor phase from the liquid phase is required before using steam in a direct cycle. Separation can be implemented in one or more stages. In a single flash plant, the geothermal fluid is separated into vapor and liquid phases in only one stage at a certain pressure: the steam feeds a steam turbine, while the brine (liquid phase) is reinjected or discharged.



1.1 FLASH SYSTEMS – DOUBLE FLASH

In a multiple flash configuration, the geothermal fluid is separated into vapor and liquid phases: the steam will feed a high-pressure (HP) steam turbine, while the liquid phase will be sent to a second separator after pressure reduction. There, it will be separated and admitted into lower pressure (LP) steam turbine. Eventually, a third pressure level can be foreseen: after the last separator, the brine (liquid phase) will be reinjected or discharged.



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1.1 FLASH SYSTEMS – SINGLE AND DOUBLE FLASH

Sample comparison of single-and double-flash cycle parameters

Name	Units	Single Flash	Double Flash
HP separator pressure	bar a	8	8
HP steam flow	kg/s	117	117
HP brine flow	kg/s	383	383
LP separator pressure	bar a	-	2
LP steam flow	kg/s	-	38
HP turbine output	MW	60	60
LP turbine output	MW	-	13.5
Net output	MW	56.5	69
Exergetic efficiency	%	35%	43%

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1.1 FLASH SYSTEMS – SINGLE AND DOUBLE FLASH

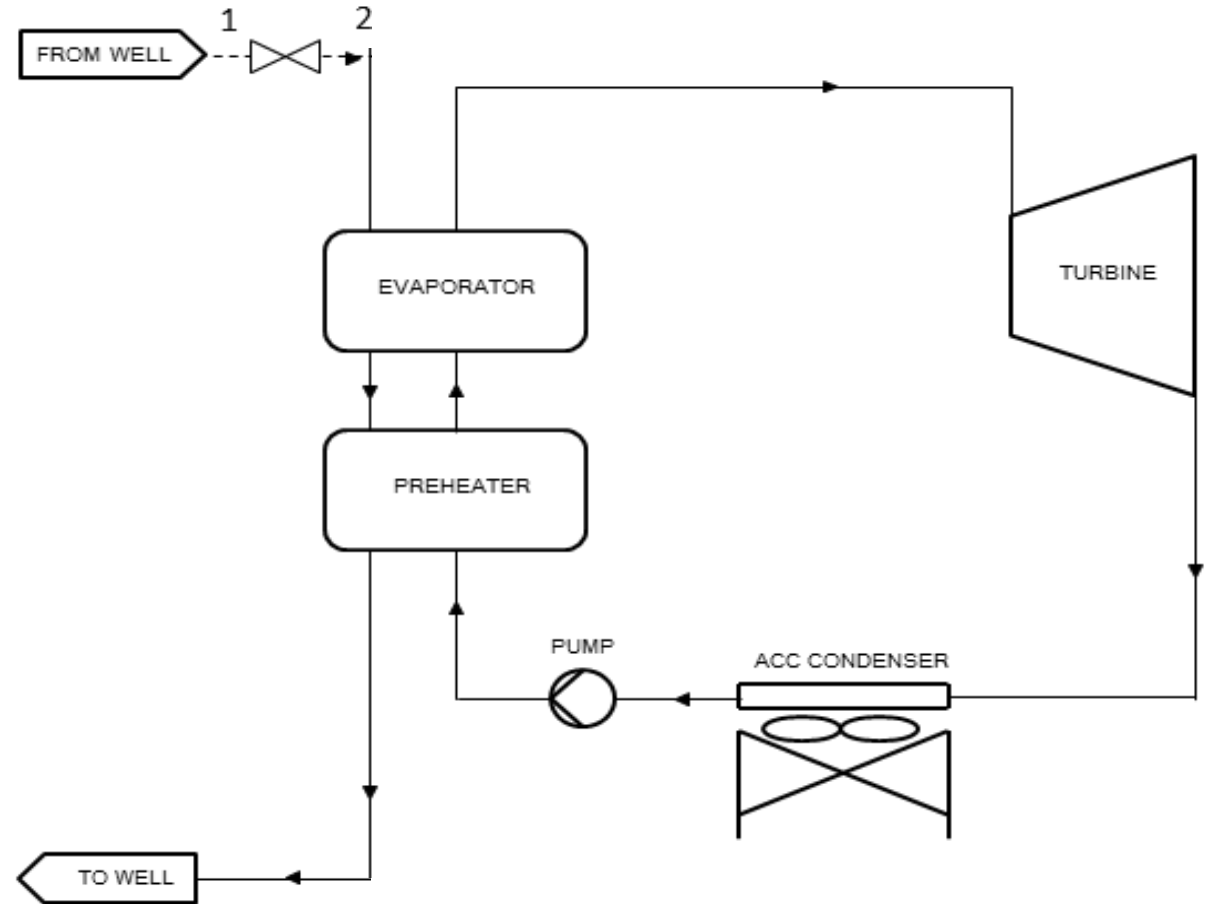
Sample comparison of single-and double-flash cycle parameters – focus on silica

Name	Units	Single Flash	Double Flash
Net output	MW	56.5	69.0
HP flash pressure	bar a	8	8
LP flash pressure	bar a	-	2
Silica concentration in injectate	ppm	735	815
Injection Temperature	°C	170	120
Equilibrium amorphous silica concentration at the injection temperature	ppm	744	458
Ratio of silica concentration to the equilibrium concentration	-	0.99	1.78



1.2 BINARY SYSTEMS

Binary technology is based on using a secondary fluid in the power cycle, which vaporizes in heat exchangers by receiving heat from the geothermal fluid.



1.2 BINARY SYSTEMS - OPTIMIZATION

The optimization problem reduces to the following system

$$\left\{ \begin{array}{l} \max[P_{net}] \\ iv = \{T_{eva}\} \\ T_{rej} \geq T_{rej\ min} \\ \Delta T_{pp} \geq \Delta T_{pp,\ min} \end{array} \right.$$

The goal is the maximization of the net power (P_{net}) and this is achieved by varying the independent variable evaporation temperature T_{eva} , considering the rejection temperature, T_{rej} and pinch point constraints .

1.2 BINARY SYSTEMS - ORC

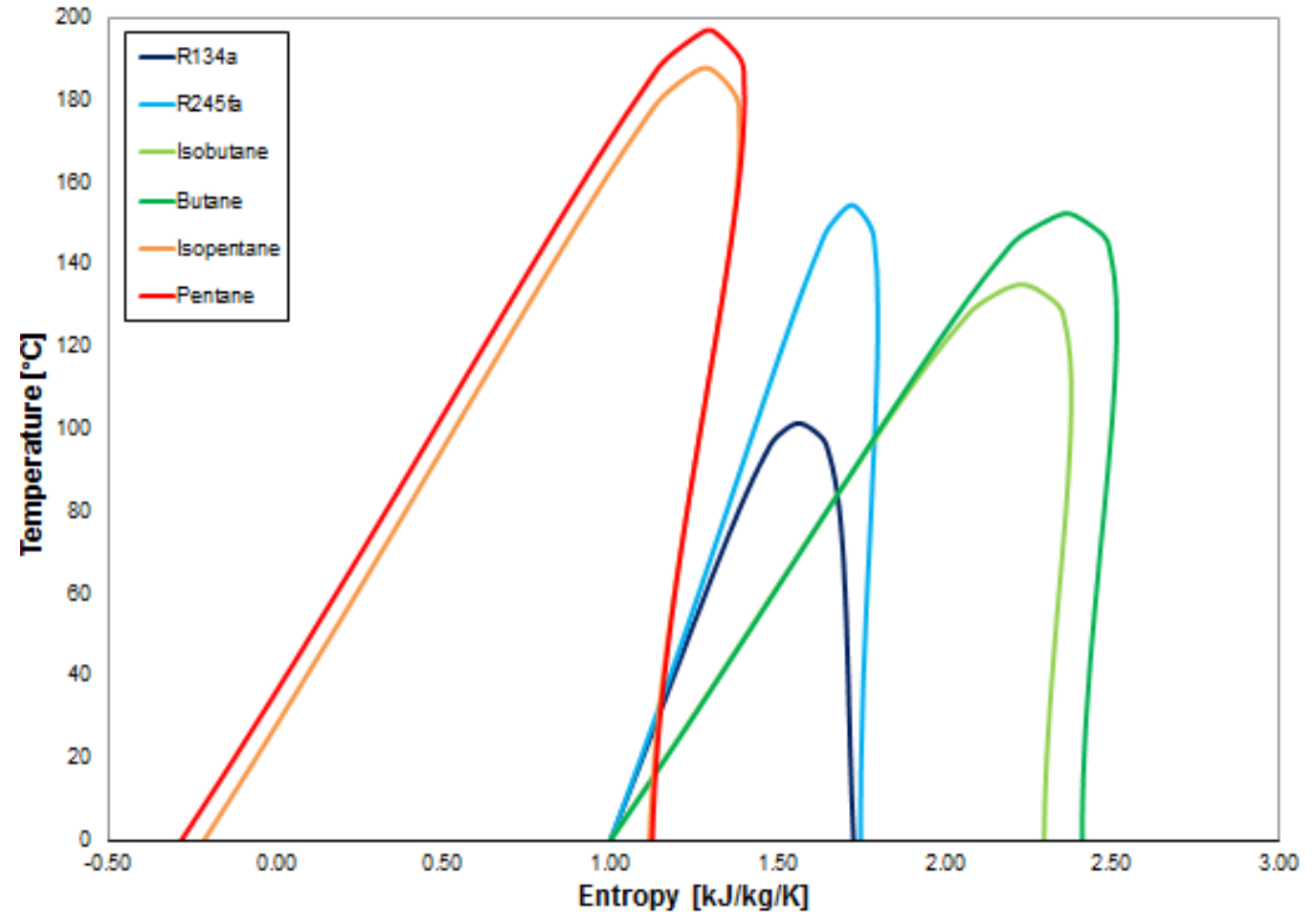
Several organic Rankine cycles are applicable to a specific geothermal resource in terms of fluid enthalpy, NCG content, wellhead conditions, chemical composition and quantity of available resources, and defined boundary conditions. The working fluid of an ORC can be chosen according to several parameters, such as the molecular weight (low or high) and the complexity (low or high), which leads respectively to wet and dry fluids (negative or positive saturation vapor curve) and the flammability (high, low, or none). Working fluids for geothermal applications generally are low-boiling.

Name	Class	Chemical formula	Molecular weight [kg/kmol]	Critical Temperature [°C]	Critical Pressure [MPa]	Boiling point at 1.013 bar [°C]	Type of expansion
R134a	HFC	CH ₂ FCF ₃	102.0	101.1	4.059	-26.1	Wet
R1234yf (R134a replacement)	HFO	CF ₃ CF=CH ₂	114.04	94.7	3.382	-21	Dry
R245fa	HFC	CF ₃ CH ₂ CHF ₂	134.0	154.0	3.651	15.1	Dry
R1233zd (R245fa replacement)	HFO	(E)CF ₃ -CH=CClH	130.5	165.5	3.57	18.3	Dry
Isobutane	HC	C ₄ H ₁₀	58.1	134.7	3.629	-11.8	Dry
Butane	HC	C ₄ H ₁₀	58.1	152.0	3.796	-0.5	Dry
Isopentane	HC	C ₅ H ₁₂	72.1	187.2	3.378	27.8	Dry
Pentane	HC	C ₅ H ₁₂	72.1	196.6	3.370	36.1	Dry
Water	-	H ₂ O	18.0	373.9	22.064	100.0	Wet

1.2 BINARY SYSTEMS – ORC

The critical temperatures of these fluids vary from 100 to 200 °C, while the critical pressure is in the range of 30 to 40 bar. Latent heat and heat capacity are generally lower for HFC, and the only fluid featured with a wet expansion is R134a.

It becomes evident that fluids with the same molecular weight will not necessarily perform with similar heat recovery efficiency while fluids with similar critical temperatures are expected to do so.



R1233 and R1234 are not reported as replacement fluids for R245fa and R134a.

1.2 BINARY SYSTEMS – CONFIGURATIONS AND COMBINED SYSTEMS

The resource can be exploited by adopting one of the many configurations:

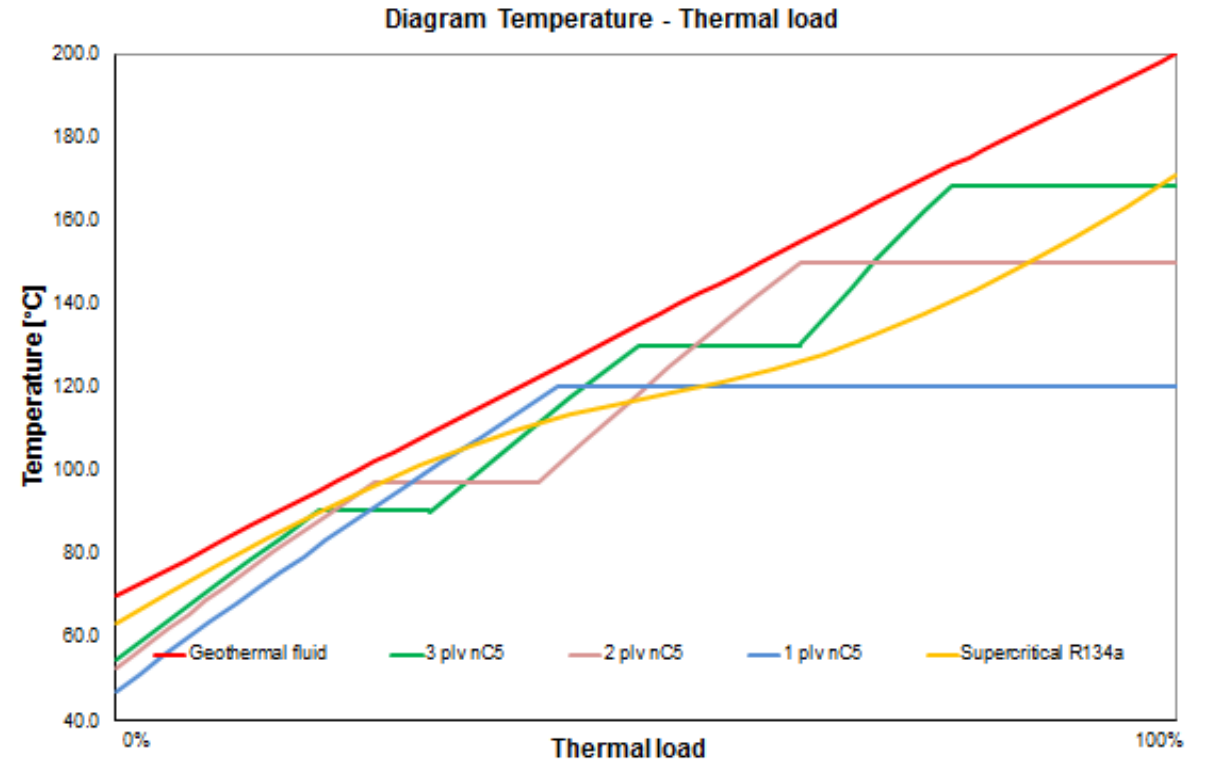
- Subcritical systems (single/double or triple pressure level system)
- Supercritical
- Bottoming and combined cycles (steam turbine + binary cycle)



5. BINARY SYSTEMS – ORC

In order to favor an easier coverage of this analysis, a numerical example is presented, aiming to compare the three subcritical solutions and the supercritical configuration. The comparison is carried out using **normal-pentane** as working fluid for the subcritical cycles and **R134a** for the supercritical cycle.

