UNITED NATIONS
UNIVERSITY

GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensasvegur 9,
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Reports 2013
Number 20

GEOTHERMAL BINARY CYCLE POWER PLANT PRINCIPLES, OPERATION AND MAINTENANCE

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ABSTRACT

Binary cycle power plants play an important role in the world, generating electricity from low and medium temperature geothermal temperature resources. This report describes a thermodynamic model of a binary cycle power plant and its components. A basic binary cycle and a binary cycle with a recuperator for different turbine inlet pressures are modelled. How the addition of a recuperator in the cycle shifts the maximum point of turbine work output, increasing the turbine work output for a given reinjection temperature and helping when the reinjection temperature is limited by the geothermal water chemistry, is analysed. The report shows that Isopentane and n-Pentane are the working fluid options for the Berlin binary cycle power plant in El Salvador. The parasitic loads for wet and air cooling systems are influenced by the seasonal fluctuations of the ambient temperature. The maintenance of binary cycle power plants is highly influenced by different factors, such as the nature of the geothermal fluid used in the primary loop, the nature of the working fluid, the technology and location of the plant, climate and weather. The operation and maintenance in both Svartsengi and the Berlin binary cycle power plants are presented.

1. INTRODUCTION

Geothermal energy resources have often been associated with the movements of tectonic plate boundaries. El Salvador, a small country in Central America, with an area of 21,040 km^2 and a population of 6.2 million, is located on the Pacific coast of Central America along the “Pacific ring of fire” where the Cocos and the Caribbean plates interact. The volcanic activity and seismicity associated with the plates are important for geothermal potential development in the country. El Salvador was the first Central American country to exploit geothermal sources. Electricity generation using geothermal energy started in El Salvador in 1975. Development reached a total capacity of 204.2 MW. In El Salvador, the geothermal resource management, exploitation and production of geothermal energy was developed by LaGeo S.A. de C.V. and the installed capacity is distributed mainly in two geothermal fields: 95 MW in Ahuachapán geothermal field and 109.2 MW in Berlin geothermal field. Figure 1 shows the location of El Salvador in Central America, together with its geothermal fields.

FIGURE 1: Location of El Salvador in Central America and its geothermal fields

Geothermal fields, systems and reservoirs are classified by temperature, enthalpy and physical state, among other factors. According to the temperature classifications, geothermal sources vary from temperatures below 150°C to temperatures above 200°C, and can be a mixture of steam and water, mainly steam or mainly water. The temperature of the geothermal resource defines the type of technologies required to exploit the available heat and the utilization of the geothermal fields. As mentioned above, El Salvador has two geothermal fields; both are classified as high-temperature geothermal fields: Ahuachapán shows temperatures between 230 and 250°C and Berlin shows a temperature of 300°C. Generally, the high temperature fields are mainly exploited for the generation of electricity, as is the case in El Salvador. The technology utilized for exploiting the Ahuachapán geothermal field consists of two single flash condensing turbines and one double flash condensing turbine, while Berlin geothermal field utilizes three flash condensing turbines and one binary cycle power plant. A project for increasing the capacity of the Berlin power plant started in 2005. The plant now has an increased capacity by the addition of a 44 MW condensing unit and a 9.2 MW binary unit. The binary power unit has a source temperature of 180°C, obtained from the separated water of the production wells. The total installed capacity of El Salvador is forecast to be about 290 MW by 2015 (Bertani, 2012).

Electricity generation from geothermal energy made a modest start in 1904 at Larderello in the Tuscany region of northwest Italy with an experimental 10 kW-generator (Lund, 2004). Since then, there has been interest in developing and exploiting geothermal resources around the world and, today, electricity from geothermal energy (a worldwide renewable energy source) has grown to 10,898 MW in 24 countries, producing an estimated 67,246 GWh/yr. The development of worldwide geothermal power production can be seen in Figure 2. The number of geothermal countries is expected to increase from 24 in 2010 to 46 in 2015. Binary power plant technology plays a very important role in the modern geothermal electricity market (Bertani, 2012). The first geothermal binary power plant was put into operation at Paratunka near the city of Petropavlovsk on Russia's Kamchatka peninsula, in 1967. It was rated at 670 kW. It ran successfully for many years, proving the concept of binary plants as we know it today. Nowadays, binary plants are the most widely used type of geothermal power plant with 162 units in operation in May 2007, generating 373 MW of power in 17 countries. They constitute 32% of all geothermal units in operation, but generate only 4% of the total power. Thus, the average power rating per unit is small, only 2.3 MW/unit, but units with ratings of 7–10 MW are coming into use with advanced cycle design (DiPippo, 2007).

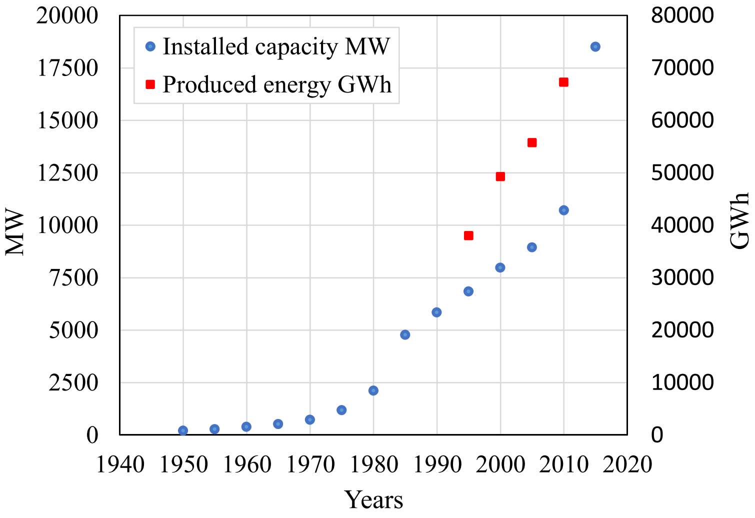


FIGURE 2: Development of worldwide geothermal power production (Bertani, 2012)

El Salvador has played a role in the worldwide development of binary power plants, with the first installed binary power plant in the country located in Berlin geothermal field. In this first unit, the organic Rankine cycle was used to generate electricity using Isopentane as a working fluid. The binary power plant was designed to utilize remnant heat from the geothermal water (waste brine) to evaporate Isopentane. This unit is currently producing electricity, however, there have been operational challenges causing tripping of equipment and even resulting in unit shut-down. Since the unit started running, maintenance and overhaul measures have been developed, and some modifications were executed on the equipment to ensure continuous operation of the plant at maximum capacity and efficiency. LaGeo has experience with this technology and is still learning about it. However, it has been a first great step for the development of electricity production using low and medium temperature geothermal energy in El Salvador.

2. GEOTHERMAL BINARY CYCLE POWER PLANTS

2.1 General characteristics of geothermal fields for utilization of binary cycle power plants

As mentioned in the introduction, the geothermal resource temperature defines the technologies required to exploit the available heat for the utilization of geothermal fields. Table 1 summarizes the classifications of geothermal fields, based on temperatures and physical states. Generally, the high temperature fields are mainly exploited for electricity generation, using dry steam and flash steam technologies. For medium and low temperature geothermal fields, binary cycle power plants show good performance. Nowadays, binary cycle power plants are the most common technology for utilizing low temperature geothermal sources for electricity generation.

TABLE 1: Classification of geothermal fields based on temperature and physical state (modified from Saemundsson, 2009)

Temperature classification	Physical state classification
Low-temperature geothermal fields have reservoirs with temperature below 150°C at a depth of 1 km. These fields are often characterized by hot or boiling springs.	Liquid-dominated geothermal fields with the water temperature below the boiling point at the prevailing pressure; the liquid phase controls the pressure in the reservoir. Some steam may be present.
Medium-temperature geothermal fields have reservoirs with temperatures between 150- 200°C at a depth of 1 km.	Two-phase geothermal fields where steam and water co-exist and the temperature and pressure follow the boiling point curve.
High-temperature geothermal fields have reservoirs with temperature above 200°C at a depth of 1 km. The fields are characterized by fumaroles, steam vents, mud pools and highly altered ground.	Vapour-dominated geothermal fields where temperature is above the boiling point at the prevailing pressure and the vapour phase controls the pressure in the reservoir. Some liquid water may be present.

In a geothermal binary cycle power plant, the thermal energy of the geothermal fluid is transferred through a heat exchanger from the geothermal fluid to the working fluid which is then vaporized and used to run the turbine coupled to a generator to produce energy. The geothermal and working fluids are confined in separate systems and never come into contact. In this way, the geothermal fluid does not contact the moving parts (mainly the turbine and all rotary equipment in the power plant), thus reducing the negative effects of potential scaling and erosion observed when the geothermal fluid is used as a working fluid. Most binary cycle power plants operate with pumped wells. The pumps are located below the flash level in a well to prevent flashing by raising the pressure above the saturation pressure for fluid temperature (Elliott et al., 1998).

Binary cycle power plants can be used to generate additional electricity from the geothermal fluid after its utilization in flash power plants. Such binary cycle power plants are known as bottoming plants. With the inclusion of a binary cycle in the geothermal system, the total energy efficiency increases. The geothermal water (brine) exiting from the primary utilization still has sufficient potential to produce turbine work output using a binary power unit as a bottoming cycle for the overall plant. No additional well costs are associated with such electricity generation from binary power plants.

Electricity can now be generated from resources below 100°C where the binary power plant using an organic Rankine cycle process is used in combination with other utilization, as in district heating projects (Lund, 2004). Binary cycle power plants are useful for harnessing low and medium temperature resources and raising the exploitability of geothermal potential worldwide (Bertani, 2012).

2.2 El Salvador geothermal power plants

The major utilization of geothermal energy in El Salvador is for power generation, but some direct uses have been implemented on a small scale, such as for drying grains and fruits. At present, there are two geothermal fields with power plants in operation in El Salvador: Ahuachapán and Berlín. The temperatures in these fields are 230°C in Ahuachapán and 300°C in Berlin. The depth range for the wells varies from 800 m in the shallow areas of Ahuachapán to 2,800 m in Berlin.

Geothermal energy production in El Salvador first started in 1975 at Ahuachapán. Ahuachapán has three condensing units, two 30 MW single flash units and one 35 MW double flash unit. The separated water from the production wells is totally re-injected into the field, using pumps. The pumping station is knowing as RTA.

Berlin started production in 1992 with two back pressure units of 5 MW each. Currently, Berlin has four units, two 28 MW condensing - single flash units, one 44 MW condensing – single flash unit and one 9.2 MW binary unit used as a bottoming plant. To generate electricity from this binary unit, the separated water is used as a heat source. After heat removal from the separated water coming from the production wells, the separated water is totally re-injected into the reservoir. The reinjection is done using pumps and gravity. The pumping station is known as RTB. Currently the total installed capacity is 95 MW in Ahuachapán and 109.2 MW in Berlin.

In Berlin, the amount of additional power that could be generated from the separated water in a binary unit depends on how much heat can be removed from the separated water before scaling becomes a problem. The geothermal water from Berlin's liquid dominated reservoir has about 1% of total dissolved solid (TDS) with an appreciable amount of calcium and boron (100 to 200 ppm). When the water is separated in cyclone separators at 10 bars and 185°C, the water contains 800 ppm of silica. And for this condition, the separated water has a silica saturation index (SSI) of 0.95 %. Additionally, when the separated water is cooled, the SSI increases, for example to 1 at 180°C and to 2.2 at 100°C (at 2.2, silica is oversaturated). A research study was conducted to minimise the scaling potential in the re-injection system, and the results recommended 130°C as the lowest temperature value and implementing acid dosing to maintain a pH between 5.5 and 6.0 (SKM, 2004).

3. BASIC BINARY CYCLE

The concept of a binary cycle power plant, known as an organic Rankine cycle (ORC), is a modification of a Rankine cycle where the working fluid is an organic fluid which has a lower boiling point and higher vapour pressure than water along all state points that compound the thermodynamic cycle.

The geothermal binary cycle power plant is formed by two cycles: the primary cycle that contains the geothermal fluid, and a secondary cycle where the organic working fluid is enclosed. The primary cycle starts at the production wells and ends in the re-injection wells. In the primary cycle, the temperature and the desired flow rates of geothermal fluid are determined by the reservoir´s field properties. The geothermal fluid can be either water or steam. When the geothermal fluid is water or brine, it is kept at a pressure above its flash point at fluid temperature along the primary cycle in order to avoid flashing of geothermal fluid in the heat exchangers. The geothermal fluid temperature, at the end of the primary cycle, is not allowed to drop to the silica scaling point.

The main components of a basic geothermal binary cycle power plant are the preheater, evaporator, turbine, condenser and working fluid pump. The schematic diagram in Figure 3 shows the main components of the cycle. The basic thermodynamic process of binary cycles is the Rankine cycle, where the vapour reaches a dry saturated condition in the evaporator and is condensed in the condenser. A simple method for describing a binary power cycle is to follow the T-s diagram shown in Figure 4. The thermodynamic states of the working fluid in the secondary cycle are shown in the P-h diagram in Figure 5. Such a diagram helps in understanding the thermodynamic cycle and different states of the working fluid.