Three cases are presented: medium-high enthalpy (200 °C), medium enthalpy (150 °C) and low enthalpy (100 °C) full liquid flows, cooled to a reinjection temperature of 70 °C.



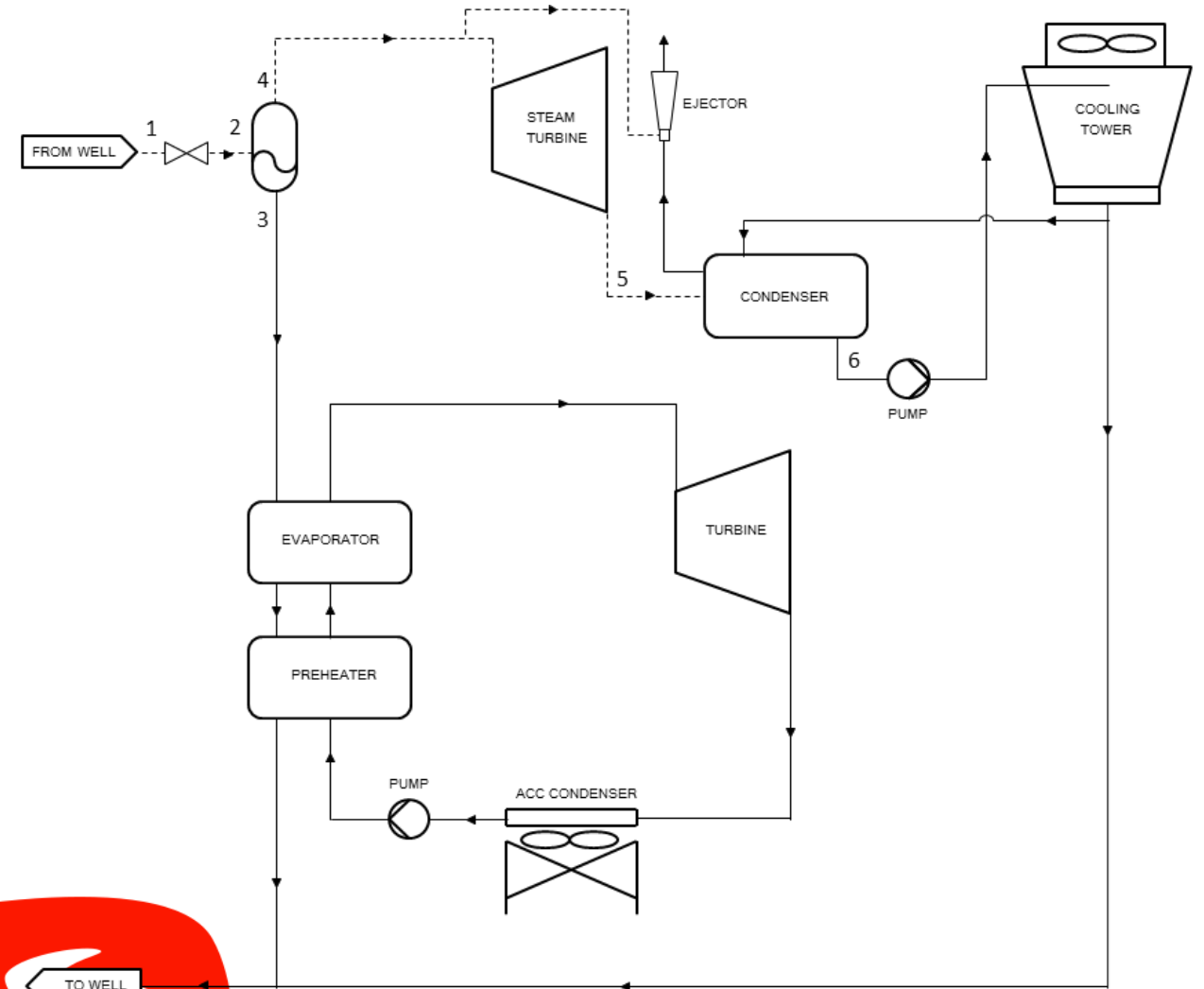
Cycle Fluid	1 pressure level nPentane	2 pressure level nPentane	3 pressure level nPentane	Supercritical R134a
Net Power	1	1.10	1.13	1.02

Medium-high enthalpy

1.2 COMBINED CYCLE CONFIGURATION

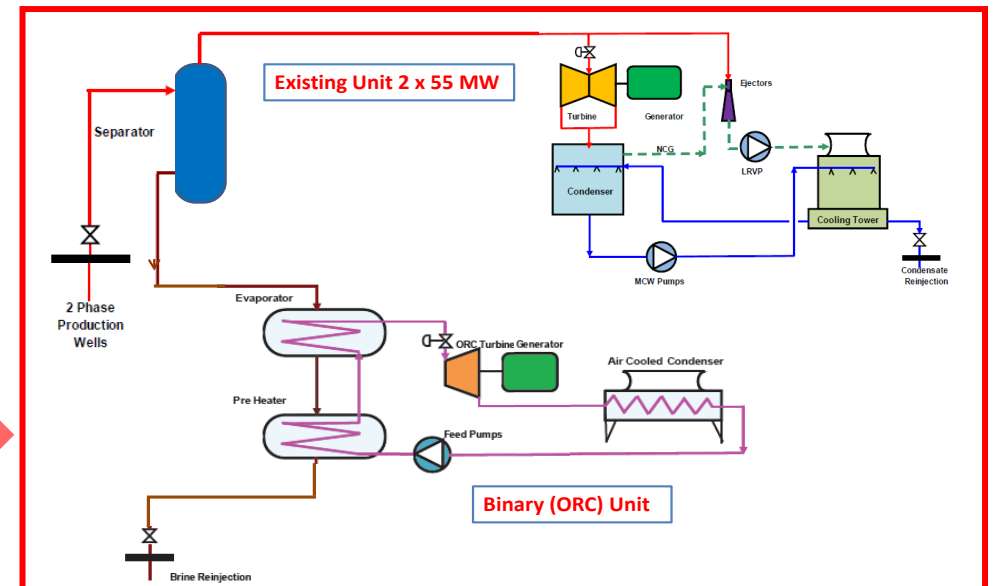
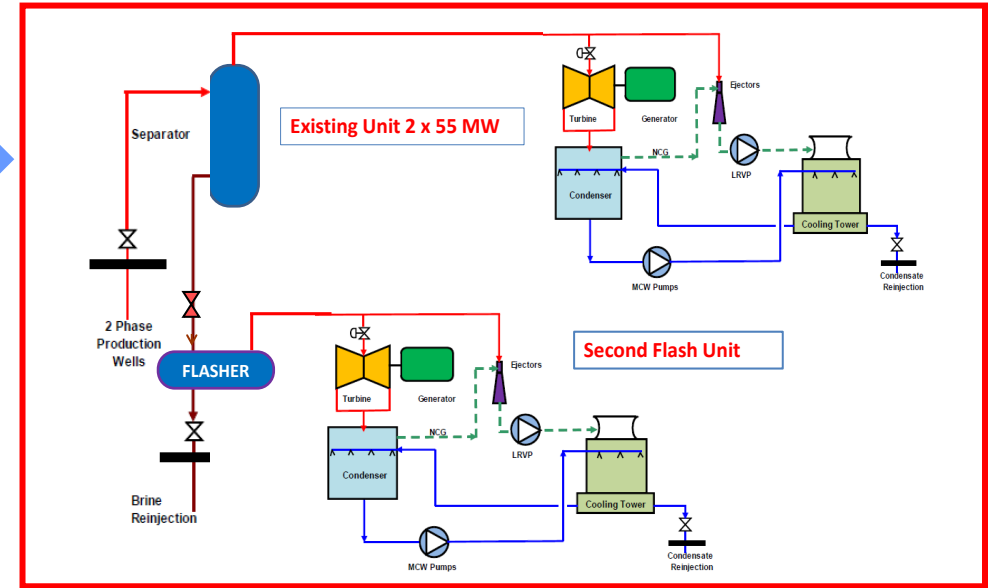
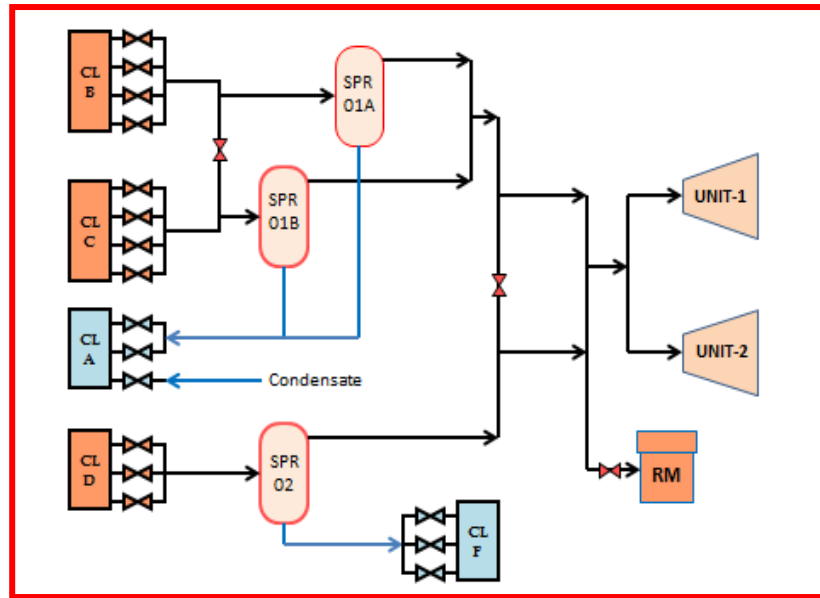
Combined systems are suited for resources with high-enthalpy and, thus, very high steam amounts. The binary unit can run parallel to the steam turbine, exploiting a geothermal liquid flow after separation, or in series, with a steam flow coming from the backpressure turbine (“bottoming” configuration).

The combined cycle configuration is usually the most efficient means of exploiting a high enthalpy resource and fits the resources with high non-condensable gas content particularly well.



1.3 EFFICIENCY OF A COMBINED SYSTEM vs DOUBLE FLASH

Single-flash capacity: 2 x 55 MW gross
 Steam flow: 836 t/h @ 175 °C (approx. 8.5 bar)
 Brine flow: 2,780 t/h @ 175 °C



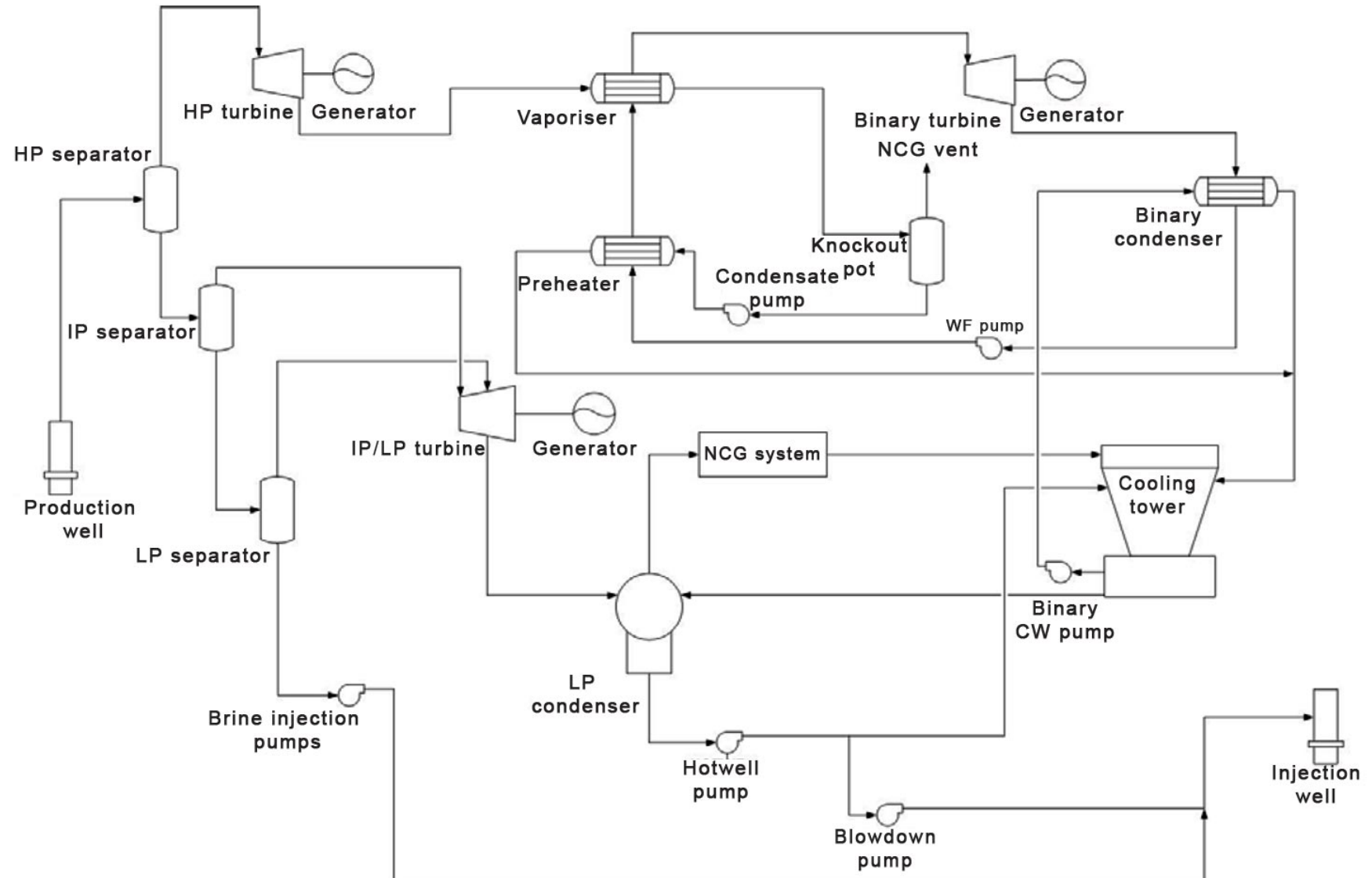
1.3 EFFICIENCY OF A COMBINED SYSTEM vs DOUBLE FLASH

Description	Second Flash Cycle	Binary Cycle (Iso-pentane)	Binary Cycle (Iso-butane)	Binary Cycle (R134a)
Generator Output (kW)	31'360	34'501	41'155	37'569
Pump Power Consumption (kW)	420	1'245	4'915	4'460
Fan Power Consumption (kW)	430	3'588	3'412	3'412
Other Aux.plant Load (kW)	234	276	329	300
Total House Load (kW)	1'084	5'109	8'656	8'172
Net Power Output (kW)	30'276	29'392	32'499	29'397
Turbine Inlet Pressure (bar abs)	2	11	41	50
Turbine Inlet Temperature (°C)	120	121	152	159
Relative Power Increase (%)	28.4	27.5	30.0	27.6

Description	Single Flash	Second Flash	Binary (i-Pentane)	Binary (i-Butane)	Binary (R134a)
Gross Power (MW)	110	139.3	144.5	151.2	147.6
Net Power (MW)	106.7	134.1	135.3	138.4	135.3

1.3 MORE COMPLEX COMBINED CYCLES

Kizildere II combined cycle simplified process flow diagram



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1.3 MORE COMPLEX COMBINED CYCLES