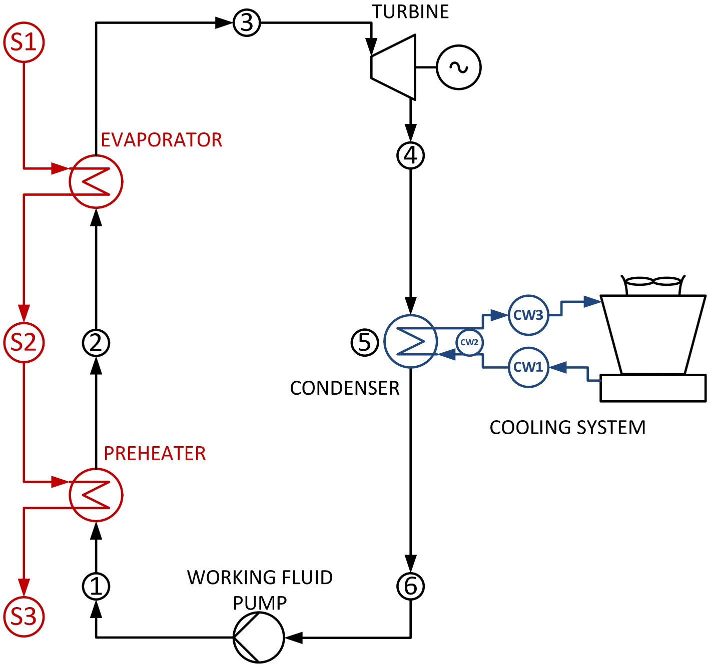


FIGURE 3: Schematic diagram of a basic binary power cycle

The binary cycle (Figure 3) consists of the following four processes:

6 – 1	Isentropic compression in the working fluid pump;
1 – 2 – 3	Constant pressure heat addition in preheater and evaporator;
3 – 4	Isentropic expansion in a turbine; and
4 – 5 – 6	Constant pressure heat rejection in a condenser.

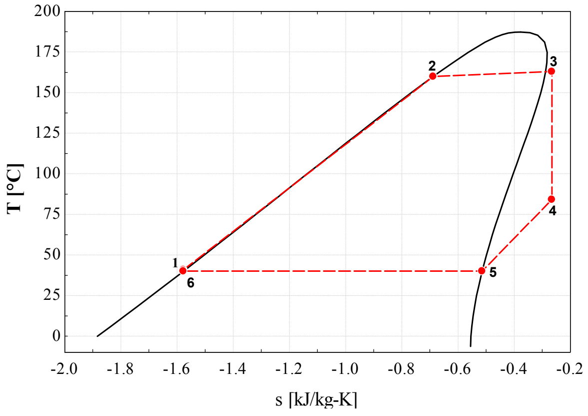


FIGURE 4: T-s diagram for a binary cycle using Isopentane as a working fluid

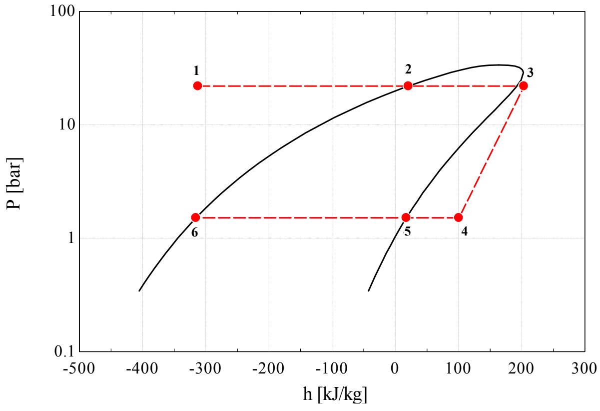


FIGURE 5: P-h diagram for a binary cycle using Isopentane as a working fluid

In the secondary cycle, the working fluid enters the pump at state 6 as a saturated liquid and is compressed isentropically to the operating pressure of the evaporator. The working fluid temperature increases during the isentropic compression process, due to a slight decrease in the specific volume of the working fluid. The working fluid enters the preheater as a compressed liquid and leaves the evaporator as a saturated vapour at state 3. Typically, in the heating-evaporating process, in the preheater the working fluid is delivered to its boiling point. The preheater and evaporator are basically large heat exchangers where the heat coming from the geothermal fluid is transferred to the working fluid at a constant pressure. The evaporator is the section where the working fluid is vaporized at a constant temperature. This saturated condition ensures that no liquid droplets enter the turbine. The saturated vapour at state 3 enters the turbine where it expands isentropically and produces work by rotating the turbine shaft connected to an electric generator. The pressure and the temperature of the vapour drop during this process to the values at state 4, where vapour enters the condenser. At this state, vapour is usually superheated. In the condenser, vapour is condensed at a constant pressure by rejecting heat into the environment. The working fluid leaves the condenser as saturated liquid and enters the working fluid pump, completing the cycle. The efficiencies of the turbine and the working fluid pumps modify the expansion and compression process and are used to determine the real work in both components.

Binary cycle power plants can be cooled by water or air; these methods of cooling are called wet and air cooling systems, respectively. In areas where water is valuable, and/or not easily accessible or conserved, dry cooling systems are used.

It is important to note that the area under processes 1-2-3 represents the heat transferred to the working fluid in the preheater and evaporator, and the area under the processing curve of states 4-5-6 represents the heat rejected in the condenser. The difference between these two areas is the network produced by the cycle (the area enclosed by the cycle curve).

4. BINARY CYCLE COMPONENTS AND ENERGY ANALYSIS

All five components associated with the basic binary cycle (preheater, evaporator, turbine, condenser and pump) are steady flow devices and can be analysed as steady flow processes. In this analysis, the kinetic and potential energy changes are usually small relative to the work and heat transfer terms and are usually neglected. The heat exchangers do not involve any work, and the pump and the turbine are assumed to be isentropic. The heat exchangers are assumed to be well insulated, and all the heat transfer is between the geothermal fluid and the working fluid. The following presents the main equations for energy analysis along with a short discussion of the main components.

4.1 Preheater and evaporator

The preheater and evaporator (Figure 6) are the first components in a binary power cycle. They receive the fluid from the geothermal production wells. These components are heat exchangers where the geothermal fluid, as a heat source, transfers some of its energy to the cold working fluid of the binary cycle.

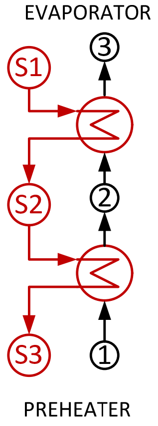


FIGURE 6: Schematic diagram for a preheater and evaporator

Point S1 is the entry of the geothermal fluid to the evaporator; at this point, the temperature and mass flow of the fluid are determined by the geothermal reservoir properties. Point S3 is the outlet of the geothermal fluid from the preheater and this point has two temperature design criteria. The first criterion is applied when the fluid coming from the preheater is considered for further utilization. A good example of this is in a district heating system, with an inlet temperature of around 80 - 85°C. The second criterion is associated with scaling problems; the outlet temperature must be kept as high as possible in order to avoid scaling on the geothermal fluid side in the heat exchangers.

Point 1 is the entry of the working fluid, fed by the working fluid pump, into the preheater; point 3 is the outlet of the working fluid vapour towards the turbine. The condition at point 3 is determined by the cycle and turbine requirements; for a binary cycle, this point would be saturated or slightly superheated.

Considering the entire package as a thermodynamic system where the amount of heat transfer to the working fluid is equal to the heat losses from the geothermal fluid, the energy balance equation is given as:

$$\dot{m}_{gf}(h_{S1} - h_{S3}) = \dot{m}_{wf}(h_3 - h_1) \tag{1}$$

where $\dot{m}_{gf}$ = Mass of geothermal fluid;
$\dot{m}_{wf}$ = Mass of working fluid; and
h = Values of enthalpies at each specific point.

If the heat capacity of the geothermal fluid is assumed to be known, in the energy balance the enthalpy difference may be replaced by the difference in temperature:

$$\dot{m}_{gf}Cp_{gf}(T_{S1} - T_{S3}) = \dot{m}_{wf}(h_3 - h_1) \tag{2}$$

where Cp_{gf} = Specific heat of geothermal fluid; and
T = Temperatures at each specific point.

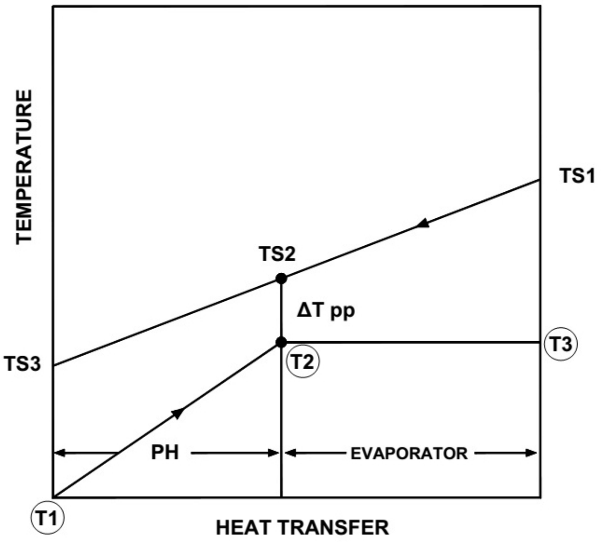


FIGURE 7: Temperature – heat transfer diagram for preheater (PH) and evaporator; Points 1-2-3 correspond to T1, T2 and T3 and are known values obtained from the working fluid process

The temperature-heat transfer or temperature-enthalpy difference diagrams play a central role in the design of heat exchangers (preheater, evaporator and condenser). Figure 7 provides a diagram for a hot geothermal fluid and a cold working fluid in the preheater and evaporator. The hot fluid must be cooled from the inlet temperature (TS1) to the outlet temperature (TS3), whereas the cold working fluid must be heated from the inlet temperature (T1) to the outlet temperature (T3). The direction of these processes is indicated by the arrows in the figure. The temperatures and mass flow rates are assumed to be fixed. The abscissa represents the total amount of heat that is passed from the geothermal fluid to the working fluid. It can be shown either in percentages or in heat units. The minimum temperature difference in the heat exchanger, between the geothermal fluid and the working fluid, is called the pinch-point, and the value of that difference is designated the pinch-point temperature difference, ΔTpp. In the analysis of this diagram, points 1, 2 and 3 are known from the cycle thermodynamics analysis. Therefore, the preheater and evaporator may be analysed as follows:

Preheater

$$\dot{m}_{gf}Cp_{gf}(T_{S2} - T_{S3}) = \dot{m}_{wf}(h_2 - h_1) \tag{3}$$

Evaporator

$$\dot{m}_{gf}Cp_{gf}(T_{S1} - T_{S2}) = \dot{m}_{wf}(h_3 - h_2) \tag{4}$$

The pinch-point temperature difference is generally known from the manufacturer's specifications; this allows TS2 to be found from the known value for T2 as follows:

$$T_{S2} = T_2 + \Delta T_{pp} \tag{5}$$

where ΔT_{pp} = Pinch-point temperature difference.

While it is theoretically possible for the pinch-point to occur at the cold end of the preheater (TS3), this practically never happens (DiPippo, 2007).

4.2 Turbine

The binary cycle turbine converts the vapour thermodynamic energy of the working fluid to mechanical work on the turbine shaft; this shaft is coupled to the generator where electricity is produced. The thermodynamic analysis of the turbine in binary cycles follows the same assumption as for steam turbines. Figure 8 show the turbine from the cycle flow diagram for reference in the following analyses. Point 3 is the vapour inlet to the turbine, and point 4 is the turbine exit. The ideal turbine is isentropic, that means the entropy at the inlet point is the same as at the outlet point. The vapour enthalpy change in the real turbine is the enthalpy change in the ideal turbine multiplied by the turbine isentropic efficiency. The work output of the real turbine is this enthalpy change multiplied by the working fluid mass flow through the turbine.

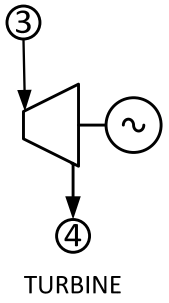


FIGURE 8: Schematic diagram for a turbine

$$\dot{W}_T = \dot{m}_{wf}(h_3 - h_4) = \dot{m}_{wf}\,\eta_t\,(h_3 - h_{4s}) \tag{6}$$

where $\dot{W}_T$ = Work output of the turbine; and
η_t = Turbine isentropic efficiency.

It is important to note that the selection of the working fluid defines some parameters in the turbine design.

4.3 Condenser

The condenser is another heat exchanger in the binary cycle. The condenser exchanges heat between the cooling fluid cycle and the working fluid vapour. The turbine exhaust vapour exits the turbine and is led to the condenser where it is condensed by the cooling fluid. The condenser may be water or air cooled. This process occurs at a constant pressure (isobaric condensation).

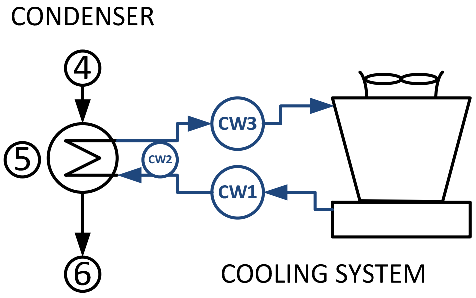


FIGURE 9: Schematic diagram for a condenser and a wet cooling system

Figure 9 shows the condenser scheme from the cycle flow diagram for reference in the following analyses. The calculations for the condenser are roughly the same in both cases as the temperature profile of cooling fluid (air or water) is very close to linear. At point 4, the vapour comes from the turbine. At point 5, the vapour reaches the dew point and it is at this point that the condensation process starts. Point 6 is the condensed fluid, normally saturated liquid, moving towards the working fluid pumps. Point CW3 is the entry of the cooling fluid and CW1 is the outlet of the cooling fluid, to and from the cooling tower.

The condenser heat transfer between the working fluid and the cooling fluid can be expressed as follows:

$$\dot{m}_{CF}\,(h_{CW3} - h_{CW1}) = \dot{m}_{wf}(h_4 - h_6) \tag{7}$$

where $\dot{\boldsymbol{m}}_{\boldsymbol{CF}}$ = Mass of cooling fluid.