Kizildere II combined cycle



Bottom-hole temperature	242 °C
Power (steam turbine)	60 MW
Power (binary cycles)	19 MW
Total auxiliaries	11 MW
Net Output	68 MW
Steam conditions to HP turbine	8.45 bar, 174.5 °C, 371,5 t/h (294,7 t/h Steam and 76,8 t/h NCG)
Steam conditions to IP turbine	3.48 bar, 147.6 °C, 128,3 t/h
Steam conditions to LP turbine	1.1 bar, 112.2 °C, 213,2 t/h
Steam conditions to ORC	1.15 bar, 100.5 °C, 371,5 t/h (294,701 t/h water bi-phase flow and 76,835 t/h NCG)
Cooling type	Water (Cooling Towers)

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2. SILICA SCALING

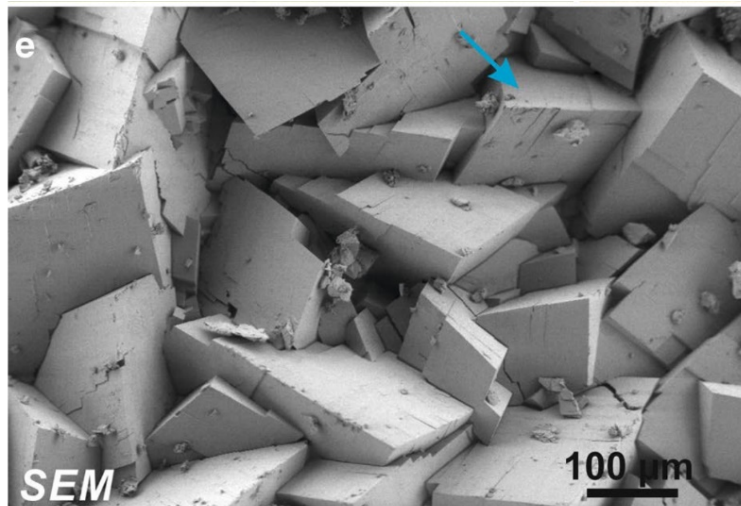


steam
geothermal energy

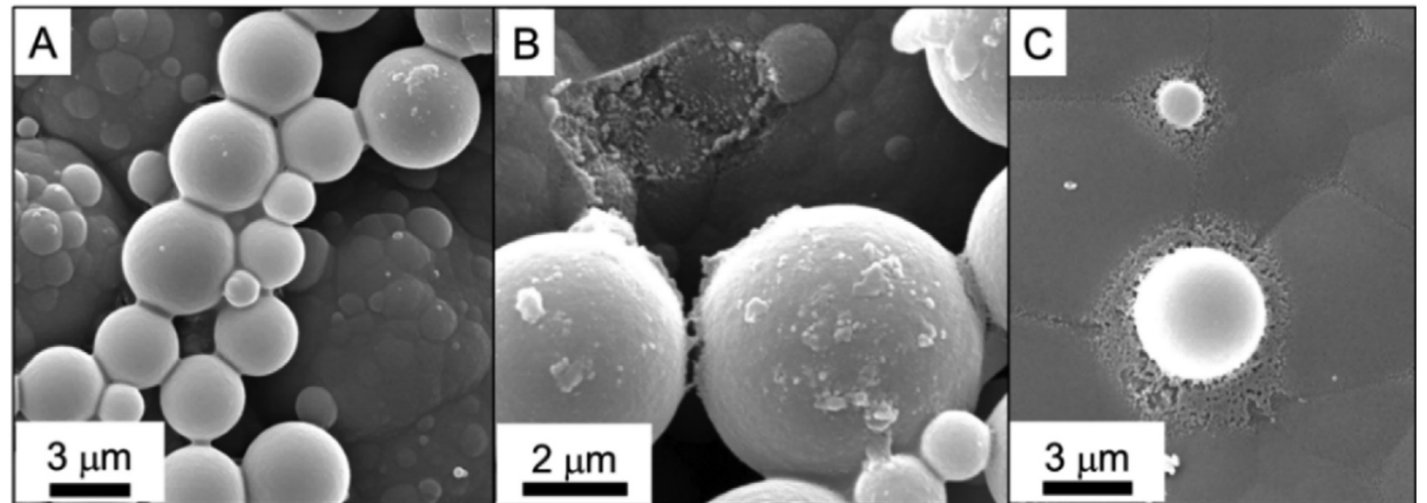
2.1 SILICA SCALING

Scaling occurs when geothermal liquids become oversaturated with a given mineral. Scaling from brine can occur as a result of different mechanisms: increased concentrations from boiling and/or boiling-related pH changes and/or cooling. The most common mineral scales in geothermal plants are:

- Carbonates (CaCO_3)
- Amorphous Silica (SiO_2)
- Metal Sulfides Scales



Scanning electron microscope (SEM) image of a scale growth surface constituted by rhombohedral calcite crystals (from Boch et al. 2017).



Scanning electron microscope (SEM) images of amorphous silica particles deposited onto a silica layer, either (A) cemented together or (B) cemented onto the surface or (C) incorporated into the silica layer (from van den Heuvel et al. 2018).

2.1 SILICA SCALING

Saturation Index > 0

$$SI = \frac{\log_{10} Q}{\log_{10} K}$$

Q = activities of products/activities of reactants in the solubility reaction;

K = equilibrium constant for the solubility reaction.

SI is temperature dependent and assumes equilibrium, which does not always occur in geothermal brines, especially between the power plant and injection well, nor do minerals always precipitate immediately when log SI is at or slightly above 0.

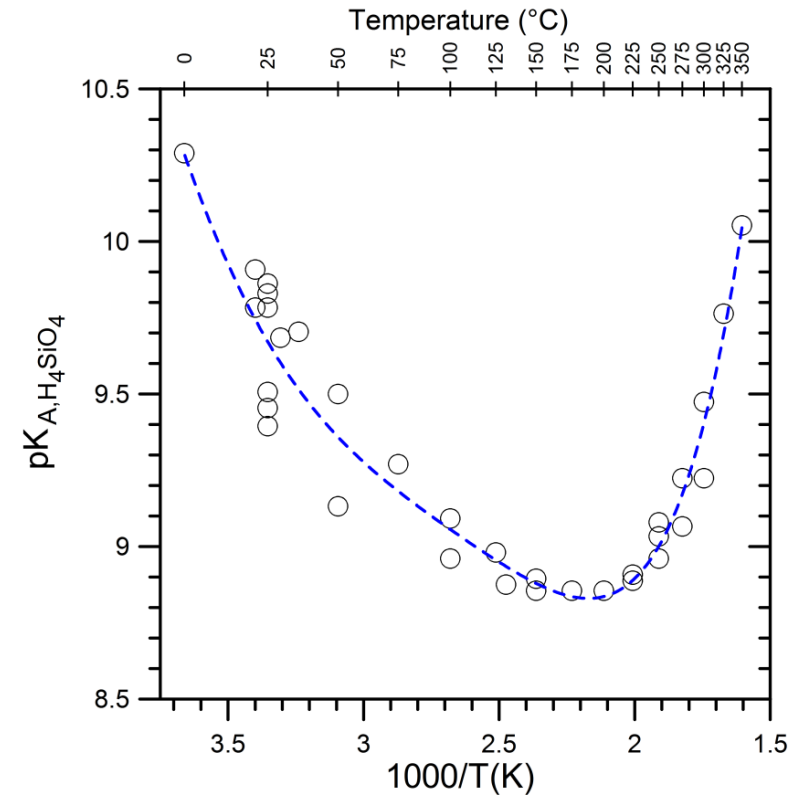
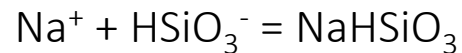
Scaling was primarily addressed by avoiding conditions that generated scale. These approaches reduced power plant efficiency.

- Plant/project design -> Fluid chemistry data or with computer program (WATCH) for prediction
- Mitigation

2.1 SILICA SCALING

In general, total dissolved SiO_2 concentration is nearly equal to undissociated SiO_2 concentration under reservoir conditions.

In fact, the pH of reservoir liquids is usually constrained by water-rock reactions in the range 5–7, whereas the pK of silicic acid dissociation varies from 10.3 to 8.8, in the 0–350 °C range. However, loss of acid gases (CO_2 and H_2S) upon steam separation (boiling) increases significantly the pH of the aqueous solution. Upon attainment of pH values higher than 7.8–9.3, depending on temperature, total dissolved silica concentration becomes significantly greater than undissociated silica concentration due to the presence of significant amounts of silicate ion produced through the dissociation of silicic acid (see previous slide). A further increase in total dissolved silica concentration is due to the complexation of silicate ion with the cations present in the aqueous, mainly Na^+ ion:



Source: Cioni and Marini (2020)

2.1 SILICA SCALING

In the geothermal reservoir, the aqueous solution is usually in equilibrium with quartz and the concentration of dissolved SiO_2 is a function of temperature (at water saturation pressure), as expressed by:

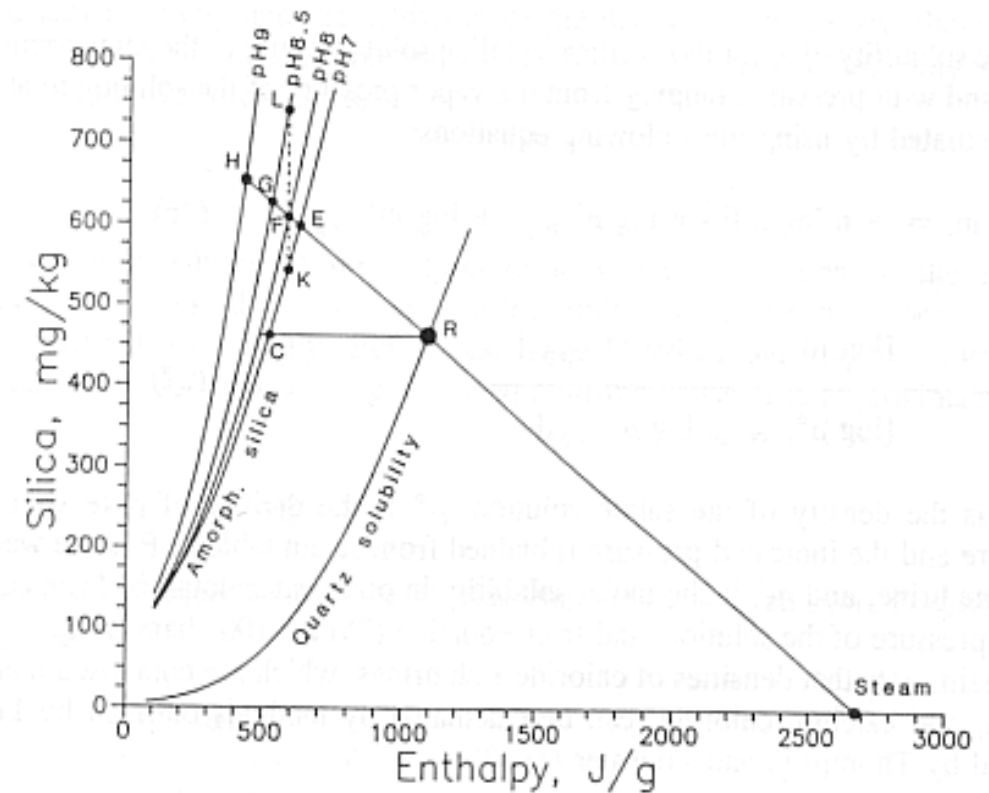
$$\log C_{\text{qz}}(\text{mg/kg}) = -1309/T(\text{K}) + 5.19.$$

Thus, at 250°C , $C = 487 \text{ mg/kg}$ (point R).

Amorphous silica is more soluble than quartz and its solubility (at water saturation pressure) is given by:

$$\log C_{\text{amsi}}(\text{mg/kg}) = -731/T(\text{K}) + 4.52.$$

Upon conductive cooling (as in binary plants) the aqueous solution becomes saturated with amorphous silica at point C ($H_L = 529 \text{ J/g}$, 126°C , ad $\text{SiO}_2 = 487 \text{ ppm}$), if pH is 7 or lower. If pH is >7 , saturation with amorphous silica would be reached at lower temperatures due to the presence of significant amounts of silicate ion (lines labelled pH 8, pH 8.5, pH 9).



Source: Fournier (1991)

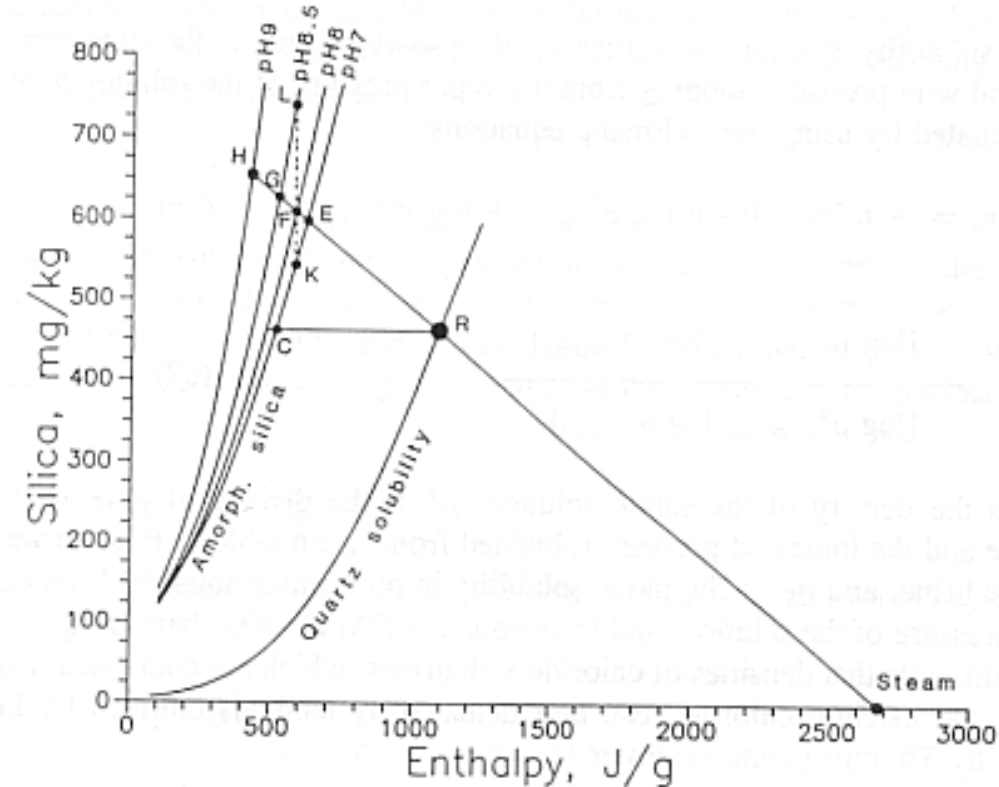
2.1 SILICA SCALING

In the case of flashing, silica concentration increases, and the enthalpy of the liquid decreases, as indicated by the line connecting the point of steam and point R.

This line intersects the amorphous silica solubility lines at decreasing enthalpies, depending on the pH of the liquid, i.e.:

- at point E for pH 7, where HL is 620 J/g, which corresponds to T of 147°C and P of 4.39 bar
- at point F for pH 8, where HL is 575 J/g, which corresponds to T of 137°C and P of 3.32 bar
- at point H for pH 9, where HL is 425 J/g, which corresponds to T of 102°C and P of 1.09 bar

Since amorphous silica precipitates fast upon attainment of supersaturation conditions (see next slides), the operating pressure of well-head steam-separators must be decided to avoid amorphous silica scaling, also considering the pH of the liquid phase.