The cooling fluid may be taken as having a constant specific heat $C_{P\text{-}CF}$ for the small temperature range from inlet to outlet. To dissipate the required amount of waste heat, a cooling tower with a specified range, TCW3 – TCW1, will need a mass flow rate determined by the following equation:

$$\dot{m}_{CF}\ C_{P-CF}(T_{CW3} - T_{CW1})\ = \dot{m}_{wf}(h_4 - h_6) \tag{8}$$

where $\boldsymbol{C_{P-CF}}$ = Specific heat of cooling fluid.

In the thermodynamics analysis of the condenser, the increase in the outlet temperature of the cooling fluid and the condenser pinch point temperature are assumed.

4.4 Binary cycle with a recuperator

The binary cycle can be modified with the incorporation of a recuperator. The recuperator is another heat exchanger and represents one additional piece of equipment in the binary cycle power plant. The incorporation of a recuperator is shown in Figure 10. The figure shows the position of the components in the cycle. The recuperator increases the temperature of the working fluid at the preheater entry (point 2) and thus leads to a higher temperature (point S3) of the geothermal fluid for re-injection. This means that the heat obtained from the geothermal fluid is replaced by the recovered heat. The recovered heat in the working fluid, at point 2, is removed from the working fluid at the turbine exhaust condition, at point 5.

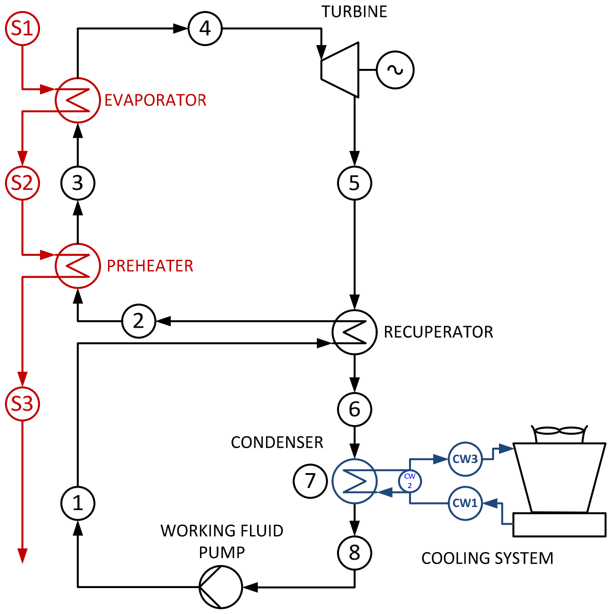


FIGURE 10: Schematic diagram of the binary power cycle with a recuperator

As mentioned in Section 4.1, point S3 is the outlet of the geothermal fluid from the preheater. This point has design temperature limits imposed by the risk of scaling or the requirements of a secondary process.

In this report, the EES computer program was used for thermodynamic calculations for different cycle simulations. This program is a general equation solver that solves thousands of algebraic and differential equations. The program provides a high accuracy thermodynamic property database for the fluids used in this research (F-Chart Software, 2012).

Figures 11 and 12 show the simulation results for a basic binary cycle and a binary cycle with a recuperator for different reinjection temperatures. The simulation for both cycles was done using Isopentane and n-Pentane as a working fluid with an inlet temperature of 180°C geothermal fluid. For the calculations, 221 kg/s of geothermal fluid and 40°C as a condensing temperature were assumed. In the recuperator, the available heat is the heat which can be removed from the turbine exit vapour until the vapour reaches the dew point. After that, the vapour temperature is the same as the condensation temperature and the recuperation process is complete. The calculation is based on an ideal binary cycle.

The addition of a recuperator causes no change in the maximum turbine work output of the binary cycle, as shown in Figures 11 and 12. The recuperation process does not increase the turbine work output, but the efficiency increases as a result of less heat input from the geothermal fluid (Valdimarsson, 2011).

The addition of a recuperator, however, causes a shift in the maximum point of turbine work output of the cycle with respect to the reinjection temperature.

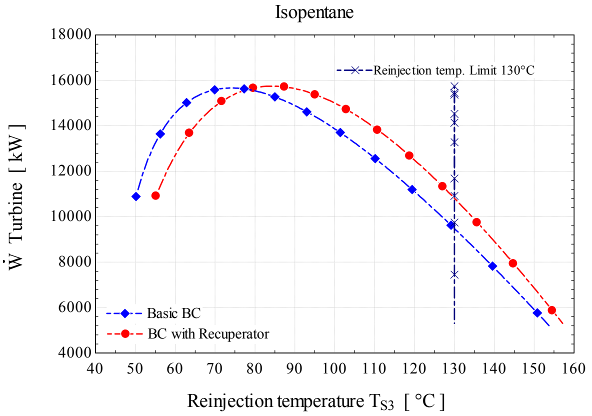


FIGURE 11: Variation of turbine work output with reinjection temperature for Isopentane

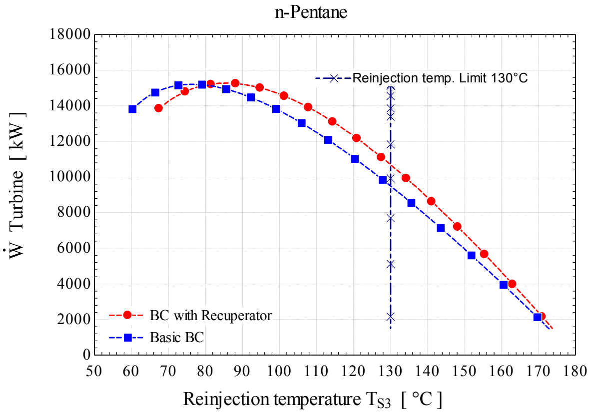


FIGURE 12: Variation of turbine work output with reinjection temperature for n-Pentane

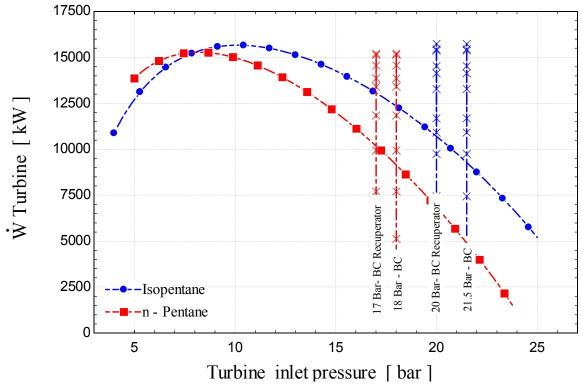


FIGURE 13: Turbine work output against turbine inlet pressure for Isopentane and n-Pentane at the same reinjection temperature (T_{S3} = 130°C)

As shown in the figures, for the Isopentane, the maximum turbine work output point is moved 20°C and the re-injection temperature is moved from 65°C to 85°C. And for n-Pentane, the maximum point is moved 10°C and the reinjection temperature is moved from 75°C to 85°C.

When the reinjection temperature is limited by the geothermal water's chemistry, adding a recuperator serves to increase the turbine work output for a given reinjection temperature. Figures 11 and 12 show that the turbine work output increases by 15% at 130°C reinjection temperature. Figure 13 shows the pressure value that fits for 130°C when Isopentane and n-Pentane are used in a basic binary cycle and a binary cycle with a recuperator.

Figures 14 and 15 show the simulation results of a basic binary cycle and a binary cycle with a recuperator for different turbine inlet pressures. The simulation uses the same parameters and

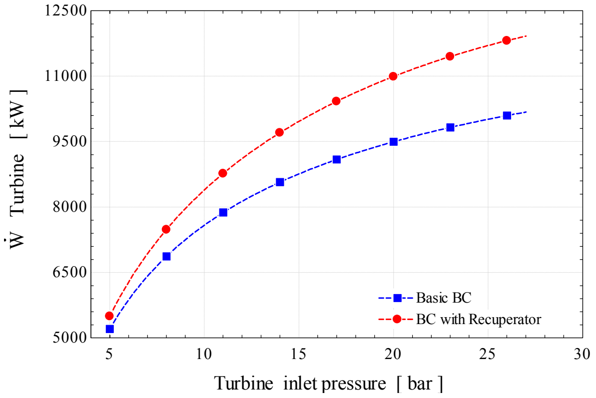


FIGURE 14: Variations of turbine work output with turbine inlet pressure for Isopentane

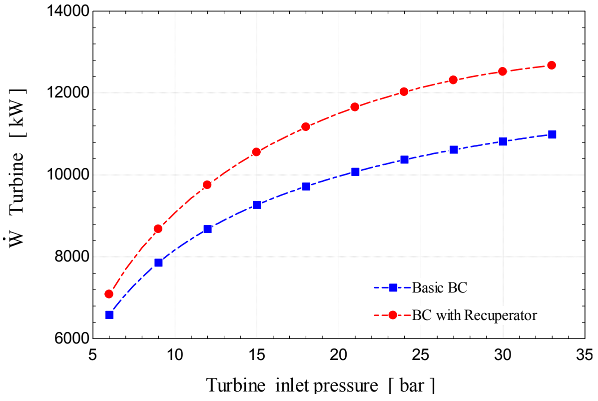


FIGURE 15: Variation of turbine work output with turbine inlet pressure for n-Pentane

assumptions as for the previous simulation and at a constant reinjection temperature of 130°C. With a constant reinjection temperature in both simulations, the same amount of available heat that could be exchanged in the preheater and the evaporator was simulated.

4.5 Heat exchanger sizing and estimated equipment cost

The geothermal binary cycle requires different sizes of heat exchangers for heat transfer processes. Each heat exchanger has its own ability to exchange the amount of heat according to its function during the process and it is this amount of heat exchange which defines the size of the equipment. The size of the heat exchanger is expressed in terms of the area needed to exchange heat, expressed in m^2. The heat transfer in the heat exchangers involves the concepts of convection and conduction and, for determining the area of the heat exchanger, it is convenient to work with the total heat transfer coefficient U that considers the effect of these two concepts (Table 2). Additionally, the log mean temperature difference (LMTD) method is applied to determine the heat transfer area.

TABLE 2: Values assumed for the total heat transfer coefficient (Ahangar, 2013)

Component	**U (W/m^2°C)**
Preheater	1000
Evaporator	1600
Recuperator	400
Condenser	800

The area of the heat exchanger surfaces (A), expressed in terms of the rate of heat transfer (Q), the heat transfer coefficient (U) and the log mean temperature difference (LMTD), can be written as follows:

$$A = \frac{Q}{U * LMTD} \tag{9}$$

and

$$LMTD = \frac{\Delta T1 - \Delta T2}{\ln(\frac{\Delta T1}{\Delta T2})} \tag{10}$$

where $\Delta T1$ = Temperature difference between the fluids at the inlet of the heat exchanger; and
$\Delta T2$ = Temperature difference between the fluids at the outlet of the heat exchanger.

Table 3 shows the values for the areas for heat exchangers used in a basic binary cycle and a binary cycle with a recuperator. These areas were calculated assuming Isopentane as a working fluid, the geothermal fluid temperature available at 180°C, a mass flow rate of 221 kg/s and 40°C as a condensing temperature.

The cost for the heat exchangers used in a binary cycle with a recuperator, compared with a basic binary cycle, follows the heat exchanger area. For an investment in heat exchangers for a binary cycle with recuperator, considering the energy cost at 120 $/MW and the operation and maintenance cost at 5% of annual income, the payback time is 1.71 years.

An overall conclusion can be drawn that when the recuperator is added, compared with a basic binary cycle, the total plant cost becomes higher. When some limit in the outlet temperature of the primary loop exists, like geothermal fluid chemistry or district heating applications, the recuperator helps to overcome these limitations and generate more turbine work output. As the basic binary cycle has a lower cost, in general, this option is the best when no such constraints exist.

In order to evaluate the area required for heat exchangers for different working fluids, a simulation was carried out. The results are shown in Figure 16. The simulations used a basic binary cycle and calculations assumed a geothermal fluid temperature of 180°C, a mass flow rate of 221 kg/s and 40°C as the condensing temperature. Figure 16 shows the variations in turbine work output with the total area required for the heat exchangers used in binary power plants. The total area required for a heat exchanger to generate the corresponding turbine work output is influenced by the properties of the working fluid selected for the binary cycle

TABLE 3: Areas and cost for a heat exchanger for a binary cycle and a binary cycle with a recuperator

Working fluid	**Turbine inlet pressure**		**Reinjection temperature (TS3)**		
Isopentante	22 bar		130°C		
		Basic binary		**Binary with recuperator**	
	Turbine output	9722 kW		11309 kW	
	Unit cost (US\$/m^2)	**Area (m^2)**	**Cost (US\$/m^2)**	**Area (m^2)**	**Cost (US\$/m^2)**
Preheater	450	1144	\$ 514,800	1401	\$ 630,450
Evaporator	500	1197	\$ 598,500	1326	\$ 663,000
Recuperator	400	0	-	2677	\$ 1,070,800
Condenser	600	1775	\$ 1,065,000	4212	\$ 2,527,200
Total		**4116**	**\$ 2,178,300**	**9616**	**\$ 4,891,450**
Output difference (MW)	**Annual generation (MWh)**	**Energy cost (US\$/MWh)**	**Annual income (US\$)**	**Areas cost difference (US\$)**	**Payback (years)**
1.587	13902	\$ 120	\$ 1,668,254	\$ 2,713,150	1.71

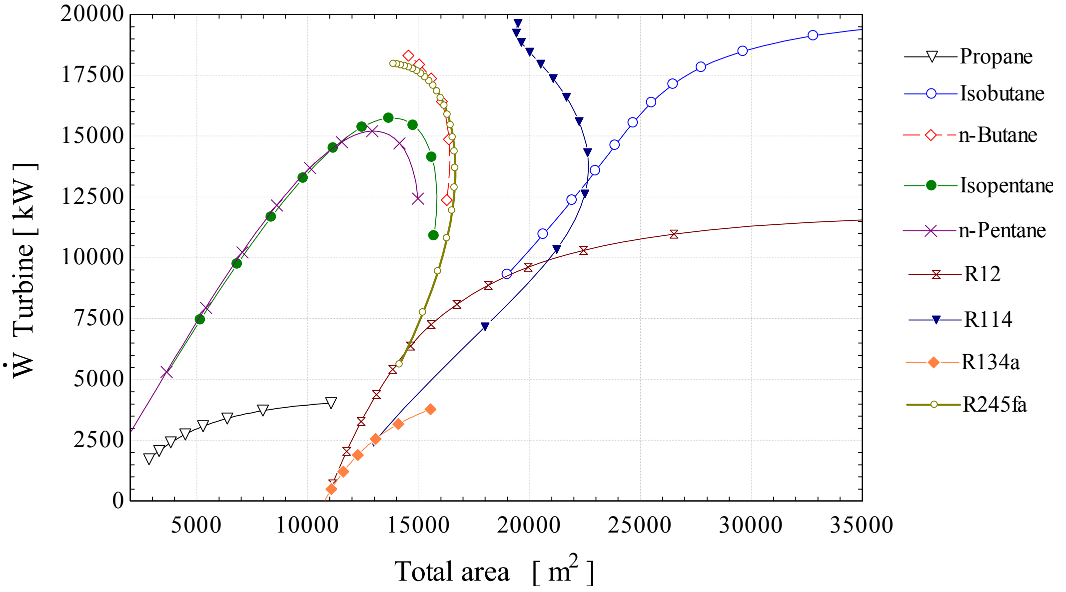


FIGURE 16: Variations of the total area required for a heat exchanger in a basic binary cycle using different working fluids

4.6 Cooling system

Cooling systems are used to reject the heat from the cycle. In binary cycle power plants, the component responsible for dissipating the heat load is the condenser. In the condenser, the vapour phase of the working fluid is condensed at a constant temperature and the heat load is rejected to the environment.

For binary cycle power plants, three types of cooling systems can be applied: the options are a water cooling system, a wet air cooling system and an air cooling system. The water cooling system consists of a shell and tube heat exchanger; this type of cooling system is used mainly when the binary power plant is located in areas with easy access to water. The good range of temperatures for the cooling water used in this cooling system can be from 5 to 25°C. Normally, horizontal double pass shell and tube heat exchangers are components in binary cycle power plants.

The wet air cooling systems use water and air as the cooling fluid, and consist of a condenser and a cooling tower. In wet cooling systems, the vapour of the working fluid from the turbine is condensed in shell and tube heat exchangers. The vapour is condensed by removing the heat and transferring it to the cooling water flowing in the condenser tubes. The cooling water, after removing the heat from the working fluid vapour in the condenser, is pumped to a cooling tower where the heat is transferred to ambient air flowing through the cooling tower. For the evaporation losses and blow down effects, make-up water is required to compensate. For a binary power plant, the most common types of cooling towers are the cross-flow and counter flow types. The typical temperature difference between the inlet and outlet cooling water is 10°C (Mendrinos et al., 2006).

In air cooling systems, air is used to condense the working fluid vapour and reject the heat to the environment. The air cooling system included in this report is also known as an air cooled condenser system. In this air condenser, the working fluid vapour flows through the tubes; the tubes form the condenser area; the heat is rejected to the ambient air via conductive heat transfer. The conductive heat transfer is created by fans that blow ambient air across the outside surface of the tubes. In an air cooling system, no water supply is necessary. A useful graph, shown in Figure 17, plots the air temperature leaving the air condenser as a function of the inlet air temperature (Mishra et al., 2010). The air cooling system is one option when the binary power plant is located in an area with little or no water, where access to water is strictly regulated, and where extremely low ambient temperature conditions exist.

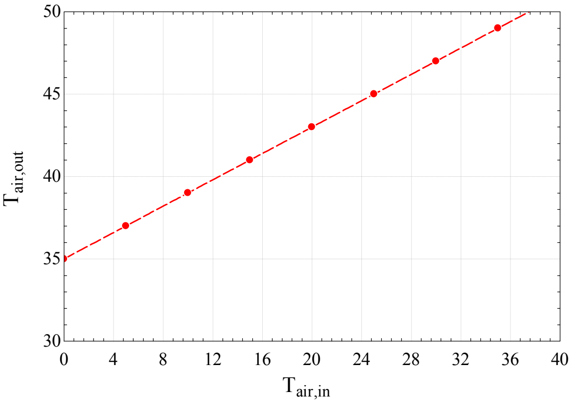


FIGURE 17: Behaviour of outlet temperature as a function of inlet temperature for the air cooled condenser (modified from Pieve and Salvadori, 2011)

Figures 18 and 19 show the variations of parasitic loads for wet and dry cooling systems with ambient temperature for a basic binary cycle. For calculations, Isopentane was used as a working fluid and the available geothermal fluid temperature was 180°C. The mass flow rate of geothermal fluid was 221

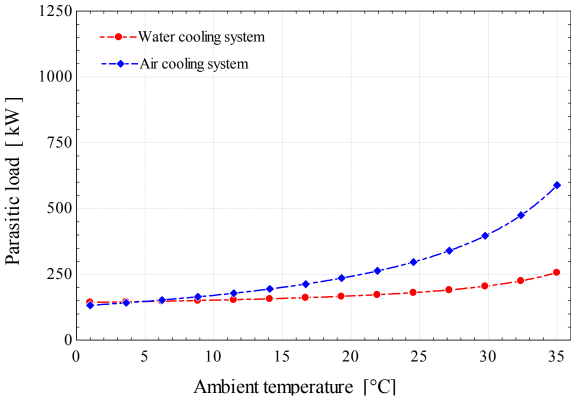


FIGURE 18: Variations of parasitic loads for cooling systems with ambient temperature

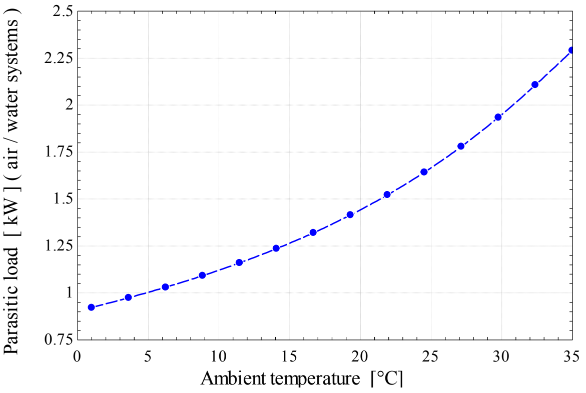


FIGURE 19: Variations of specific parasitic work for cooling systems

kg/s and 40°C was the condensing temperature. Figure 18 shows an almost constant parasitic load of the wet cooling system with respect to the ambient temperature. Figure 19 shows variations of the parasitic work ratio for air cooling and water cooling with ambient temperature. In general, the performance of the cooling systems is influenced by the seasonal fluctuation of the ambient temperature. The heat sink temperature for the cycle is the air temperature and affects the overall cycle performance.

5. WORKING FLUIDS

Organic fluids are used as working fluids in binary cycles. The right selection of a working fluid in binary cycle power plants is very important as it has a primary effect on the efficiency of the power plant, the sizes of power plant components, the design of the expansion turbine, power plant stability, safety, performance, economy and environmental concerns. Because of the low temperature of the heat source, thermodynamic losses occurring in heat exchangers have a significant impact on the overall efficiency of the cycle. These inefficiencies are highly dependent on the thermodynamic properties of the working fluid. A common characteristic of all working fluids used in binary cycle power plant is their low boiling point. They also have critical temperatures and pressures lower than water. Because of the low critical temperature, some organic working fluids can operate under supercritical conditions in geothermal binary cycles. This allows for a better match between the temperatures of the two fluids in heat exchangers. Numerous fluids can be used as a working fluids in binary cycle power plants, except for those having too high or low critical temperature. The working fluid options include: hydrocarbons (HCs), perfluorocarbons (PCFs), chlorofluorocarbons (CFCs), hydrofluorcarbons (HFCs), hydrofluoroolefins (HFOs), hydrochlorofluorocarbons (HCFCs), alcohols, siloxanes, fluorinated ether, and ether. With reference to the thermodynamic characteristics, the most practical options are hydrocarbons, hydroflurocarbons, hydrochlorofluorocarbons, perfluorocarbons, and chlorofluorocarbons. Nevertheless, when a working fluid is selected, factors such as safety, health and environmental impact issues should be considered. Because of their strong effect on the ozone layer depletion, fluorocarbons were forbidden to be used in binary cycle power plant applications (Lukawski, 2009).

The determination of appropriate working fluids for use in binary cycle power plants is a complex task and has a direct relationship with the heat recovery process in the thermodynamic cycle. The working fluids can be classified according to their saturation vapour states, one of the most important characteristics for working fluids in binary cycles.

Figures 20, 21 and 22 show three types of vapour saturation curves in a temperature-entropy (T–s) diagram: a wet working fluid with negative slopes; an isentropic working fluid with nearly infinitely

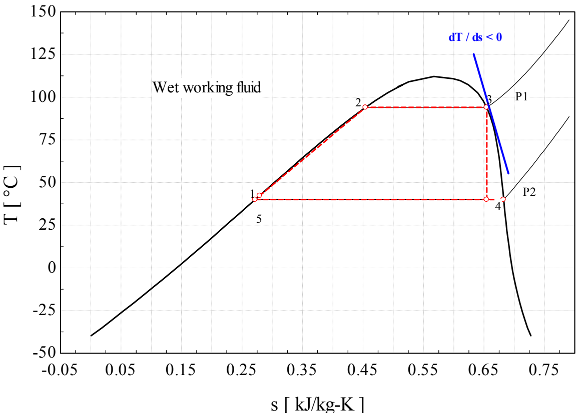


FIGURE 20: T-s diagram for wet working fluids (dT/d s<0)

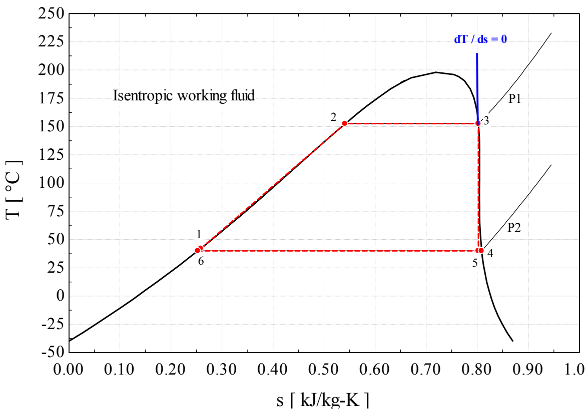


FIGURE 21: T-s diagram for isentropic working fluids (dT/d s = 0)

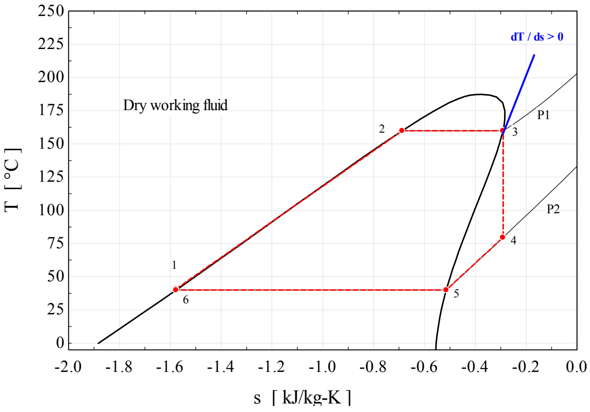


FIGURE 22: T-s diagram for dry working fluids (dT/ds > 0)

large slopes; and a dry working fluid with positive slopes (dT/ds). It is observed from the T-s diagram that for wet working fluids, a superheater is employed to superheat the vapour, and after isentropic expansion in the turbine, the wet working fluid becomes a mixture of liquid and vapour. The saturated vapour of a dry working fluid becomes superheated after isentropic expansion in the turbine. An isentropic working fluid has an almost vertical vapour saturation curve. Since the vapour expands along a vertical line on the T–s diagram, vapour saturated at the turbine inlet will remain saturated throughout the turbine without condensation. The saturation condition persists during expansion in the turbine. The fact that there is no need for installing a recuperator makes isentropic working fluids ideal working fluids for binary cycle power plants. As mentioned above, because of the negative slope of the saturation vapour curve for a wet working fluid, after isentropic expansion in the turbine, the working fluid exists in two phases. Typically, when a wet working fluid is used in the cycle, the minimum dryness fraction at the outlet of a turbine is kept above 85%, for preventing erosion and damage to the turbine blades. The problems of erosion and damage to the blades are more severe with steam turbines. To satisfy the minimum dryness fraction after isentropic expansion in the turbine, wet working fluid at the inlet of the turbine should be superheated. Isentropic and dry working fluids do not need superheating, so the concerns about liquid droplets on the turbine blades are reduced (Bao and Zhao, 2013). Therefore, the dry or isentropic working fluids are more suitable for binary cycle power plants. These types of fluids are known as a retrograde fluids. Table 4 shows a list of different working fluids.