Source: Fournier (1991)

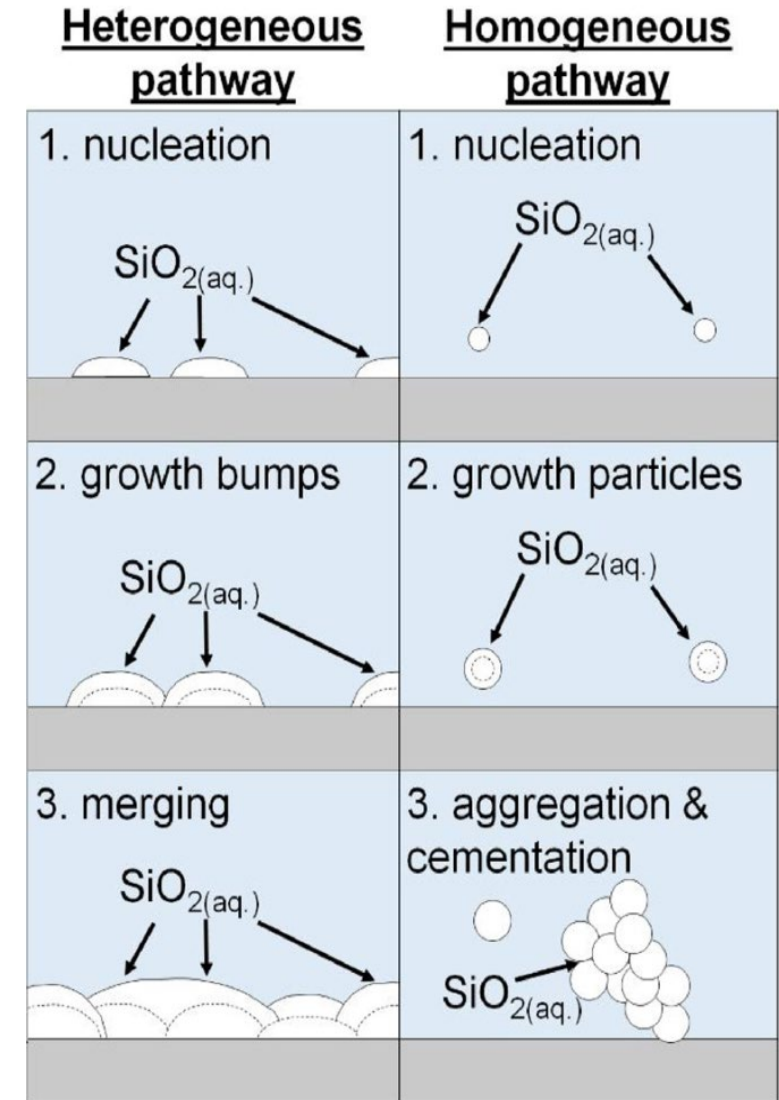
2.1 SILICA SCALING

Amorphous silica forms through polymerization of silicic acid monomers (H_4SiO_4 or H_2SiO_3 or $\text{SiO}_2(\text{aq})$) that can occur:

- either at an interface \rightarrow “heterogeneous nucleation”
- in the bulk fluid \rightarrow “homogeneous nucleation”

In both cases, once silica nuclei have reached a critical size (< 0.5 to 2 nm) they grow spontaneously by addition of silica (mainly monomeric) from the solution.

Experimental evidence shows that silica polymerization, nucleation and particle growth are enhanced at slightly alkaline pH, high temperature, and medium to high ionic strength.



Schematic of the two silica precipitation pathways ($\text{SiO}_2(\text{aq})$ = silica monomers in solution) as they occur inside the pipelines of the Hellisheiði geothermal power plant (from van den Heuvel et al., 2018) 28

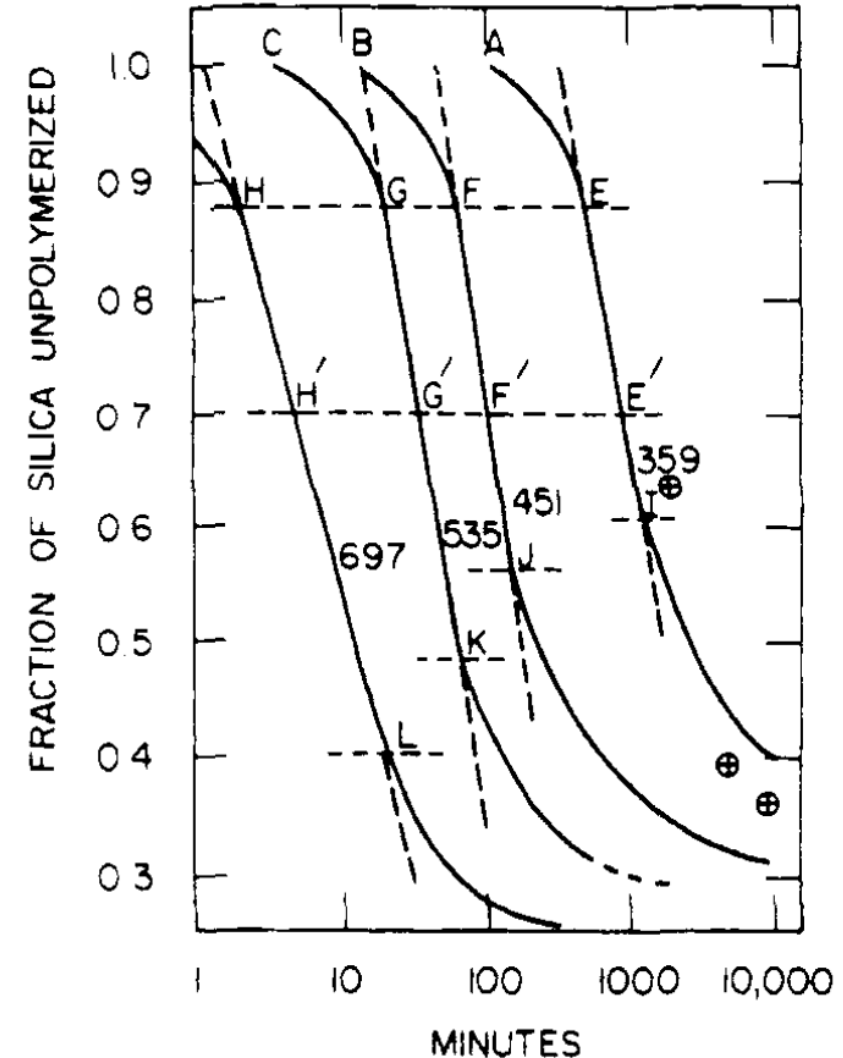
2.1 SILICA SCALING

The amorphous silica polymerization process frequently comprise an initial **induction time** (or delay time or lag time) during which the concentration of the monomer (i.e., silicic acid) does not change.

After some period of time, the concentration of silicic acid starts to decrease, indicating that polymerization is occurring.

The induction time can be considered the interval of time during which polymerization proceeds so slowly that no changes can be detected in the concentration of silicic acid.

When colloidal silica is present at the start of the experiment, there is no induction period.



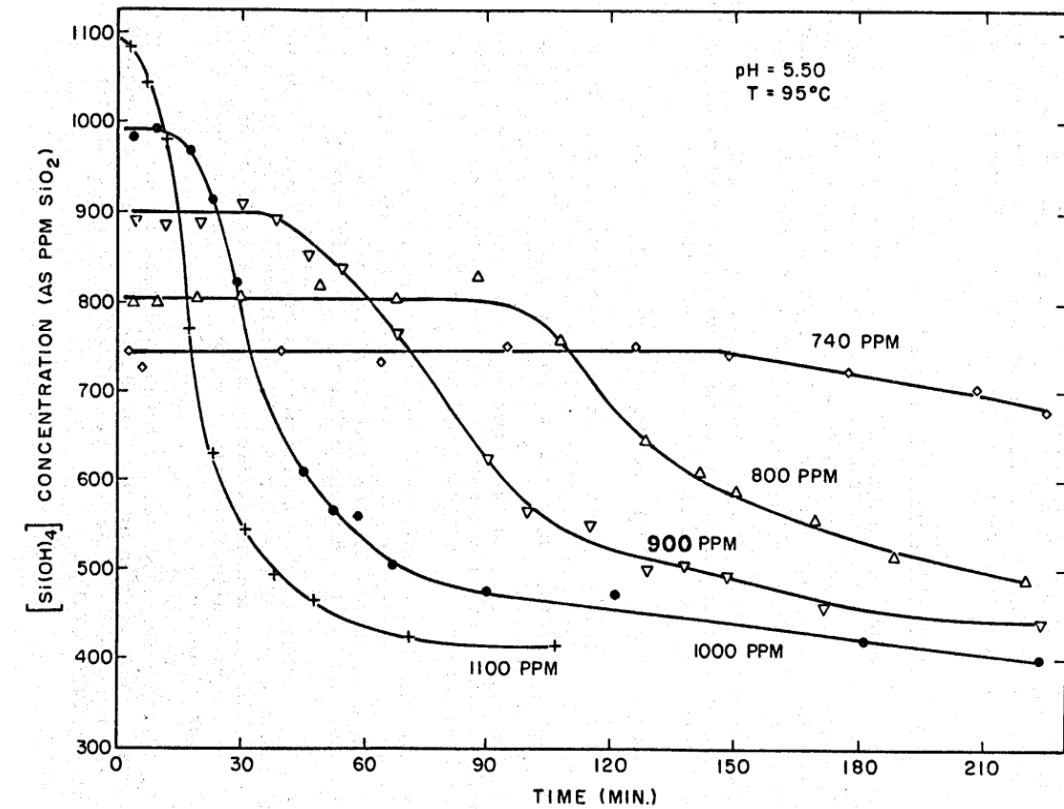
Disappearance of monosilicic acid versus time at different concentrations of 359-697 ppm SiO₂. Temperature 25°C; pH = 8.0. Points A, B, C = induction times at which polymerization begins. Points E, F, G, H = appearance of nuclei (from Iler, 1979).

2.1 SILICA SCALING

There are several experimental studies on the kinetics of silica polymerization, some of which consist in monitoring the concentration of molybdate-reactive (monomeric?) SiO_2 in geothermal brines or simple Na_2SiO_3 solutions.

At pH 5.5 there is no silicate ion. At 95°C, saturation with amorphous silica is attained at 342 mg/kg (see previous slides). Thus, the concentrations reported by Makrides et al. (1978) correspond to the following values of the saturation ratio and saturation index:

SiO ₂	Sat. Ratio	Sat Index
ppm	ppm/ppm	Log [(ppm/ppm)]
740	2,2	0,33
800	2,3	0,37
900	2,6	0,42
1000	2,9	0,47
1100	3,2	0,51

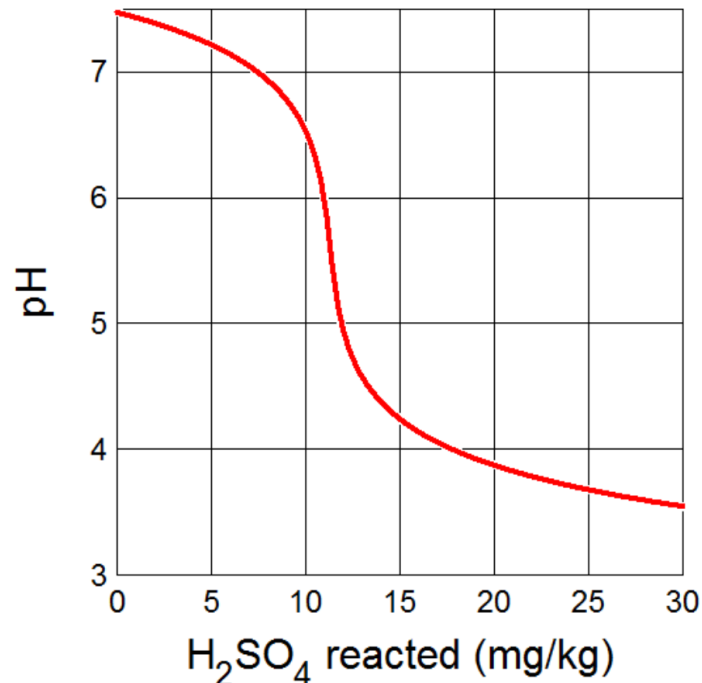
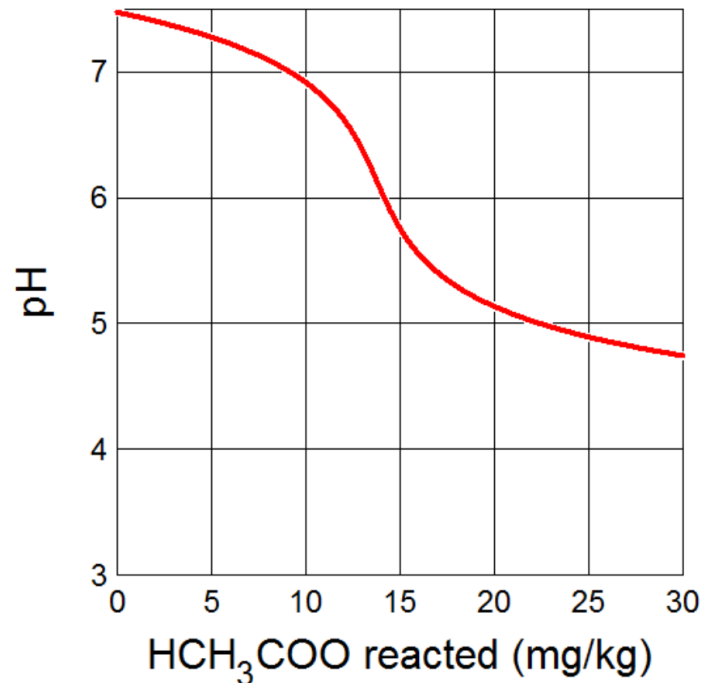


From Makrides et al. (1978), The induction time decreases with increasing saturation ratio and vice versa.

2.1 SILICA SCALING

To avoid silica scaling in pipelines and other surface equipment, the transit time of the brine from the pressure separator to the re-injection well must be lower than the induction time of silica polymerization.

To increase the induction time, the brines to be re-injected are often acidified to pH 5.0 – 5.5 by addition of sulfuric acid (cheaper, but pH control is poor) or acetic acid (more expensive, pH control is effective).



Scaling in the reservoir nearby the re-injection well presumably does not occur if the re-injected brine is quickly heated up, but there is no certainty on this point.

Left Plot: effect of adding acetic acid to a brine with 0.24 meq/kg HCO₃ = 12 ppm alkalinity as CaCO₃. Adding 17 ppm acetic acid decreases pH to 5.5; adding 21 ppm, a 25% excess, further decreases pH only to 5.1.

Right Plot: Adding 13 ppm H₂SO₄ to the same brine decreases pH to 5.5; adding 16 ppm, a 25% excess, decreases pH to about 4.1, risking serious corrosion

2.1 SILICA SCALING

As discussed by Gallup (1997), a potential problem is the precipitation of impure amorphous silica, containing significant amounts of other metals (e.g., Al, Fe), instead of pure amorphous silica.

This impure amorphous silica may precipitate at temperatures higher than those predicted for pure amorphous silica. Sometimes the precipitation temperature is 25 – 75 °C higher than that for pure amorphous silica. So, when temperatures, pressures, and other operating parameters are set in order for pure amorphous silica in pure water to be at or less than the equilibrium solubility of pure amorphous silica in pure water, unexpected siliceous scale deposition occurs.

According to Gallup (1997), amorphous silica rich in Al and Fe precipitates in several geothermal fields.