TABLE 4: Thermodynamics, health and environmental properties of some candidate working fluids for geothermal binary cycles (Modified from DiPippo, 2007)

Fluid	**Formula**	**Critical temp. (°C)**	**Critical pressure (bar)**	**Molar mass (kg/kmol)**	**Toxicity**	**Flammability**	**ODP***	**GWP****
Propane	C_3H_8	96.95	42.36	44.09	Low	very high	0	3
i-Butane	i-C_4H_{10}	135.9	36.85	58.12	Low	very high	0	3
n-Butane	C_4H_{10}	150.8	37.18	58.12	Low	very high	0	3
i-Pentane	i-C_5H_{12}	187.8	34.09	72.15	Low	very high	0	3
n-Pentane	C_5H_{12}	193.9	32.40	72.15	Low	very high	0	3
R-12	CCl_2F_2	112.0	41.14	120.9	non-toxic	non-flam.	1.0	4,500
R-114	$C_2Cl_2F_4$	145.7	32.89	170.9	non-toxic	non-flam.	0.7	5,850
R134a	CH_2FCF_3	101.0	40.59	102.0	Low	non-flam.	0	1,430
R254fa	$C_3H_3F_5$	154.0	36.51	134.0	Low	non-flam.	0	1030
Ammonia	NH_3	133.6	116.27	17.03	Toxic	Lower	0	0
Water	H_2O	374.1	220.89	18.02	non-toxic	non-flam.	0	-

*Ozone Depletion Potential ** Global Warming Potential

In order to evaluate the performance of different working fluids, a simulation was carried out. The results are shown in Figures 23 and 24. The simulations use a binary cycle with a recuperator and calculations assume a geothermal fluid temperature at 180°C, a mass flow rate of 221 kg/s and 40°C as a condensing temperature.

Figure 23 shows the variations of turbine inlet pressure with the reinjection temperature of the geothermal water. For temperatures ranging from 80°C to 160°C, only Isopentane and n-Pentane can be selected as a working fluid. These types of working fluids are selected when the reinjection temperature is limited by the geothermal water chemistry or another design condition. For reinjection

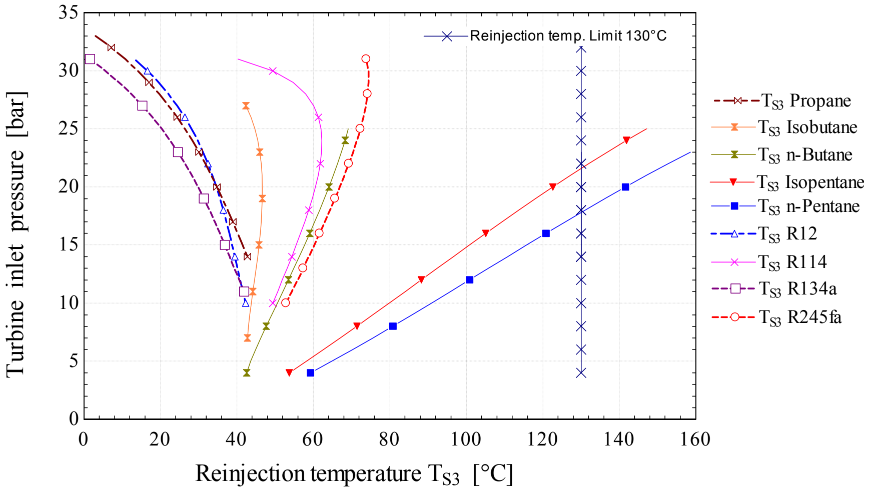


FIGURE 23: Variation of the turbine inlet pressure of different working fluids with the reinjection temperature of geothermal water

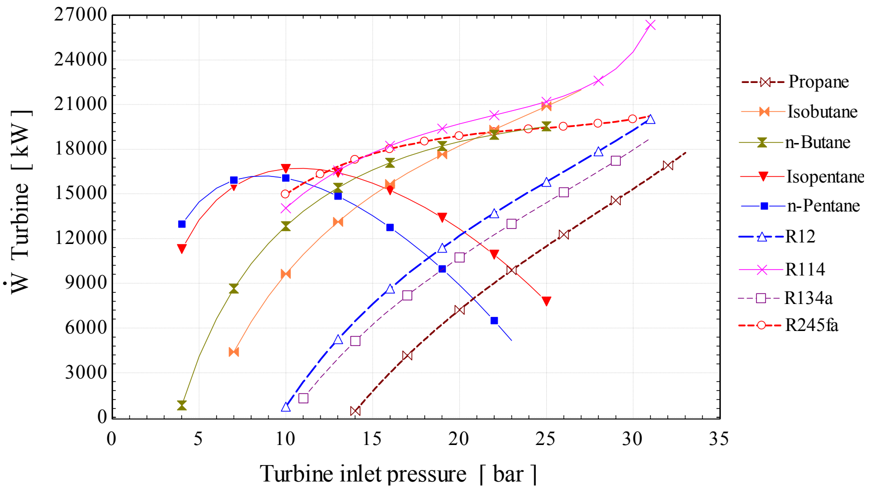


FIGURE 24: Turbine work output for different turbine inlet pressures with different working fluids

temperatures between 40 and 80°C, the working fluid options are Isopentane, n-pentane, isobutene, n-butane, R114 and R245fa. These fluids can be selected when the geothermal fluid has no limitations on temperature and can be cooled down approaching the condensing temperature. Once the working fluid has been evaluated in accordance with the desired reinjection temperature, the next step in the selection is to evaluate the turbine work output that can be obtained. Figure 24 shows the variation of turbine work output for different values of turbine inlet pressures. As seen from the figure, Isopentane and n-pentane have a maximum point of turbine work output, and the maximum work occurs in the range between 9 -10 bars. R245fa shows an increasing stable behaviour for the turbine work output, from 15 to 30 bars. For R114, isobutane and the other working fluids shown, the turbine work output increases at higher turbine inlet pressure until its critical pressure is reached; the complete opposite behaviour is observed for Isopentane and n-pentane. Finally, to make a working fluid selection, the following parameters must be known: the temperature available from the geothermal fluid (heat source), the reinjection temperature limit, if it exists, for the application, and the turbine inlet pressure which is defined by the manufacturer. Also, consideration concerning safety, health and environmental factors should be taken into account.

6. WORLDWIDE BINARY CYCLE POWER PLANTS

Binary cycle power plants play an important role in the world for generating electricity from low geothermal temperature fields. The number of countries utilizing geothermal energy is increasing every year, with many countries focusing on electricity generation using binary cycle technology. According to Bertani (2012), in 2010, 1.1 GW was generated using binary cycle power plants. However, binary cycle power plants are 44% of the total geothermal power plants. Appendix I shows the binary power plants installed around the world.

7. GENERAL DESCRIPTION AND OPERATION OF SVARTSENGI AND BERLIN BINARY POWER PLANTS

7.1 Svartsengi binary units

Svartsengi power plant is located on the Reykjanes Peninsula in Iceland. The geothermal power plant is located at the high-temperature field near the town of Grindavík. Svartsengi power plant supplies electricity to the national grid and district heating water, serving 20,000 people (Thórólfsson, 2005). Svartsengi began to generate electricity in 1976 when the first combined heat and power plant started (Power Plant 1). In 2008 the last phase (Power Plant 6) was finished. This power plant was built in six phases (Table 5); the production capacity in Svartsengi is 75 MWe and 150 MWt (HS Orka, 2013).

TABLE 5: Installed capacity in Svartsengi power plant at each phase (HS Orka, 2013)

Phase	Building years	Technology	Units	MWe/Unit	MWt/Unit
Plant 1	1976 - 1979	Back pressure steam turbine	2	1	0
Plant 2	1979 – 1980	Heat exchanger	3	0	25
Plant 3	1980	Back pressure steam turbine	1	6	0
Plant 4	1989 – 1993	Isopentane binary units	7	1.2	0
Plant 5	1998 – 2000	Extraction-condensing steam turbine	1	30	75
Plant 6	2006 - 2007	Condensing steam turbine	1	30	0

In Svartsengi, Plant 4 consists of binary power units, as shown in Table 5. There are a total of 7 binary units, designed by Ormat, using Isopentane as a working fluid and each unit generates 1.2 MW. The binary units at Svartsengi are known as Ormat4 to Ormat10 (Figure 25). The heat source for those units comes from the low pressure geothermal steam exhaust of a back pressure steam turbine (Plant 3). The amount of exhaust steam available from Plant 3 is 38.5 kg/s saturated steam at 1.2 bars (Verkís, 2013). The temperature corresponding to these conditions for the exhausted steam is 103°C. As mentioned above, the power from each unit is the same, but they have different condensing systems. Those condensing systems are air systems and water systems. In the air condensing systems, the vapour of the working fluid goes directly to the air cooled condenser. The air cooled condenser is a heat exchanger with tubes fixed at the ends to inlet and outlet header boxes with a passage in-between for the flow of air blown by fans. In Svartsengi, Ormat 7, 8, 9 and 10 units are air cooled.

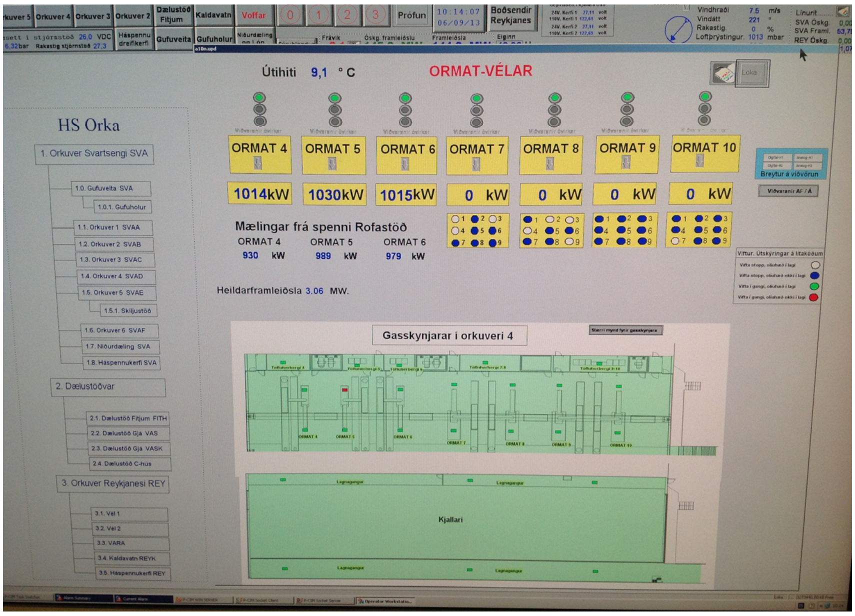


FIGURE 25: Screen from control room in Svartsengi power plant

The water condenser systems are comprised of shell and tube heat exchangers. The exhaust working fluid vapour from the turbine is passed to the shell side of the condenser where it is condensed by cooling water circulating through the tubes. The cooling water enters the condenser at a temperature of 5°C and leaves the condenser at 22°C. In Svartsengi, ORMAT 4, 5 and 6 units are water cooled.

The Ormat units are based on the organic Rankine cycle and consist of the following components: preheater/evaporator, separator, condenser, turbine, gearbox, generator, feed or working fluid pumps and a power and control cabinet. Figure 26 shows the P&ID diagram and a photo of one binary Ormat unit where the components can be identified. The saturated steam passes through the tubes of the preheater-evaporator to heat and evaporate the working fluid (Isopentane) in the shell side of the evaporator. The vapour of the working fluid then moves into the separator where droplets are removed. The level of the working fluid in the evaporator is regulated automatically by a controlled feed valve. In normal operation conditions, the vapour from the separator passes through the main valve to the turbine.