Table 1. Bulk elemental XRF analyses of major elements in scale samples obtained from injection piping (wt%)

Sample location	SiO ₂	Al ₂ O ₃	CaO	FeO	MgO	Na ₂ O	K ₂ O	+H ₂ O	Total
Salton Sea; acidified injection brine; pH 5	78.7	8.2	0.6	1.5	0.1	1.3	0.8	4.5	95.7
Awibengkok; injection brine; pH 6.8	66.1	10	2	0.4	0.1	2.2	1.3	3.2	85.3
Silangkitang; injection brine; pH 8.5	74.4	9.3	0.9	4.7	<0.1	2.4	3.4	5.3	100.4
Bulalo injection brine; pH 6.5	78.8	7.5	0.9	2.7	0.5	1.6	2.3	4.2	98.5

2.2 SCALING MANAGEMENT: AMORPHOUS SILICA

Due to the large volumes of water to be treated, any process to stop silica scaling must be relatively cheap.

Avoidance of amorphous silica saturation

The difference in solubility between quartz and amorphous silica allows energy to be extracted while still keeping the amorphous silica under-saturated. Even at low levels of supersaturation ($SSI < 1.2$ say), the level of scaling may be acceptable, or there may be a sufficiently long induction period, that silica scaling is avoided in reinjection wells and reinjection pipelines.

Ex. to reinject geothermal brine at high enough temperature to prevent thermodynamic scaling by silica. This is a common solution but it decreases the plant efficiency.

Inhibition of colloid formation (acidification)

The rate of colloid formation decreases at lower pH. When the pH is lowered to 4.5 – 5.0, the polymerization can often be halted for several hours. However, this is only a kinetic effect, and the silica will eventually polymerise and possibly deposit. The target pH for this method is usually a compromise between retarding the silica polymerisation and having acceptable corrosion of carbon steel.

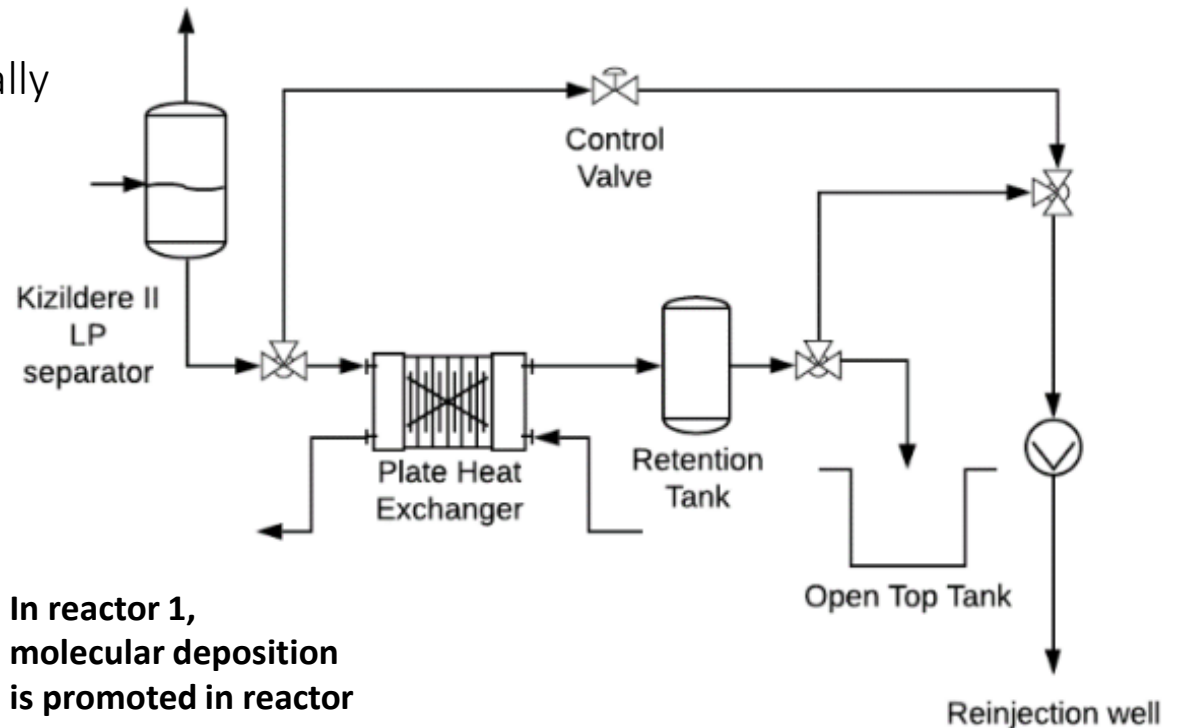
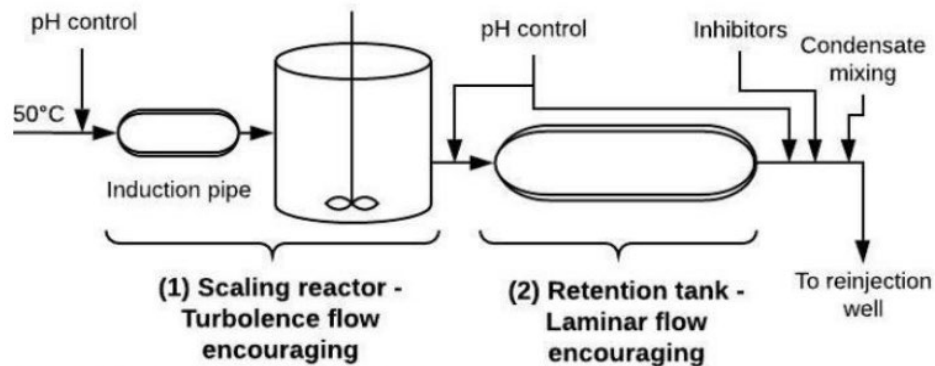
Sulphuric acid is used as it is available at 98% concentration. However, where there is a possibility of anhydrite (CaSO_4) or metal sulphides deposition, hydrochloric acid can be used. Acetic acid is an option.

2.2 SCALING MANAGEMENT: AMORPHOUS SILICA

Aging of the brine

Silica polymerization is used for example to lower silica scaling potential in Nesjavellir and Hellisheiði power plants in Iceland: brines are aged in retention tanks or pipes allowing the monomeric silica in excess of amorphous silica solubility to polymerize.

In some processes, the extracted silica can potentially be treated as a byproduct to sell on the market.



**In reactor 1,
molecular deposition
is promoted in reactor
2 silica polymerization
is promoted**

2.2 SCALING MANAGEMENT: AMORPHOUS SILICA

Colloid stabilisation (antiscalant)

By adding chemicals to the solution, it is possible to change the surface characteristics of the colloid such that the energy barrier to approach another colloid is increased. There are currently a number of programs in progress to develop and test these “colloidal dispersants” led by commercial interests. One of this is Geogard-SX (GSX) polymer (Phosphino Carboxylic Acid Copolymer) this has been tested extensively by PNOC–EDC in the Philippines (Bacon-Manito Geothermal Business Unit). It acts to keep long chain silica polymers from coalescing thus preventing particle growth which leads to increased particle mass and eventual deposition. F3680 (a polyacrylic acid copolymer) is another chemical inhibitor, which acts through threshold and lattice distortion as well as by dispersion. But it also acts as a deflocculant. The polymer appears to form a thin, self-strippable layer on the surface and thus preventing hard silica deposits to form on the surface of the pipe that are hard to clean

Removal of the silica

A number of different methods are available to treat the colloidal suspension to precipitate and remove the silica. This sometimes has the added advantage of removing other objectionable compounds, like arsenic. Addition of lime (CaO) is one possible treatment that has received some attention. However, the major use of silica removal is in the CRC process for the Salton Sea brines. Removal of silica colloids of a specific size and having specific surface properties can be very lucrative and research is continuing in this area.

2.2 SCALING MANAGEMENT: AMORPHOUS SILICA

Raising the pH

Silicic acid becomes soluble by converting the dissolved silica to the silicate ion. This involves raising the pH by adding caustic. Experiments at Ohaaki (Lichti et al., 2000) showed that at 100°C, silica scaling is prevented by raising the pH at 100°C to 9.0. There seemed to be no problems with corrosion of steel in this experiment. The major drawback is the cost of the alkali. A possible side effect is the deposition of calcite, but this can be controlled by the addition of antiscalant.

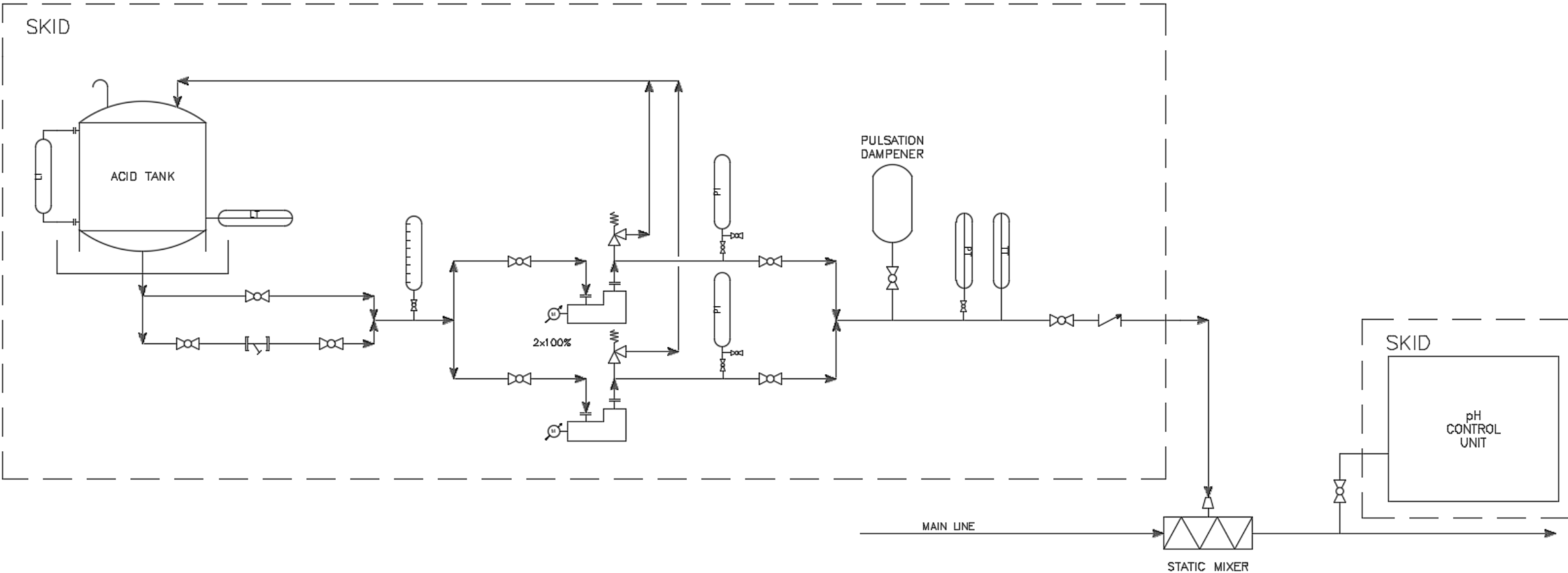
Rapid cooling of the brine

Rapid cooling of the brine can produce very small colloids which have been shown to be less likely to form a scale. The kinetics are normally such that the brine must be cooled in a matter of seconds rather than minutes for the particle size to be sufficiently small.

Coatings

Both organic and inorganic coatings have shown limited fouling when exposed to environments simulating geothermal brine (Polyphenylene sulfide (PPS) blended with polytetrafluoroethylene (PTFE) onto a carbon steel or sol-gel TiO₂ deposited onto a stainless steel substrate).

2.2 SCALING MANAGEMENT: ACIDIFICATION SYSTEM



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2.2 SCALING MANAGEMENT: ACIDIFICATION SYSTEM

The typical scope of supply includes:

- Selection of the dosing features (conceptual design)
- Supply of the acidification skid
 - Acid pumps, valves, instruments and line components
 - Control system
 - Pre-mixer (optional)
 - IBC for acid storage (optional)
- Supply of the main mixer (to be installed online)
- Supply of the pH control unit
- Design of the interconnecting piping

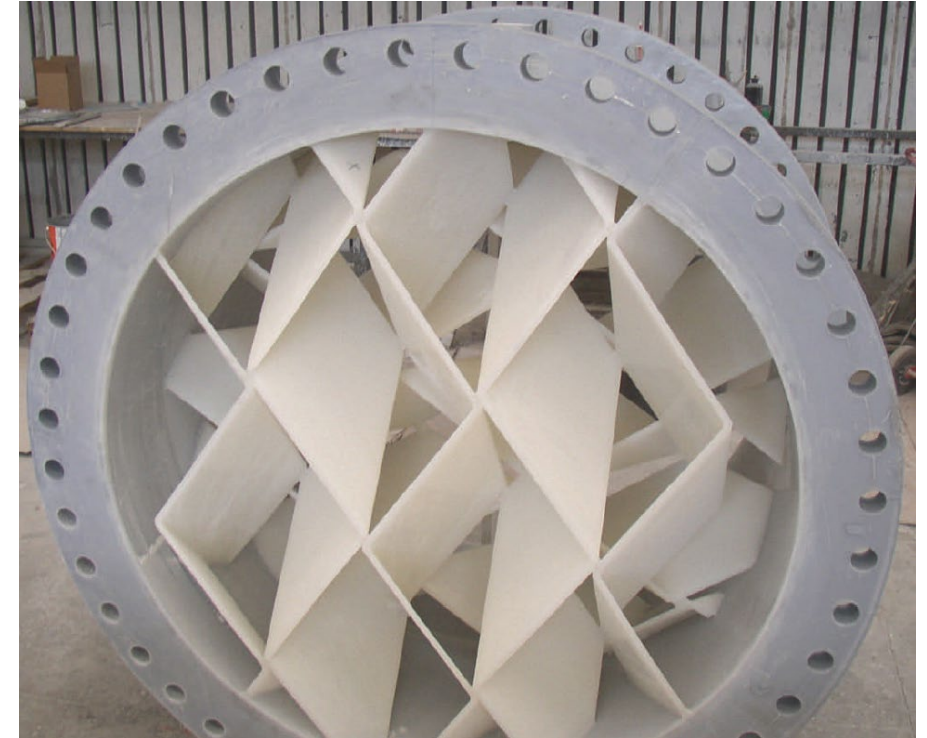
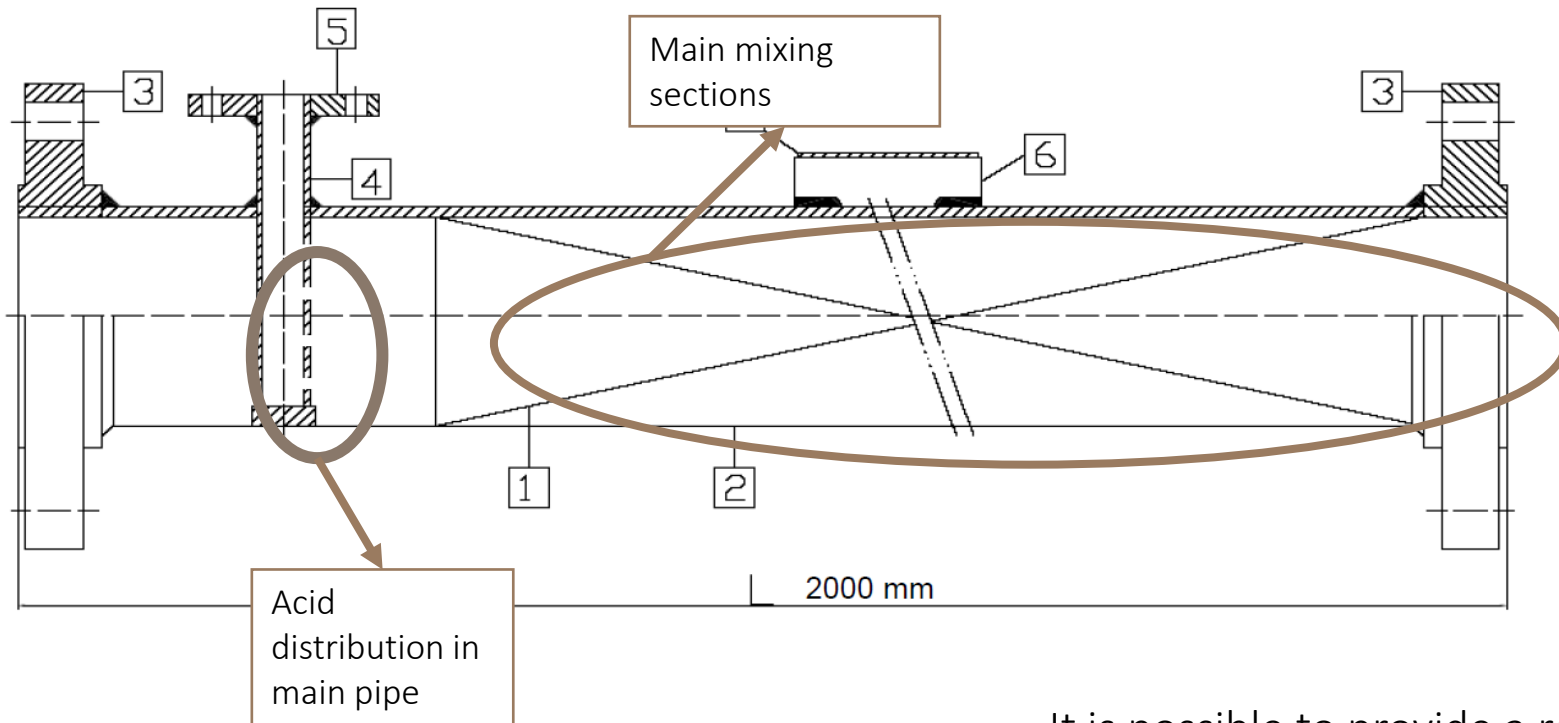


2.2 SCALING MANAGEMENT: ACIDIFICATION SKID



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2.2 SCALING MANAGEMENT: STATIC MIXER



It is possible to provide a removable mixing element for cleaning purposes.