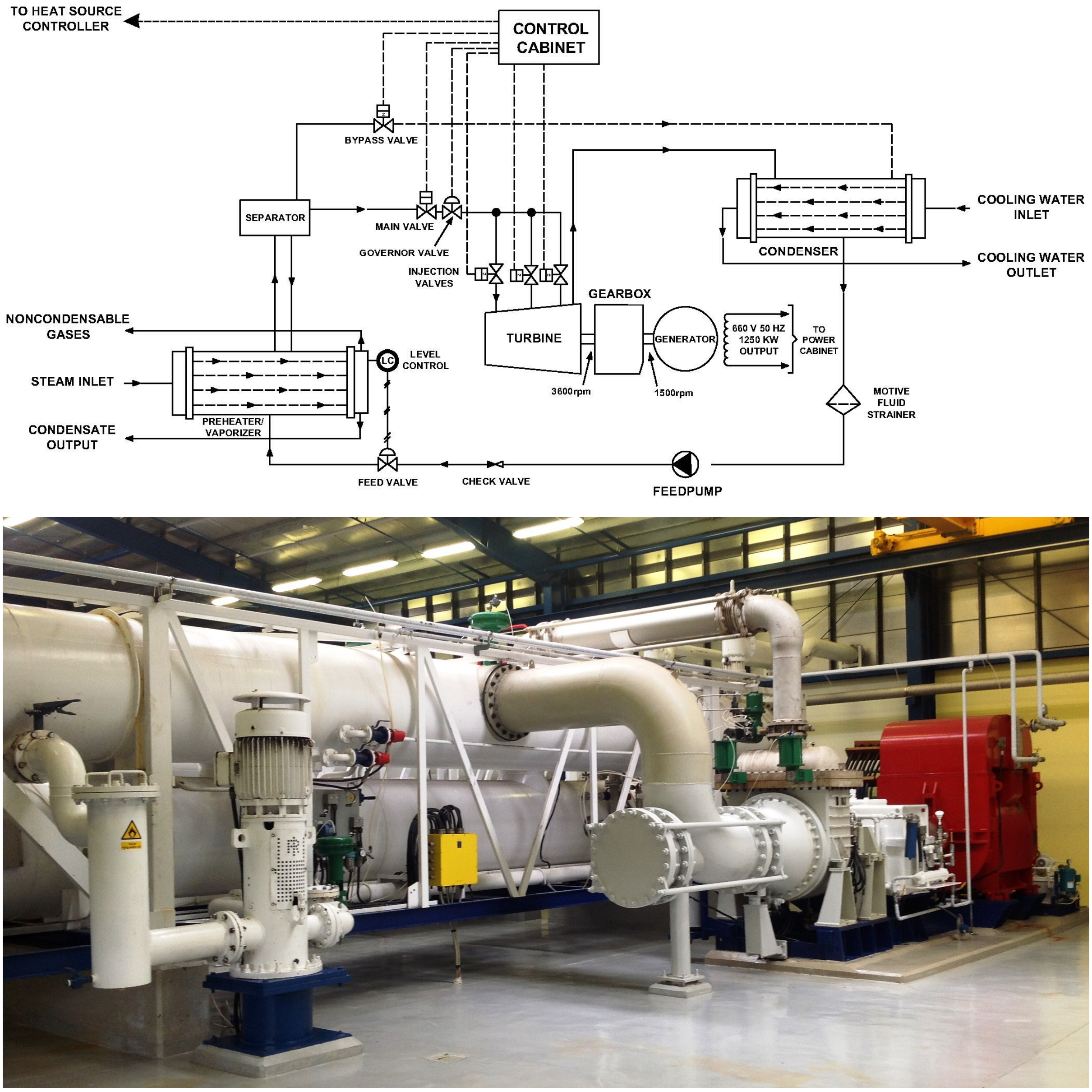


FIGURE 26: Binary Ormat unit at Svartsengi, water cooled condenser

The working fluid vapour expands in the turbine, and the turbine drives the generator using a gearbox at 3600/1500 rpm. The units have a bypass that, in case of a stop or under abnormal operating conditions, allows the vapour from the evaporator to reach the condenser directly. The generator has a nominal power output of 1300 kW at 660 V and 50 Hz. The exhaust working fluid vapour is cooled and condensed to liquid by the condenser system. The working fluid is removed from the condenser by the working fluid pump and returned to the preheater/evaporator to complete the heat cycle. The unit is controlled by control devices and circuits contained in a power and control cabinet. In Table 6, the operating parameters, type of equipment, and other important characteristics of the preheater-evaporator and turbine that are part of the binary units are summarized.

TABLE 6: Technical data of the preheater-evaporator and turbine

Preheater-evaporator and separator		**Turbine**	
Type	Shell and tube heat exchanger	Type	Impulse
Fluid at tube side	Saturated steam	Stages	Single
Fluid at shell side	Working fluid (Isopentane)	Working fluid	Isopentane
Evaporator outlet pressure	5.5 bar	Net power output	1,200 kW
Heat source inlet temp.	103°C	Vapour inlet pressure	6.2 to 8.3 bar
Heat source outlet tem.	95°C	Vapour inlet temp.	95°C
Saturated steam flow	5 kg/s	Vapour outlet temp.	44°C
Working fluid flow	25 kg/s	Speed	3600 rpm
		Mechanical seal	Oil lubricated
Other	Evaporator fitted with a safety relief valve	Other	Turbine has capacity to operate at partial or full capacity

The gearbox is used to reduce the turbine shaft's speed from 3600 to 1500 rpm and to drive the generator. The gearbox uses two double – helical gears placed in a cast iron housing. The gearbox has an independent lubrication system for cooling and to lubricate the gear mesh and its bearings. The oil temperature in the gearbox should be 40 +/- 10°C. For cooling the oil used in the gearbox, the cooling arrangement is integrated into the lubrication system which uses 1.2 kg/s of water at a maximum 25°C. The gearbox has protection against high temperature and low pressure failures in the lubrication system.

The working fluid pumps (Figure 27) that remove the Isopentane from the condenser are vertical, centrifugal and multistage type. Each pump has 10 stages; the impellers are made of bronze, and the housing is made of cast iron. The working fluid pumps are driven by a three phase electrical motor. The outlet pressure of the pumps is 6.3 bars.

FIGURE 27: Isopentane pump belonging to the water cooled binary Ormat units at Svartsengi; it shows the Isopentane return pipeline from the condenser to the pump

The generators are designed for continuous operation and, as was mentioned, they are driven by the turbine via a gearbox. The generators are three phase, brushless revolving field synchronous type for the units with a water condenser system, and an asynchronous type for units with an air cooled condenser system. The generator design construction has two bearings for placing the shaft in the generator. The generator is cooled by a heavy fan, mounted on one end of the shaft, and also has an extra cooling system to maintain the air temperature at the required temperature level. This extra cooling system is provided by air – water cooler heat exchangers. The power and control cabinets contain all the control devices and electrical circuits required for controlling the units.

The units have auxiliary systems which allow automatic control and monitoring of the binary cycle generation process. The auxiliary systems are the pneumatic, lubrication, instrument and control systems. The pneumatic systems use compressed air to feed the actuators on the automatic valves. The lubrication system mainly supplies oil to the turbine and generator bearings, as well as supplying the seal oil in the turbine's mechanical seal; the pressure in the mechanical seal chamber is 8.2 bars. The pump used in the lubrication systems is a gear pump type and the maximum discharge pressure is 15 bar. The instrument and control system's purpose is to control the start-up procedure, normal operations and shutdown procedures. This system has a program, measuring instruments and input devices, auxiliary controls and relays, indication lights and a synoptic panel.

In Svartsengi power plant, the operation is totally automatic and remotely monitored. According to the operation manual for a binary unit (Ormat, 1992), these units have the following operating procedures: preconditions for startup, start up, normal operation, normal shutdown and automatic shutdown procedure (Tesema, 2002).

The shift operator in the power plant is responsible for troubleshooting and carrying out emergency maintenance. For operating the binary units there are only two workers, the operator and the daily maintenance manager.

7.2 Berlín binary power plant

The Berlín binary cycle power plant is located at Berlin, Usulután in El Salvador. The Berlín binary cycle power plant is located at the platform of Well TR-9 in Berlín geothermal field, and is called Unit 4. The Berlín geothermal field has 4 power plants; the developmental history is summarized in Table 7. The Berlín binary cycle started its construction in 2005 and was commissioned in 2007. The goals of this binary power plant were to generate electricity and to supply the demand with a geothermal resource, increase the efficiency of the Berlín geothermal field and contribute to local sustainable development. The binary cycle power plant technology was used for the first time in El Salvador in this unit.

TABLE 7: Berlin geothermal field development in El Salvador (Guidos and Burgos, 2012)

Phase	Building years	Technology	Units	MWe/Unit
Well head units	1992	Back pressure steam turbine	2	5, Out of operation
Units 1 & 2	1999	Condensing steam turbine	2	28
Unit 3	2005	Condensing steam turbine	1	44
Unit 4	2007	Isopentane binary cycle unit	1	9.2

In Berlin, the geothermal wells produce a two phase fluid, geothermal water and steam. The steam is used to feed the turbines in the flash steam power plant and the geothermal water is re-injected in the wells, downstream of the production wells and power plant. The binary cycle power plant in Berlín is designed to remove internal energy from the geothermal water before reinjection, which has a temperature of 180°C, to generate electricity. The geothermal water used in this unit comes from Wells TR4/5 and TR2/9; the steam from these wells is used to generate electricity in units 1 and 2. The Berlin binary cycle power plant is a good example of a bottoming power plant.

The organic Rankine cycle is utilized to generate electricity. This binary power plant uses Isopentane as its working fluid. The gross power output is 9.2 MWe and its own energy consumption for the circulation pumps, cooling water pumps, cooling tower fans and other electrical and auxiliary equipment is taken from the same generation. Therefore, the net power production delivered to the grid is 7.8 MWe.

In Berlin binary cycle power plant, the process is divided into three loops. The first loop is the geothermal water circulation, the heat source. The second loop is the working fluid process, and the third loop is circulation of cooling water. In the first loop of this binary power plant, the heat source comes from two reinjection systems; one pipeline collects the geothermal water from wells TR2 and TR9. The system is called TR2/9. Another pipeline collects the geothermal water from wells TR4 and TR5 and the system is called TR4/5. Figure 28 shows the process diagram for the first loop. System TR4/5 carries 221 kg/s of hot water at 22 bars. System TR2/9 carries 79 kg/s at 11 bars. The geothermal water exchanges heat with the working fluid in the preheaters and the evaporators; this exchange takes place in both systems and the vapour of the working fluid leaves the evaporators at 22 bars. The geothermal water is cooled down from 180 to 140°C before being re-injected.

The second loop is the Isopentane process cycle; the mass flow of working fluid used in the Berlin power plant is 123.3 kg/s. Table 8 shows the changes along the loop and the parameters of the working fluid under design conditions.

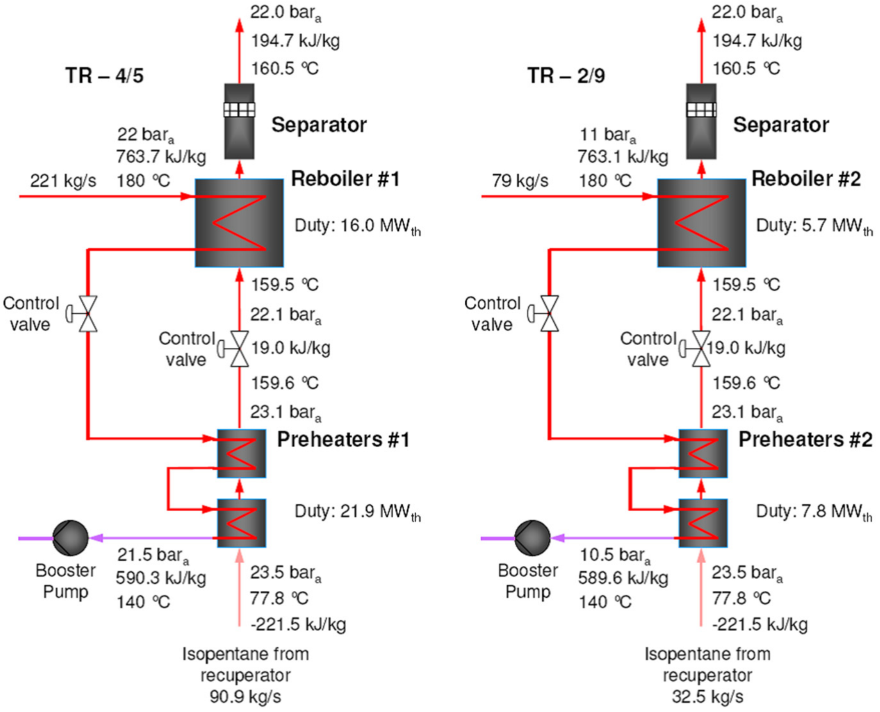


FIGURE 28: Preheaters, evaporators and the first loop process diagram (Enex, 2007)

The third loop corresponds to the cooling water cycle; the flow of water in this cycle is 1,013 kg/s. In this loop, the water removes the heat from the working fluid through the condenser, which is a shell and tube heat exchanger type. The water evaporates the removed heat into the atmosphere in the cooling tower. A set of pumps is used to circulate the water from the condenser to the cooling tower. Due to evaporation during the heat exchange, blow down, and drift, constant make-up water is needed. The make-up pumps deliver 20.3 kg/s of condensate water from the pond of the condensation units.

TABLE 8: Design condition for the working fluid at each step of the cycle's process

Working fluid phase change	Parameters		
Evaporation:	Temperature	159.5	°C
Expansion:	Turbine inlet pressure	22	bar
	Turbine outlet pressure	1.85	bar
	Turbine inlet temp.	160.5	°C
	Turbine outlet temp.	92.9	°C
Cooling:	Recuperator outlet temp.	52.6	°C
Condensation:	Condenser pressure	1.8	bar
	Condenser outlet temp.	44.8	°C
Compression:	Pump discharge pressure	23.78	bar
	Pump discharge temp.	46.1	°C
Heating in recup.:	Outlet temperature	77.7	°C
Heating in preheat:	Outlet temperature	159.5	°C

In the Berlin binary cycle, the turbine-gearbox-generator is mounted on a structural steel skid. In the turbine, the working fluid expands from the inlet to the outlet pressure in two steps: The first step takes place in the inlet guide vanes (IGV; variable nozzles) and the final steps take place in the radial wheel or rotor (Figure 29). The turbine converts the kinetic energy into mechanical work, transmitted by the shaft to the generator via the gearbox (GE-Energy, 2013). The turbine case is sealed at the shaft by a dry face mechanical seal. Nitrogen and air are injected as a sealing and cooler fluid. The mechanical seal has an internal division in the labyrinth seal: a front labyrinth (working fluid) side and a back labyrinth (lubrication oil) side. The nitrogen goes through the front labyrinth side and is mixed with the vapour, to ensure that the working fluid is retained in the turbine. The mix of air and purged nitrogen goes through the back labyrinth side of the mechanical seal and flows toward the vent cavity; this mix removes any heat generated in the mechanical seal and ensures that the lubrication oil mist does not migrate to the expander process side. The gearbox is connected to the turbine through a power shaft and connected to the generator through a low speed coupling. This gearbox reduces the turbine shaft speed from 6490 to 1800 rpm. The generator is a brushless excitation type ABB unit with a horizontally mounted rotor and air to water closed circuit cooling. It produces a voltage of 13.8 kV and 60 Hz.