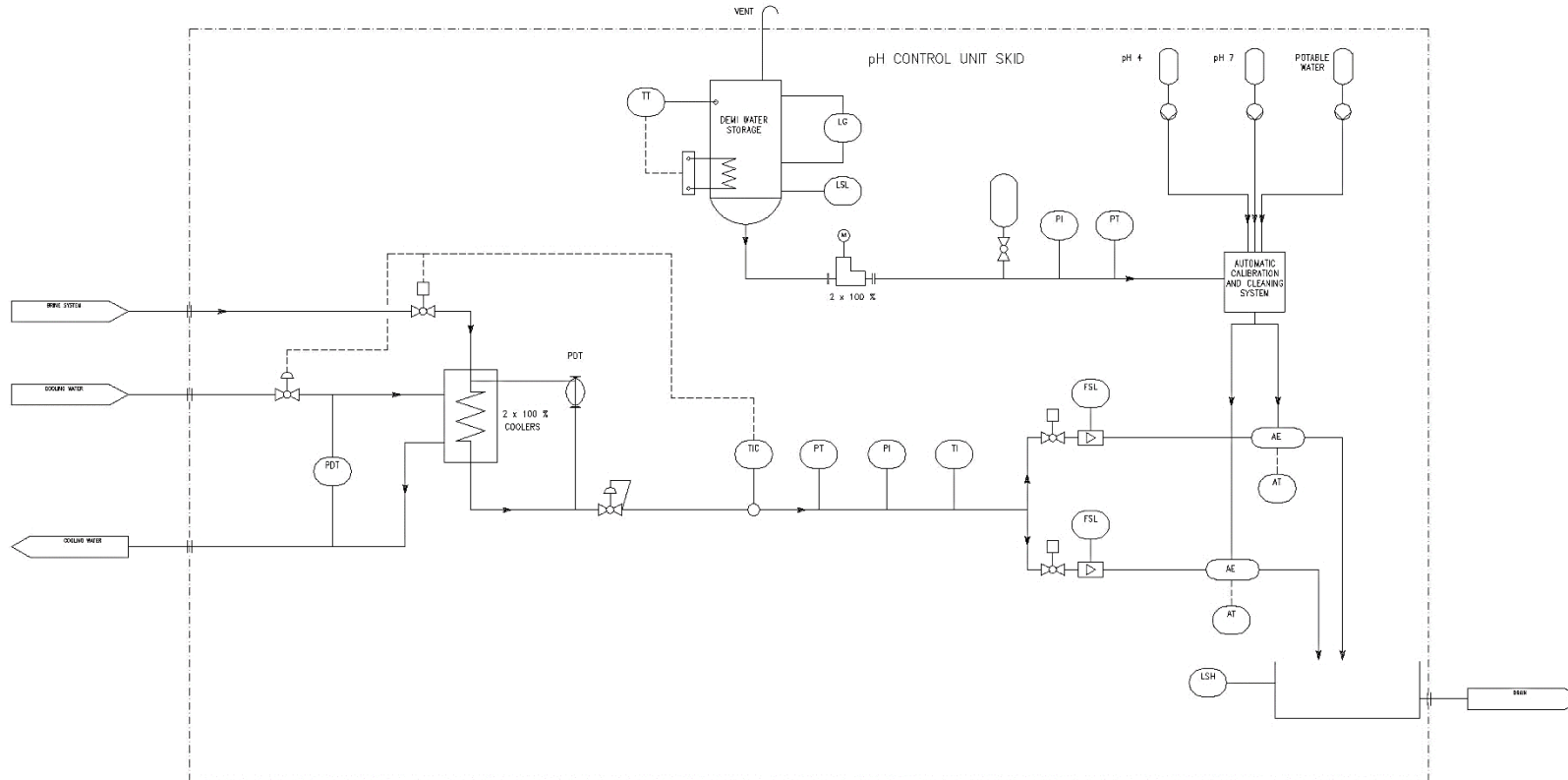
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2.2 SCALING MANAGEMENT: STATIC MIXER

The system is either onboard on the acidification skid or installed inside a container equipped with lighting and air conditioning. It is composed of the following sections:

1. Sample cooling system (2x100% coolers)
2. pH measuring system (sensor and transmitter)
3. Automatic Calibration and cleaning system



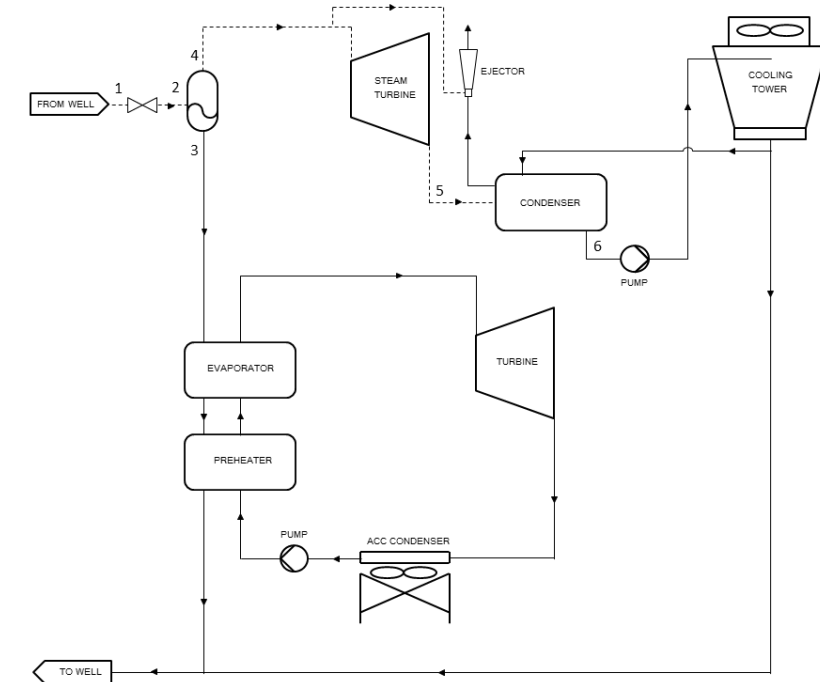
3. SILICA SCALING MANAGEMENT IN COMBINED CYCLES



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3. GEOTHERMAL FLUIDS IN HIGH-ENTHALPY RESERVOIRS

- **Silica content** in a geothermal fluid depends on the characteristics of the **reservoir**
- For water-dominated 260 °C reservoir: saturation concentration of the quartz is approx. 470 ppm
- At **150 °C separation temperature, silica** concentration is at **saturation** (620 ppm)
- Cooling of the hot brine in a ORC bottoming plant implies a **temperature decreasing with a constant silica concentration**
- This will lead to a **supersaturated brine**



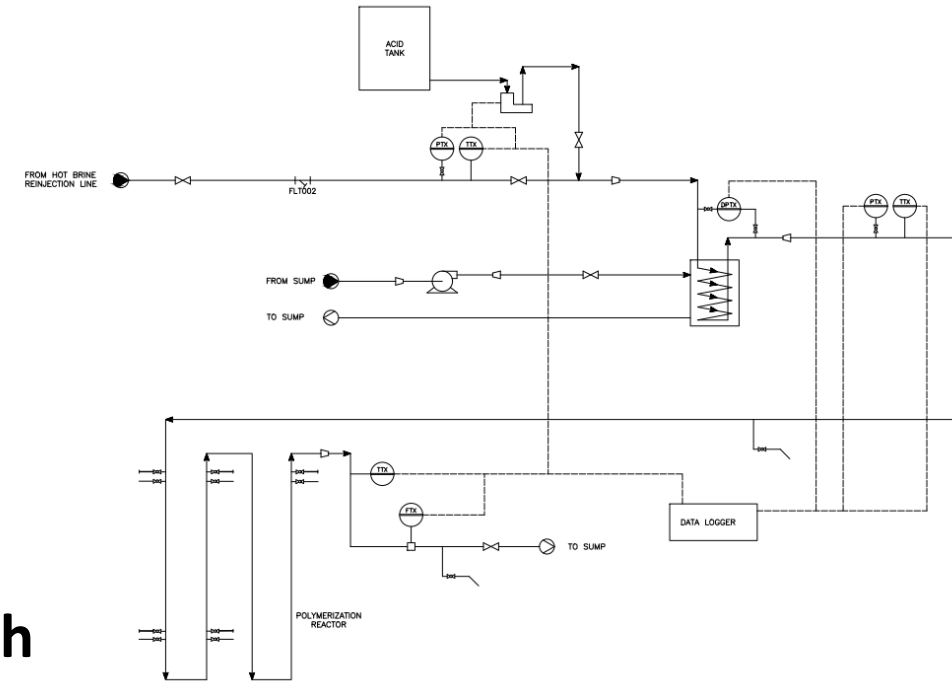
3. HARVESTING THERMAL POWER FROM SUPERSATURATED BRINE

- Supersaturated brine may cause **scaling** in the **heat exchangers**, the **reinjection lines** and **wells**
- Scaling can be managed through **brine treatment** with acids and/or inhibitors
- To find the **optimal working point**, we perform:
 1. **Trial tests** or rig tests of chemical dosing
 2. Technical-economic **optimization**
 3. Design of the **treatment system** and the ORC



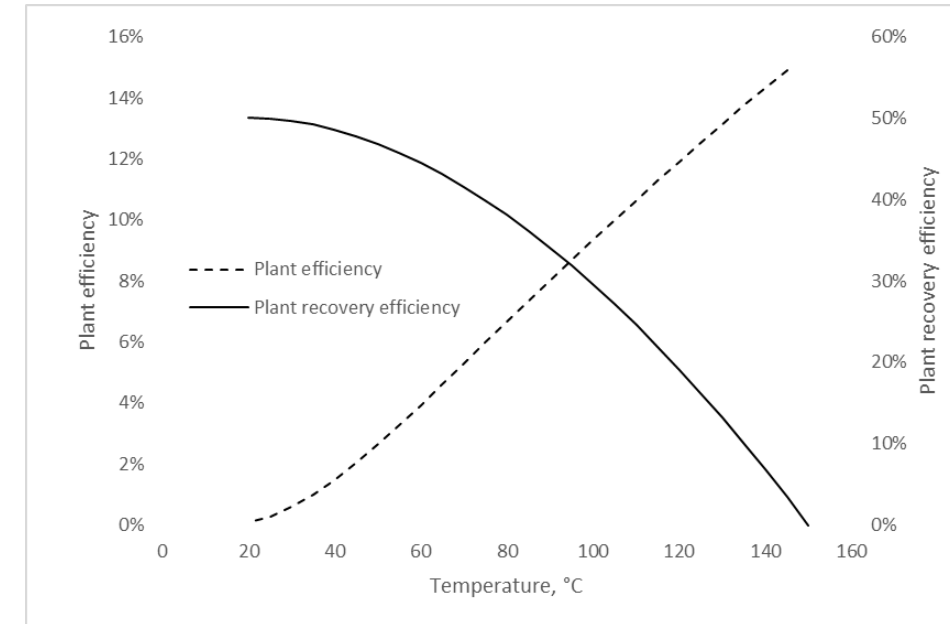
3. PHASE 1 – RIG TESTING

- Tests are performed in a dedicated **pilot plant** where the operation conditions are replicated in flowing mode
- **Acid/inhibitor is dosed**
- Several tests are performed at **diverse**
 - **Injected ppm** of the acid/inhibitor
 - **Outlet temperature**
 - **Residence time**
- If acid is dosed, the **resulting pH is controlled**
- For each simulation, **scaling is measured and both liquid and deposition are analyzed**



3. PHASE 2 – TECHNICAL-ECONOMIC OPTIMIZATION

- The best result of a bottoming power plant can be reached through a technical-economic **optimization of the reinjection temperature**
- **Produced power** suffers **decreasing cycle efficiency** at decreasing reinjection temperature
- **CAPEX increase with increasing thermal power** processed by the bottoming plant
- **OPEX increase with lower temperatures** due to the more chemical dosing needed



3. PHASE 3 – DESIGN – SELECTION OF THE ACID

Acid dosing is regulated with feedback from the pH control unit. If dosing varies, the pH variation shows a substantially different behavior comparing weak and strong acids.

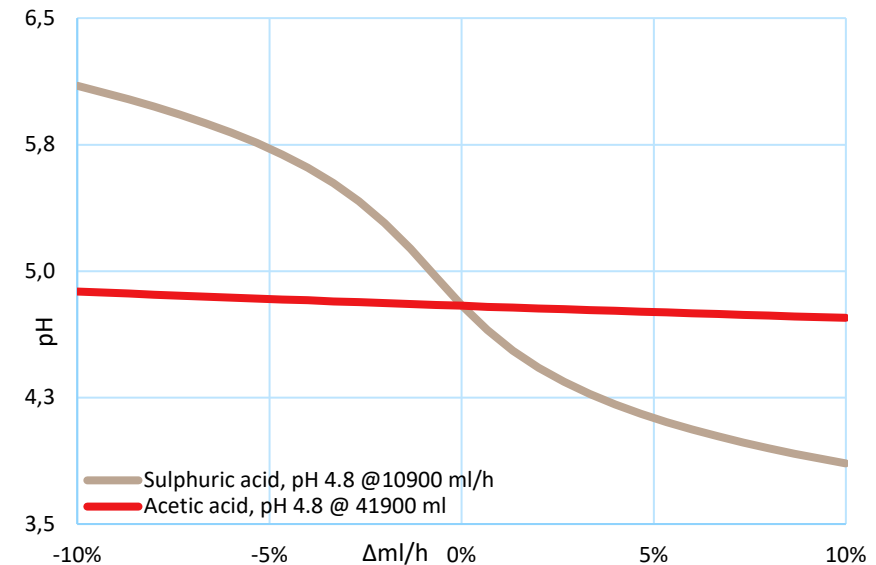
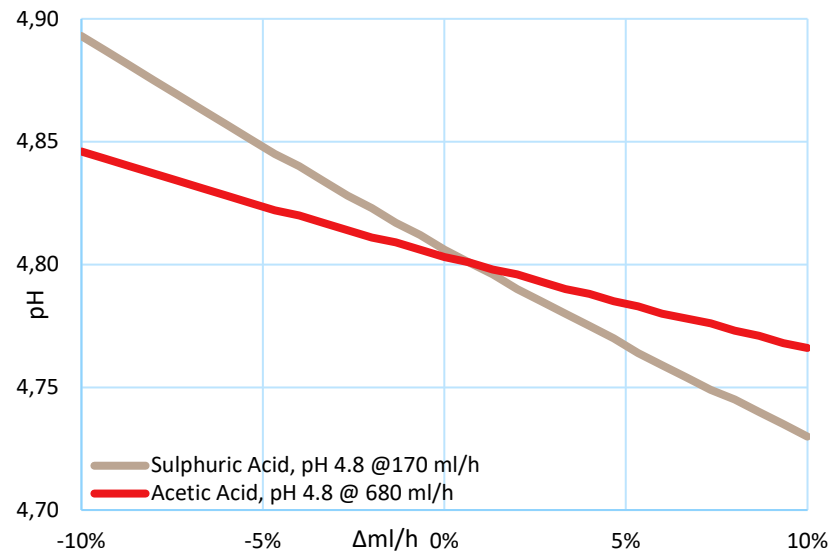
Considering the same percentage error of the acid dosing rate:

For sulphuric acid:

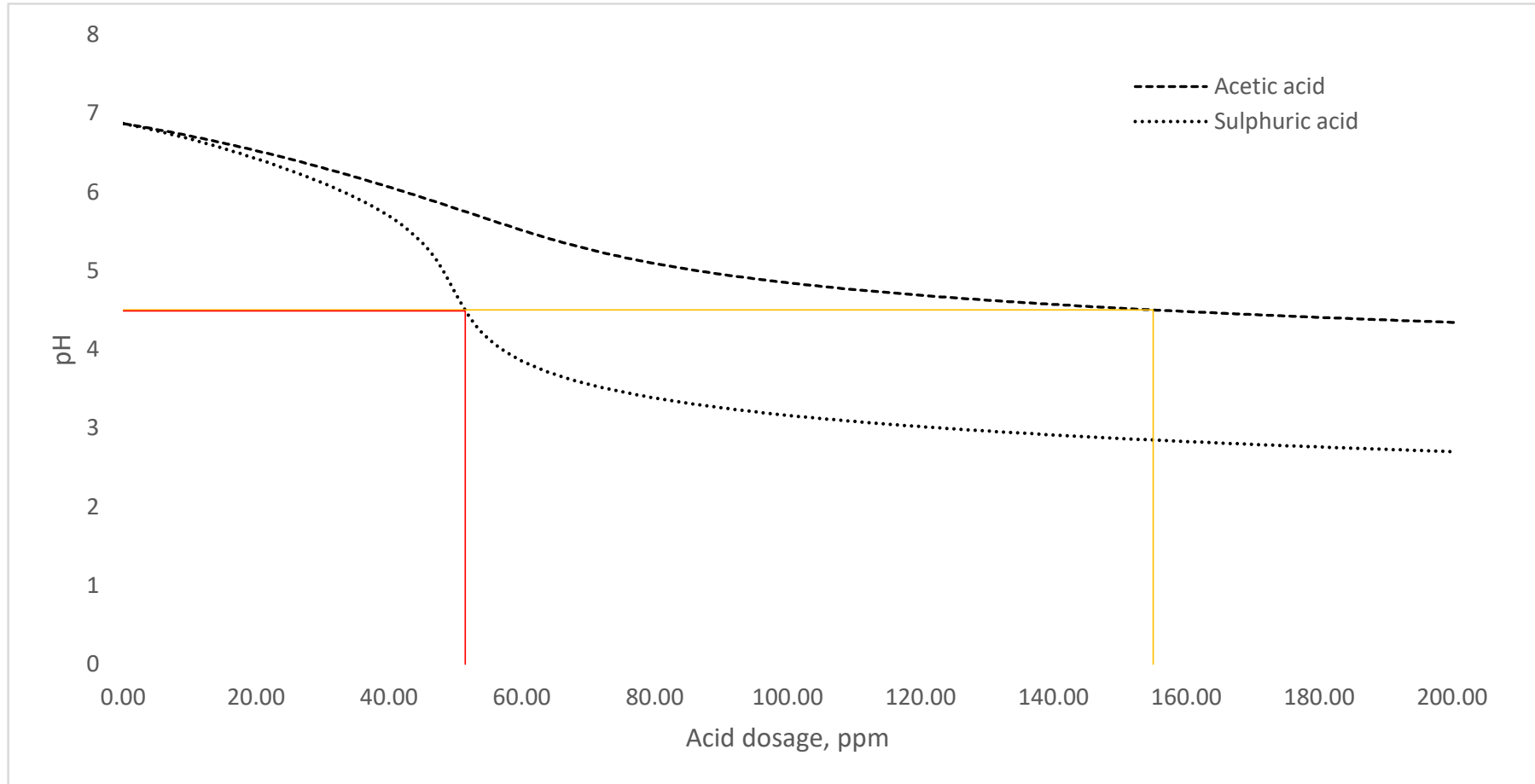
- Lower flow rate than optimal -> pH target is not achieved, scaling risk
- Higher flow rate than optimal -> Sensible pH decrease, corrosion risk

For acetic acid:

- More manageable variation of the pH



3. PHASE 3 – DESIGN – SELECTION OF THE ACID – TITRATION CURVE



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3. PHASE 3 – DESIGN – SELECTION OF THE ACID

Item	Acetic acid	Sulphuric acid
Density [kg/m ³]	1050	1840
Viscosity [cP]	1.2	27.0
PROs	Moderate Corrosivity; Weak acid (Easy pH control)	Not Flammable; Less expensive
CONs	Flammable (ATEX zone 2) High melting point (> 16 °C)	High Corrosivity; Strong acid (Difficult pH control)
References in geothermal	Central America	Asia



3. CONCLUSION

- There is **no “standard solution”** for the optimization of a binary bottoming plant
- **Pilot testing** before the definition of the scaling management strategy is **highly recommended**
- An **automatic system** with **pH control** measurement gives the best results in terms of **safety and operability**, especially in case of strong acid



3. CASE STUDIES BY STEAM

- Supply of the **acid dosing system** to for **EDC Mindanao M3** 3.6 MW bottoming plant (Philippines)
- Supply of the **acid dosing system** to for **Northern Negros** 6 MW bottoming plant (Philippines)
- **Owner's Engineering** services for Polaris **San Jacinto ORC binary bottoming** 12 MW project featuring acetic acid injection and support to the testing of inhibitors (Nicaragua)
- **Geofluid management** geochemistry consultancy projects in Indonesia



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1. CHARACTERISTIC CURVE OF A PRODUCTION WELL



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1. CHARACTERISTIC CURVE OF A PRODUCTION WELL

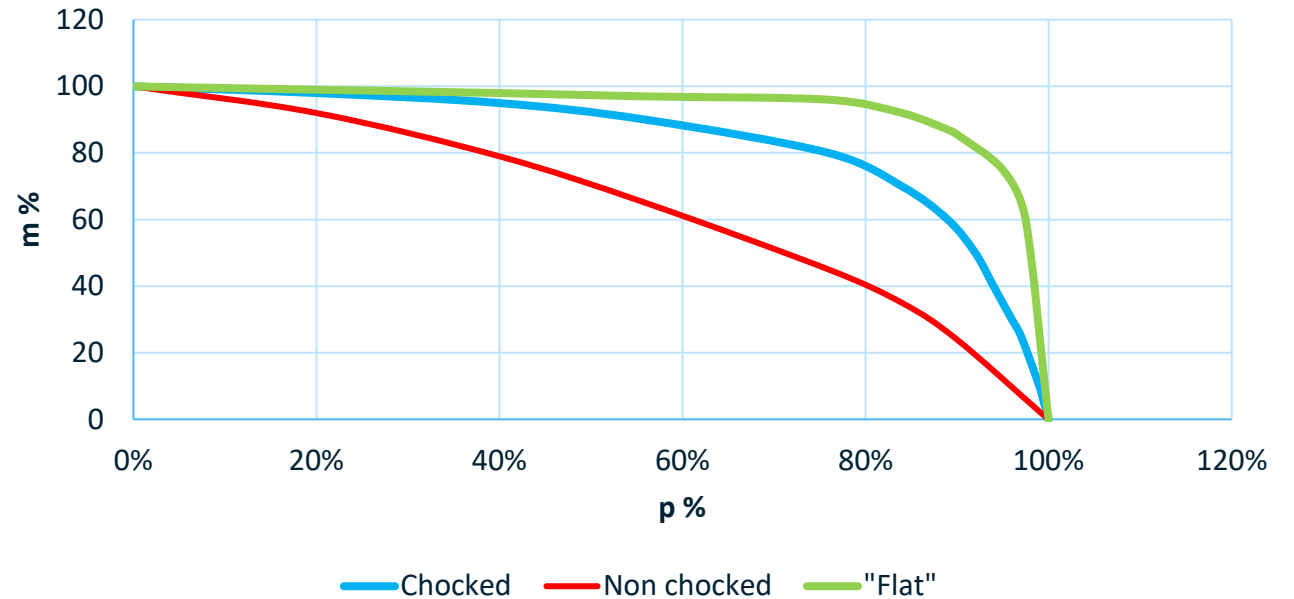
Geothermal wells feature production curves having maximum pressure where the flow is zero (closed valve) and maximum flow (choked flow) where the pressure is minimum.

Many wells do not reach their maximum flow rate unless at very low wellhead pressures (non-choked well flow).

Some wells experience a “flat” curve.

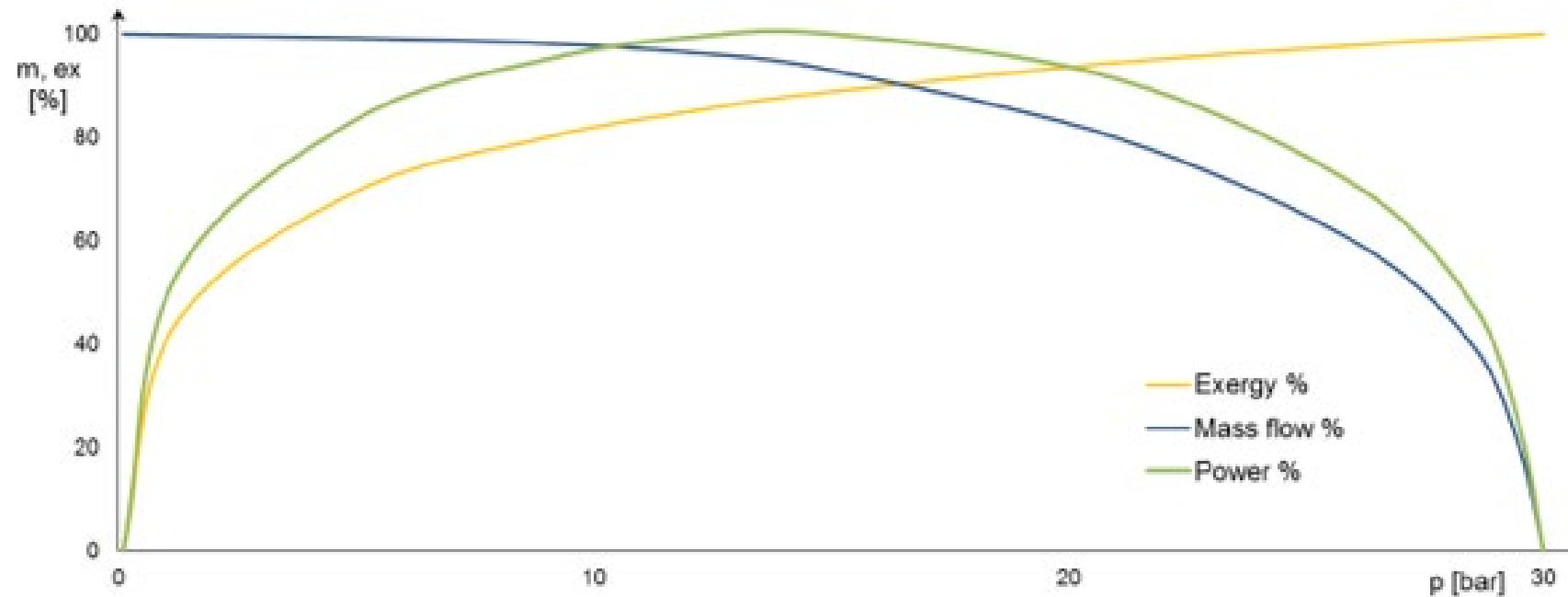
The shape of the production curve and pressure and mass flow values vary significantly from one reservoir to another.

Typical geothermal well production curves



1. CHARACTERISTIC CURVE OF A PRODUCTION WELL

The well production pressure can be optimized for maximizing the power production



2. PLANT GENERAL DESIGN



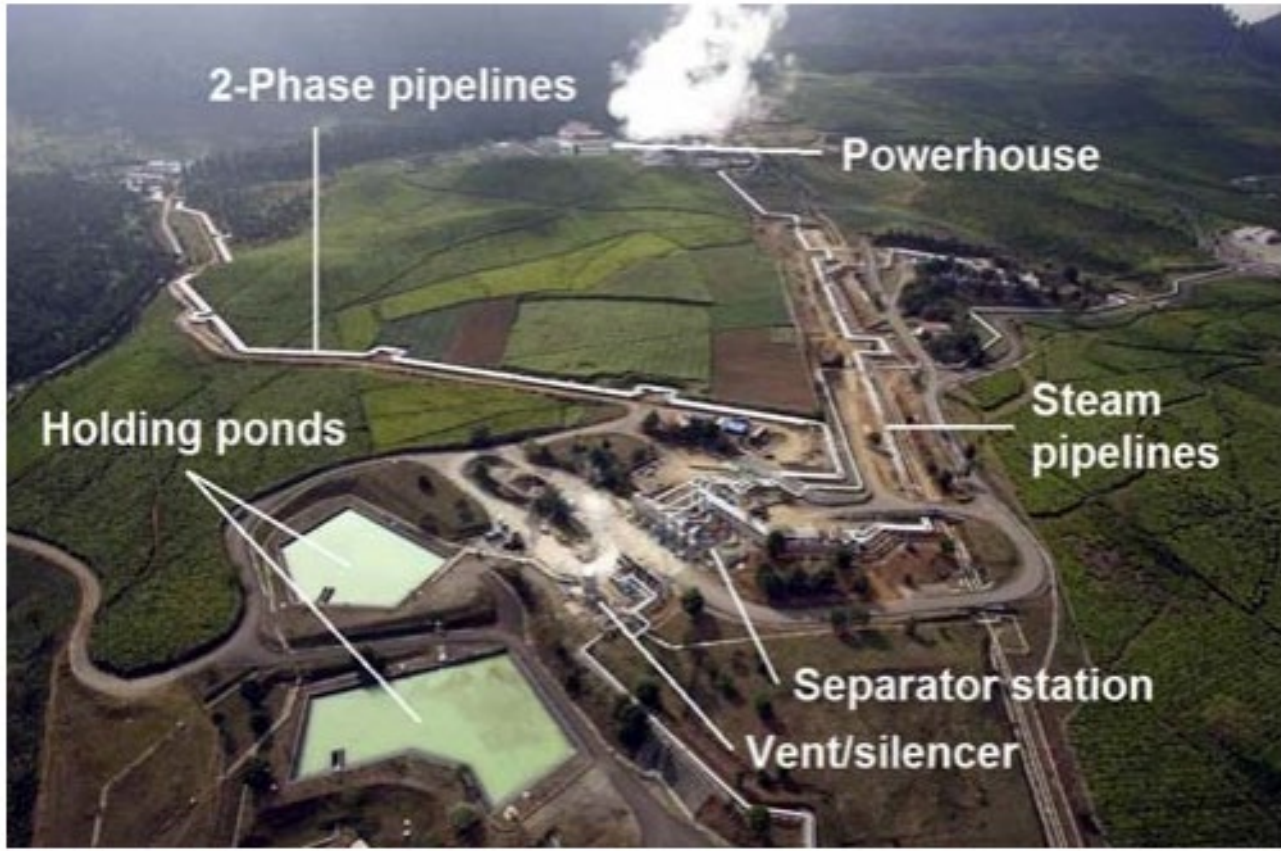
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2. PLANT GENERAL DESIGN