FIGURE 29: Inlet guide vanes (IGV) and radial wheel of turbine (GE-Energy, 2013)

The heat exchangers in the Berlin binary cycle are used to transfer heat between different fluids. Figure 30 shows the arrangement of all the shell and tube heat exchangers in this plant. Basically, the heat exchanger transfers heat from the geothermal water to the working fluid in the preheater and evaporator, transfers heat between the exhaust vapour and the liquid working fluid in the recuperator, and transfers heat from the working fluid to the cooling water in the condenser. The working fluid along the process flows in the shell side in this equipment.

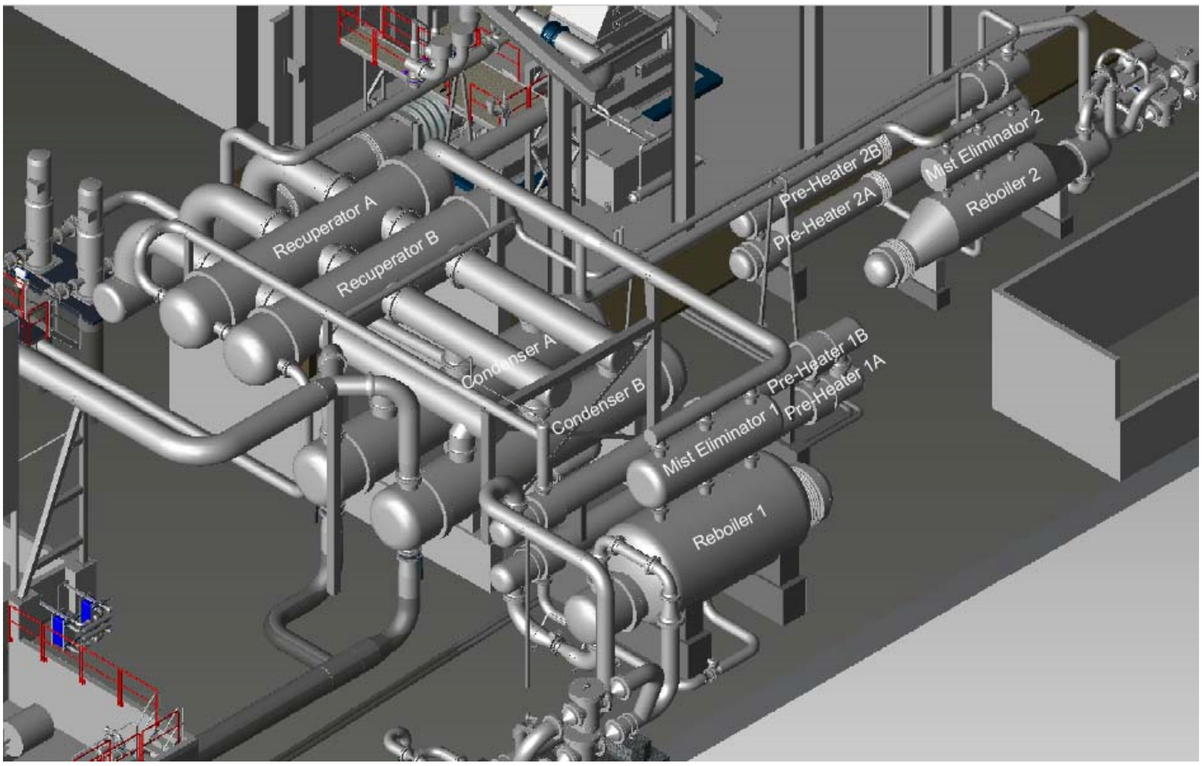


FIGURE 30: Shell and tube heat exchanger in Berlin binary plant (Enex, 2007)

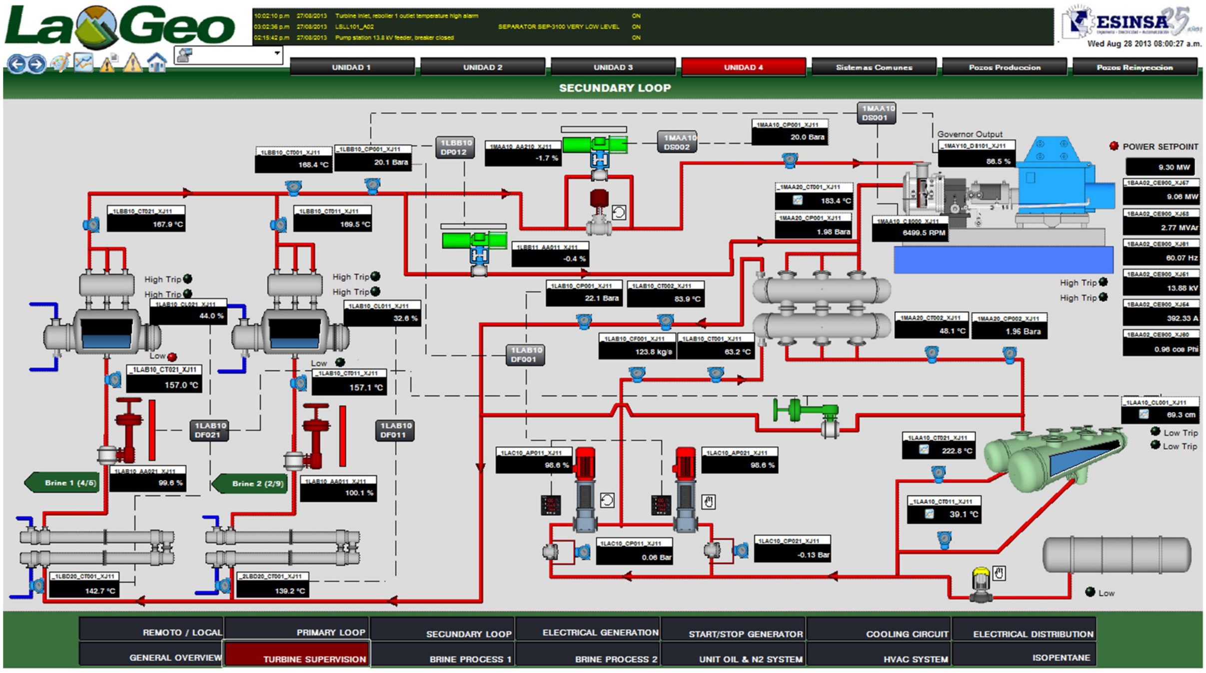
The cooling tower's main function is to remove the heat from the water used in the condenser. The cooling tower acts as a final heat sink in the process by delivering this heat into the environment. This cooling tower is a counter-flow type and has two fans that draw air upward against the flow of water falling from the top. Operating under design conditions, the tower can handle a flow of up to 4,122 m^3/hr. The water from the condenser to the cooling tower is pumped by centrifugal pumps that are designed as a single stage, double suction and horizontal split volute type.

The working fluid pumps are of the vertical, centrifugal and multistage type. The pumps are equipped with a mechanical seal, with a cartridge design that allows changing the seal without taking the pumps apart. The mechanical seal is flushed by an American Petroleum Institute (API) plan. The API helps to select the type and control for a mechanical seal application. For working fluid pumps in the Berlin binary unit, the temperature at the seal should be a maximum of 10°C above the pumped working fluid temperature. The working fluid pumps are driven by a three phase electrical motor.

As mentioned above, the mechanical seal used in the turbine casing works with nitrogen on the working fluid side; both fluids exist as a mix in the outlet of the turbine. To remove the non-condensable nitrogen from the working fluid, a nitrogen extraction system was installed in the condenser, where the working fluid liquefies and the nitrogen remains in the gas phase which is ejected to the atmosphere from a gas separator.

The units have auxiliary systems which allow for automatic control and monitoring of the Berlin binary cycle. These include the nitrogen generator system, pneumatic, ventilation, fire protection, inhibitor, auxiliary cooling water for the generator-gearbox-turbine set, lubrication, instrument and control systems.

In the Berlin binary cycle power plant, the operation is totally automatic, locally and remotely monitored. Figure 31 shows the actual screen for the process that is used by the operator to monitor the cycle. According to the operation manual for a binary unit (Enex), these units have the following operation procedures: preconditions for start-up, start-up, turbine start-up, turbine warm start, normal operation, normal shutdown, turbine trip and trip of the working fluid cycle. For operation of the Berlin binary plant, there is only one operator in each shift. The operator is responsible for monitoring all the parameters of the unit, troubleshooting and executing start-ups and shutdown procedures. The operators work in 8 hour shifts.



```
10:02:10 p.m  27/08/2013  Turbine inlet, reboiler 1 outlet temperature high alarm                    ON
03:02:36 p.m  27/08/2013  LSLL101_A02                          SEPARATOR SEP-3100 VERY LOW LEVEL     ON
02:15:42 p.m  27/08/2013  Pump station 13.8 kV feeder, breaker closed                                ON
```

FIGURE 31: Screen of second loop in Berlin binary cycle power plant

8. BINARY CYCLE MAINTENANCE WORK AND EXPERIENCES

The maintenance of a binary cycle power plant includes a series of activities carried out on each component of the binary plant in order to ensure its continuous performance. The maintenance of binary cycle power plants is highly influenced by different factors, such as: the nature of the geothermal fluid used in the primary loop, the nature of the working fluid, the technology and location of the plant, climate and weather. In order to operate a binary cycle power plant as a base load unit, a perfect maintenance programme configured to ensure high availability and reliability is a challenge. Corrosion and scaling are the most common problems in binary power plants.

To develop the maintenance activities, a maintenance management programme is needed to help in coordination, control, planning, implementing and monitoring the necessary activities required for each component of the binary plant. There are a variety of maintenance programmes and methods dealing with the following basic maintenance strategies: corrective, preventive, predictive and proactive maintenance. The best maintenance programme analyses and applies the correct combination of strategies for each component of the whole power plant. Also, nowadays software is available that can help to manage these activities; examples of these tools are Dynamic Maintenance Management (DMM), used in Svartsengi power plant, and Maximo software, used in the Berlin power plant. These software programmes have been designed to manage assets and help to automate all aspects of maintenance. These software programmes have the following common functions: machine history, preventive maintenance schedules, work orders, condition monitoring, condition based flagging, time accounting, fault reports, improved safety, expense tracking, procurements, trending and performance reports (DMM,2013; Projetech, 2013).

In this report, the basic maintenance strategies are summarized, and the major mechanical maintenance activities carried out on the turbine, heat exchangers, pumps and cooling towers of the binary cycle power plants are described. The report also describes certain experiences from Svartsengi and Berlin binary cycle power plants during their operation and maintenance.

As was mentioned above, the basic maintenance strategies are corrective, preventive, predictive and proactive maintenance. A corrective maintenance strategy proposes running the machinery until it fails. This strategy seems to be economic because the manpower requirements and their costs are minimal. But, when the machinery fails at some unexpected time, it is required to schedule manpower at the site for emergency shifts, have a complete stock of parts available in a warehouse, and make a contract with a specialist in case of emergency. The shut down time depends on the magnitude of the failure. In addition, an unexpected failure can lead to an unsafe environment or conditions, both to personnel and the facilities. All these factors need to be considered for a corrective maintenance strategy; since failures cannot be predicted so the cost will be high.

Preventive maintenance consists of scheduling maintenance activities aimed at preventing failures and breakdowns in the machinery. The main goal of this strategy is to prevent the failure before it occurs. The preventive maintenance activities consist of equipment checks, lubrication, oil changes, looking for leaks, tightening bolts, mechanical adjustments, partial or complete overhauls, etc. At the same time, the operating hours, according to the manufacturer's recommendations, are scheduled for the change of worn parts before they really fail. This strategy has the advantage that during maintenance, the workers can identify if the machinery needs maintenance; also, they can record the deteriorations in machinery and suggest/schedule the next maintenance. The associated costs for this technique are related to long availability and the service life of the machinery. The strategy helps in controlling the shut down time period of the machinery. The disadvantage of this strategy includes unnecessary maintenance and incidental damage to components while the risk of unexpected failures still prevails. Preventive maintenance includes the predictive strategy maintenance.

The predictive maintenance strategy mainly focuses on measuring the operating conditions of the machinery and ascertaining if the machinery is working under certain standard conditions.

Measurements are logged over time. The strategy suggests taking corrective measures when the measurements go beyond standard operation limits. This strategy requires new tools, software and specialized technicians to obtain and analyse the data, as well as to predict when the machinery must be repaired. Vibration monitoring conditions are the most common technique used to monitor operating conditions (for example, the continuous monitoring systems installed on the bearing pedestals on the turbine-gearbox-generator set). But, the vibration technique is limited to monitoring mechanical conditions; therefore, other monitoring and diagnostic techniques that can be useful for maintaining reliability and efficiency of the machinery include: an acoustic analysis, motor analysis technique, thermography, tribology, process parameter monitoring, visual inspections and other non-destructive testing techniques.

Proactive maintenance focuses its work on reducing the failure recurrence or unexpected failure, determining the root cause of previous failures (Asaye, 2009).

In a binary cycle power plant, besides the different maintenance practices that are summarized above, major overhauls are carried out according to the manufacturer's recommendations. The common major overhaul period for a binary cycle power plant is between 40,000 to 48,000 hours. The principal mechanical maintenance activities developed during the major overhauls of the main equipment, as well as the experiences of maintenance and development, in Svartsengi and Berlin binary cycle power plants, are mentioned below:

8.1 Turbine

The turbine is a key component in binary cycles. For this component, the maintenance activities include the following:

- Disassemble the turbine wheel and nozzle ring;
- Check condition of turbine wheel and nozzle ring;
- Check condition of turbine mechanical seal, o-rings and bearings;
- Check and clean the oil tank filter and change oil;
- Check the gearbox; and
- Perform non-destructive testing, such as liquid penetrant, magnetic particles and ultrasonic.