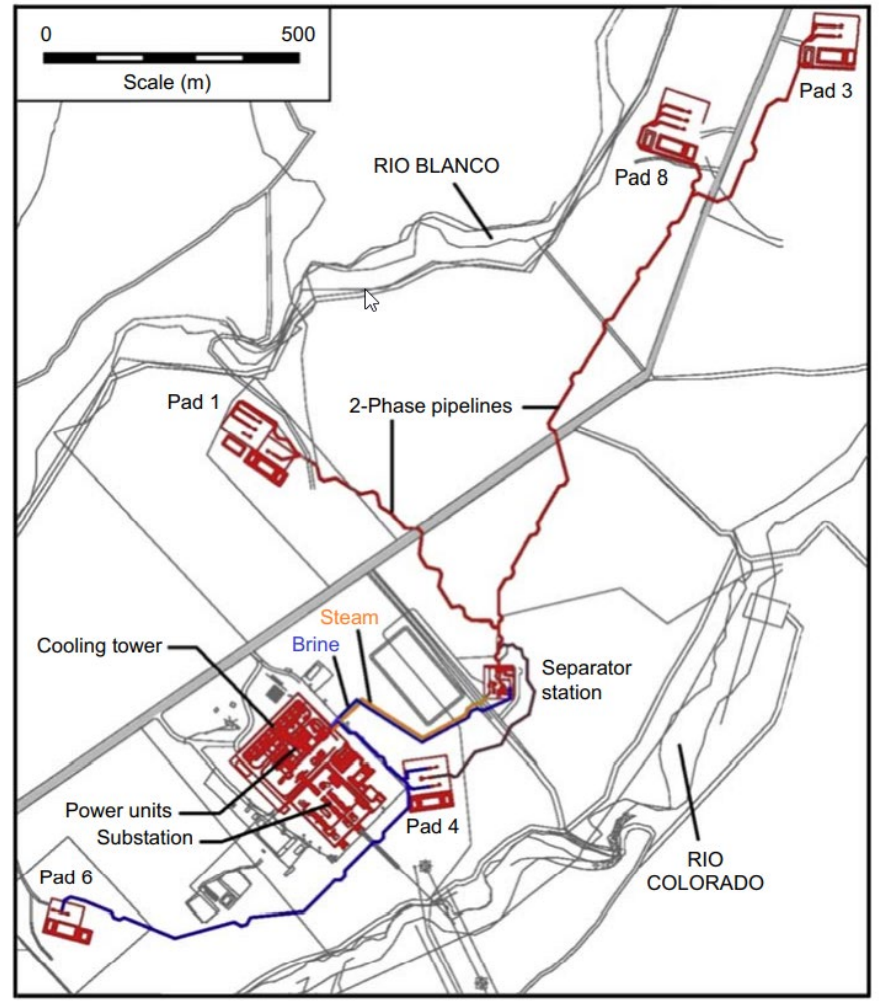
- A. Production Area
- B. Resource Gathering System
- C. Power Plants
- D. Reinjection area
- E. Substation
- F. Balance of Plant



2. PLANT GENERAL DESIGN



Wayang Windu single-flash power plant, Java, Indonesia



Las Pailas geothermal plant
Guanacaste Province, Costa Rica

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2.A PRODUCTION AREA - WELLPAD

Geothermal energy must be used close to the reservoir since the hot water and steam lose much of their stored energy when transported over long distances via pipelines.

A Production Well Pad is usually composed of:

- One or more than one well and relevant wellhead assembly
- Atmospheric flash tank (AFT) with or without a weir box
- A pond where to collect the discharged liquid from the AFT
- Piping connecting the well/s to the AFT
- Piping leaving the well pad to convey the fluid to the separation station (or to the power plant in case of a dry steam reservoir)



2.A PRODUCTION AREA – SEPARATION AND VENT STATION

A Separation Station is usually composed of:

- one separator or more
- one brine tank or more if the water fraction is very high
- atmospheric flash tank (AFT) with or without a weir box
- A pond where to collect the discharged liquid from the AFT
- Steam pipes leaving the separation station
- Brine line leaving the separation station
- Pipes connecting the separator to the AFT

A Vent Station is usually composed of one rock muffler or more.



2.B RESOURCE GATHERING SYSTEM

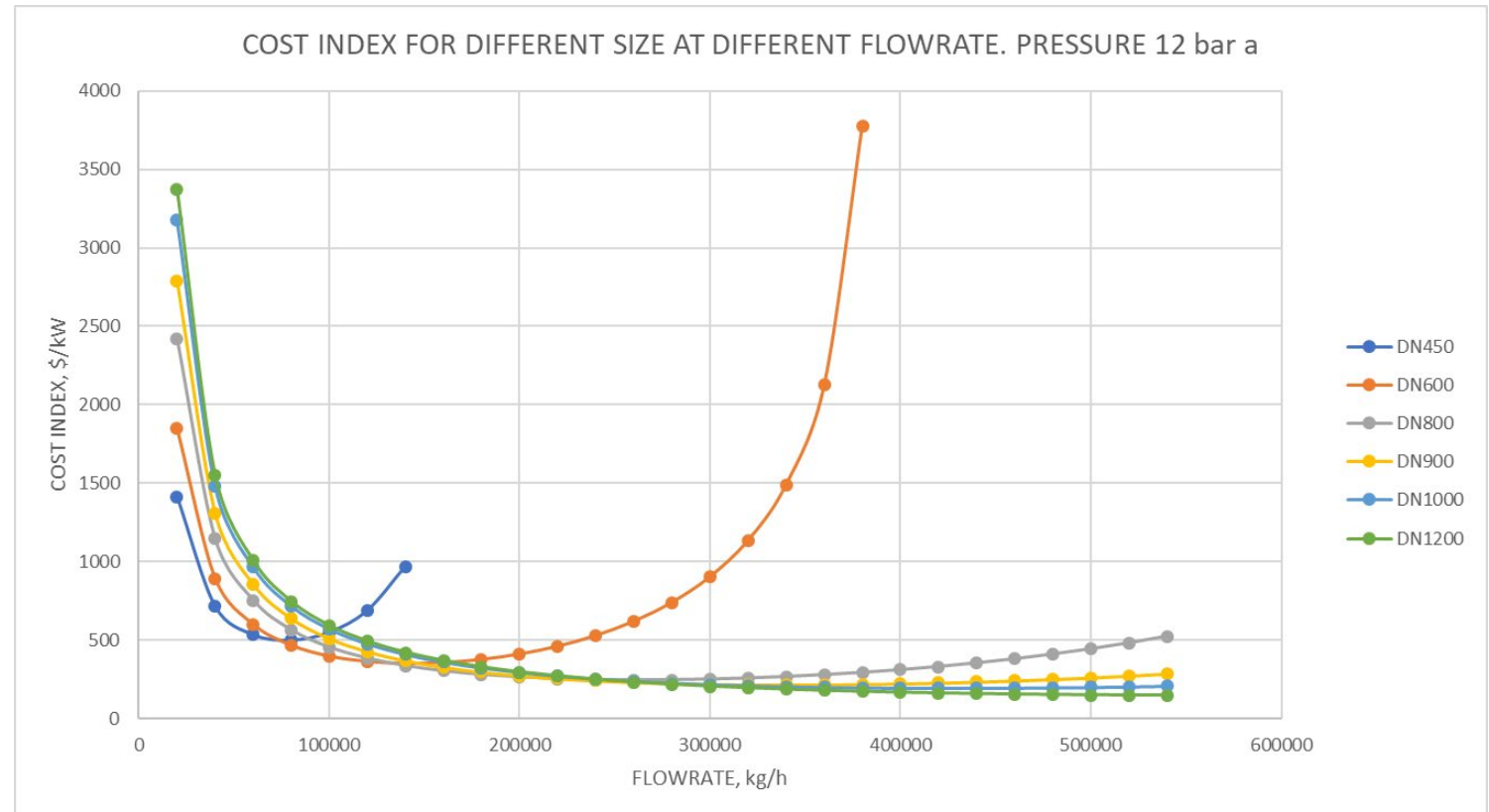
The piping system gathers and delivers the geofluid from wells, which may be scattered widely across the field, to a central point where the power station is constructed and to the reinjection well.

The system includes many elements, such as valves of all sizes and types, straight pipes, and elbows, ...

Site terrain plays a vital role in the layout and design of the piping system due to **gravity**.

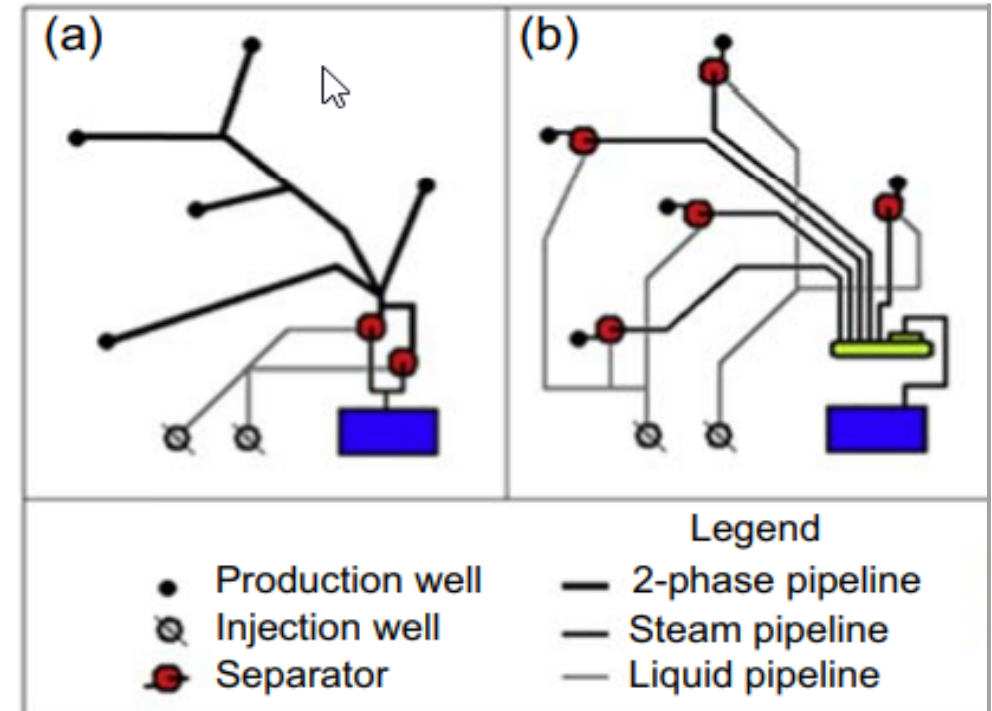
There are many options for conveying the geofluid from wells to power plants. The balancing of thermodynamics and economics gives the optimal solution.

- $\Delta P \downarrow$ to preserve the power potential of geofluid
- $D_{\text{pipe}} \uparrow$ to avoid high-pressure losses, but the cost \uparrow
- $D_{\text{pipe}} \downarrow$ to decrease costs but $\Delta P \uparrow$ velocity \uparrow erosion \uparrow



2.B RESOURCE GATHERING SYSTEM

- For example, many plants use two-phase, liquid-vapor pipelines from each well to a separator station near the powerhouse. This works well when the wellheads are higher in elevation than the powerhouse.
- The opposite alternative has separators at each well with steam lines running to the powerhouse and liquid pipelines to reinjection wells.
- By using satellite separator stations in the well field, various combinations are possible.



2.C POWER PLANT

Based on the type of resource, several types of energy conversion equipment are available:

- Dry steam system → Steam Turbine → In this case steam must be purged of any impurities and liquids.
- Liquid-dominated system → Flash plant or binary plant with Steam turbine or organic-fluid turbine.

The exact characteristics of the geofluid and the local conditions will determine which of the many conversion system options is best for any given prospect.

Since it is unlikely that all the wells that initially feed the plant will last the entire lifetime of the electromechanical equipment, replacement wells will need to be drilled. This sets geothermal plants apart from conventional plants in which a continuous supply of fuel is available and where only the electromechanical equipment need to be monitored and maintained.



2.D REINJECTION SYSTEM

It consists of reinjecting waste geofluids in reinjection wells. They can be divided into two categories:

- Disposal wells: they are located quite far from the production zone. While they may contribute to maintaining pressure in the reservoir, most likely the fluid will move away from the reservoir and never be seen again.
- Recharge wells: wells are judiciously sited within the production zone and are intended to replace some of the fluid being withdrawn via the production wells.

It is potentially challenging to locate them so that they will not interfere with producing wells, together with a requirement for full reinjection; hence the power developed from a given field can be restrained by a lack of sufficient reinjection capability, regardless of the ability of production wells.

2.D REINJECTION WELLPAD

A (Cold Or Hot) Reinjection Well Pad is usually composed of:

- one or more wells and relevant wellhead assembly
- atmospheric flash tank (AFT) with or without a weirbox
- a pond where to collect the discharged liquid from the AFT
- piping connecting the well/s to the AFT
- piping entering the well pad to convey the fluid to wells



2.D SUBSTATION

A substation will be required as part of most geothermal power stations, to transform the generated electrical power to a voltage suitable for transmission and provide switching, protection and connection facilities for the generators and transmission circuits.



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2.E BALANCE OF PLANT

Geothermal steam contains H_2S , which is generally vented to atmosphere. When the plant is built in nations which have emissions limits, abatement systems for the vented NCGs are installed.

Some of the H_2S abatement techniques used include:

1. Incinerators or regenerative thermal oxidation, when the NCGs contain sufficient flammable constituents such as H_2S , H_2 , or CH_4 . The burner/scrubbers at The Geysers, and the AMIS systems at Larderello are examples of these processes.
2. Liquid redox methods, which convert H_2S to elemental sulfur, which is disposed of as a solid. These methods would include the Stretford systems at The Geysers and LO-CAT at Coso in California.
3. BIOX, which uses biocides in the cooling water to convert H_2S to water-soluble sulfates. This technique is used at the John Featherstone plant in the Salton Sea.
4. Separation/injection where H_2S is removed from the NCGs and reinjected to the reservoir. Experiments are under way at the Hellisheidi plant in Iceland for this technique.

Abatement equipment can be a major capital and operating cost burden.

Flammability of fluid used in the ORC binary plant can become problematic in case of fluid leakage to the outside. ATEX-compliant equipment must be used and a specific areas are identified based on the ATEX CLASSIFICATION (EN 60079-10-1).