The objectives during the major overhaul include looking for wear, cracks and damage in the movement parts; furthermore, some critical parts should be replaced according to the manufacturer's recommendations.

Since operations began in Svartsengi binary power plant, the major corrective maintenance activity was associated with the mechanical seal. The mechanical seal showed failures on the seal faces caused by using the wrong type of lubrication oil. Nowadays, the mechanical seal is working well and the failure was eliminated by lubricating the mechanical seal with high thermal resistance oil. Figure 32 shows the mechanical seal damages.

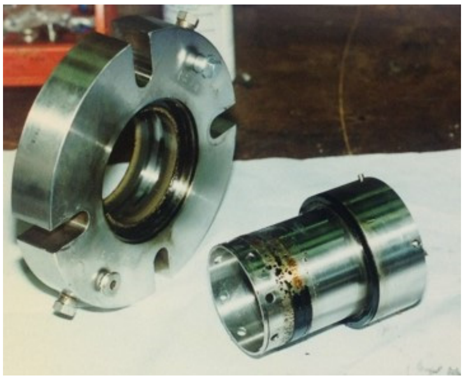


FIGURE 32: Mechanical seal, contaminated and damaged (Svartsengi binary power plant)

In the Berlin binary cycle power plant, the mechanical seal is of the dry face seal type; this type of seal has a disadvantage. The disadvantage is the requirement for the injection of seal gas during operations and even during shutdown time. It is required in order to dissipate heat generated by the dry face seal and for avoiding contact of the seal faces with the lubricating oil and oil mist on one side, and working fluid on the other. Figure 33 shows mechanical seal damage.

When the mechanical seal is damaged, the amount of seal gas flowing to the working fluid side increases the discharge pressure and decreases the turbine work output, because of the presence of incondensable seal gas flowing in the process.

In the Berlin binary cycle power plant, the nozzle ring of the turbine was changed because of erosion and jamming problems. The change included a new design for the nozzle ring.

FIGURE 33: Mechanical seal, contaminated and damaged (Berlin binary cycel power plant)

8.2 Heat exchangers

The heat exchangers are the components in which the geothermal fluid, the working fluid and the cooling fluid interact. The major maintenance work on heat exchangers is cleaning the heat exchange area, depending on the processing conditions. As is known, the geothermal fluid flows through the tubes, so the major problems found in the heat exchangers are associated with the chemistry of the fluid, and scaling problems. The working fluid side, theoretically, does not require a cleaning process. The cleaning process can be carried out with pressurized water and chemical cleaning. A recommended practice is to run a pressure test to verify the seal of the heat exchanger, to avoid contamination of the working fluid.

In Svartsengi, the geothermal fluid used in the binary power plant is steam, and there have been no major problems. However, in the Berlin binary cycle power plant, geothermal water is used in the primary loop, and scaling problems associated with the chemistry of the fluid are present. In Berlin, both chemical and pressurized water cleaning processes are used during maintenance work. A pressure test was done in the Berlin binary cycle, to ensure the tightness of the heat exchanger. During this test, when tubes were identified with leakages, in order to avoid contamination of the working fluid with geothermal fluid, these tubes were blocked.

8.3 Working fluid pumps

The working fluid pumps are the components that circulate the working fluid in the binary cycle. For these components, the maintenance activities are as follows:

- Check the intermediate bearing sleeves and bushing against wear;
- Check the shaft and impellers;
- Check the causing wear ring and the impeller wear ring for any wear;
- Check the parts for corrosion and erosion;
- Carefully check the coupling for any wear;
- Check the bearing cage for any wear;
- Check the run out of the shaft;
- Check condition of pump mechanical seal and o-rings;
- Change oil; and
- Check the coupling alignment.

In Svartsengi binary power plant, a major overhaul is carried out for the working fluid pumps after every 40000 hours and, during this work, the shaft, sleeves, bushing, wear ring, bearing, mechanical seal and shaft are replaced. The pump is equipped with a single mechanical seal and the cartridge design allows for changing the mechanical seal without taking it apart.

In the Berlin binary cycle power plant, the working fluid pumps have the same overhaul schedule as in Svartsengi. The mechanical seal in Berlin binary cycle power plant has been changed from a single to a double seal type. The advantage of the double mechanical seal is that it eliminates leakage of the working fluid into the atmosphere, and working fluid losses are eliminated during a failure of the seal. The cartridge design allows for changing the mechanical seal without taking it apart.

8.4 Cooling systems

The main function of the cooling system is to condense the working fluid and dissipate the removed heat to the environment. The condensers in Svartsengi are water and air coolers; the maintenance activity is to clean the heat exchange areas and check the seals in the system. In Svartsengi power plant, if the air cooled condenser has a leak, the leakage will be stopped by installing a short sleeve inside each tube where it ends in the end of header box. These sleeves will be installed using hydraulic tube expansion technology. The sleeve will be expanded for tight contact with the parent tube in the header box. Figure 34 shows the air condenser, the leakage zone and the sleeves that used to seal the condenser.

FIGURE 34: Air condenser and the leakage zone

The Berlin binary cycle has a wet cooling system, and mechanical maintenance work is carried out on the circulating water pumps, gearbox and fans. For these components, the maintenance activities are as follows:

- Check the intermediate bearing and bushing against wear;
- Check the shaft and impellers;
- Check the parts for corrosion and erosion;
- Carefully check the coupling for any wear;
- Check condition of pump mechanical seal and o-rings;
- Check the coupling alignment;
- Check the gears for any wear;
- Check the fan blades; and
- Change the gearbox oil.

In the Berlin binary cycle power plant, the circulation water pumps were changed after corrosion problems were found. The construction material of these pumps was changed from cast iron to stainless steel, and the stuffing box was changed to a mechanical seal. The corrosion was caused by the chemistry of the condenser water that was used as a cooling fluid.

9. CONCLUSIONS

The production of electricity from binary cycle power plants is useful for harnessing low and medium temperature resources and raising the total exploitable geothermal potential worldwide. The number of countries utilizing geothermal energy is increasing every year, with many countries focusing on electricity generation using binary cycle technology.

The concept of a binary cycle power plant, known as an organic Rankine Cycle (ORC), is a modification of the Rankine cycle where the working fluid, instead of water, is an organic fluid having a lower boiling point and a higher vapour pressure than water.

Dry or isentropic working fluids are more suitable for binary cycle power plants then wet working fluid. To select a working fluid, the temperature of the geothermal fluid, the reinjection temperature limit, the turbine inlet pressure, and considerations of safety, health and environmental factors should be known.

The addition of a recuperator causes no change in the maximum turbine work output of the binary cycle, but causes a shift in the maximum point of the turbine work output of the cycle with respect to the reinjection temperature. However, when the reinjection temperature is limited by the geothermal water chemistry, or by other design constraints such as district heating applications, adding a recuperator serves to increase the turbine work output for a given reinjection temperature and helps to overcome these limitations.

The addition of a recuperator causes an increase in the condenser area required for cooling. The total area for a binary cycle using a recuperator increases by 42% over that of a basic binary cycle. The cost for heat exchangers using a recuperator, when compared with a basic binary cycle, increases almost by the same ratio.

The overall economic conclusion can be drawn that when the recuperator is added, the total plant cost is higher. As the basic binary cycle has a lower cost, in general, this option is the best when no constraints exist.

When the reinjection temperature is in the range of 80°C to 160°C, according to this research Isopentane and n-Pentane are the most suitable working fluids. In El Salvador, Isopentane is the working fluid in the binary power plant. However, n-pentane is another working fluid option for designing binary cycle units for the Berlin power plant.

The best option for the cooling system of a binary cycle is the wet cooling system. The dry cooling system is an option when the binary power plant is not located near water, or water is strictly regulated, or for where extremely low ambient temperature conditions exist.

The primary working fluid can be either water or steam. The advantage of using steam is that scaling problems are minimized.

The maintenance of binary cycle power plants is highly influenced by different factors such as: the nature of the geothermal fluid used in the primary loop, the nature of the working fluid, the technology and location of the plant, climate and weather. Corrosion and scaling are the most common problems in binary power plants.

To develop the maintenance activities, it is necessary to have a maintenance management programme to help in coordination, control, planning, implementing and monitoring the necessary activities required for each component of the binary plant.

ACKNOWLEDGEMENTS

I want to especially thank my employer, LaGeo S.A. de C.V., for giving me the opportunity to attend this training to strengthen my knowledge in geothermics for the near future. My most sincere thanks go to Mr. Lúdvík S. Georgsson and Dr. Ingvar B. Fridleifsson, current and former director, respectively, of the United Nations University Geothermal Training Programme (UNU-GTP), for inviting me and giving me the opportunity to participate, grow academically and personally in this course. Thanks go to the staff of the UNU-GTP, Ms. Málfrídur Ómarsdóttir, Ms. Thórhildur Ísberg, Mr. Markús A. G. Wilde, and Mr. Ingimar G. Haraldsson, for their enthusiastic help and support during my stay in Iceland. I want to give special thanks to my supervisors, Dr. Páll Valdimarsson, Mr. Geir Thórólfsson, and Ms. María Gudjónsdóttir, for their dedication, availability, support and guidance while working on this geothermal report.

I want to thank all 2013 UNU Fellows; special thanks go to my friends, Claudia, Idalia and Mariela for an unforgettable friendship, memorable moments and times during these six months. For my utilization colleagues and friends, I want to say "thank you so much".

This report is dedicated to my family, especially my wife, Xochilt, for her love, patience and support.

My gratitude goes to the people who gave me their invaluable support for attending this training. These include Mr. Jorge Burgos, Ms. Evelyn de Velis, Mr. David Lopez, Mr. Jorge Castillo, and Mr. José Luis Henríquez.

Last, but not least, I owe my deepest gratitude to J. Estevez, A. Rugamas, C. Melgar, and O. Cideos for helping me with technical information, commenting on my manuscript and answering my questions.

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APPENDIX I: Binary power plants installed in the world

China

Plant		Year	Type	MW-rated	N° Units	MW-Total	Comments
Dengwu	Unit 2	1977	Binary	0.2	1	(0.2)	Retired
Huailai		1971	Binary	0.285	1	(0.285)	Retired
Wentang		1971	Binary	0.05	1	(0.05)	Retired
Xiongyue		1978	Binary	0.1	1	(0.1)	Retired
Tuchang		1985	Binary	0.3	1	(0.3)	Inactive
Nagqu	Unit 1	1993	Binary	1	1	1	
				Totals	**1**	**1**	

Iceland

Plant		Year	Type	MW-rated	N° Units	MW-Total	Comments
Svartsengi	Unit 4	1989	Binary	1.3	3	3.9	
	Unit 4 Extension	1993	Binary	1.2	4	4.8	
Husavik		2000	Binary	2	1	2	Kalina Cycle
				Totals	**8**	**10.7**	

Italy

Plant		Year	Type	MW-rated	N° Units	MW-Total	Comments
Travale 21		1991	Binary	0.7	1	0.7	
				Totals	**1**	**0.7**	

Japan

Plant		Year	Type	MW-rated	N° Units	MW-Total	Comments
Otake Pilot		1978	Binary	1	1	(1)	Retired
Hatchobaru 3		2003	Binary	2	1	2	
Takigami Binary		1997	Binary	0.49	1	0.49	
Nigorikawa Pilot		1978	Binary	1	1	(1)	Retired
				Totals	**2**	**2.49**	

Mexico

Plant		Year	Type	MW-rated	N° Units	MW-Total	Comments
Los Azufres	Units 11&12	1993	Binary	1.5	2	3	
Maguarichic	Piedras de Lumbre	2001	Binary	0.3	1	0.3	
				Totals	**3**	**3.3**	

New Zeland

Plant		Year	Type	MW-rated	N° Units	MW-Total	Comments
Wairakei	Bottoming Unit	2005	Binary	5	3	15	
Kawerau	TaraweraOrmat	1989	Binary	1.3	2	2.6	
	TG2	1993	Binary	3.9	1	3.9	
Mokai	Mokai I	2000	Flash-Binary	25.5	1.6	55	
	Mokai II	2006	Flash-Binary	34.8	1.1	44	
Ngawha		1998	Flash-Binary	4.5	2	9	
Rotokawa	Combined cycle	1997	Flash-Binary	13,4.5	1.3	26.5	
	Extension	2003	Flash-Binary	4.5	1	4.5	
				Totals	**13**	**160.5**	

Philippines							
Plant		**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Luzon:	Binary I, II, III	1994	Binary	3	5	15	
Makiling-Banahaw	Binary	1994	Binary	0.73	1	0.73	
Leyte	Upper Mahiao Units 4-7	1996	Flash-Binary	34,12,5.5	5	142	
				Totals	**11**	**157.73**	
Russia							
Plant		**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Paratunka	Unit 1	1967	Binary	0.68	1	(0.68)	Retired
				Totals	**0**	**0**	
United States: California							
Plant		**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
East Mesa	GEM I	1979	Binary	13.4	1	(13.4)	Dismantled
	ORMESA I	1987	Binary	0.923	26	(24)	Original Plant
	ORMESA I	2003	Binary	10.1	4	22	
	ORMESA II	1988	Binary	0.825	20	16.5	
	ORMESA IE	1988	Binary	0.8	10	8	
	ORMESA IH	1989	Binary	0.542	12	6.5	
Heber	Binary Demo	1985	Binary	45	1	(45)	Dismantled
	Heber 2	1993	Binary	2.75	12	33	Orig. SIGC
	Gould	2006	Binary	2.5	4	10	
				Totals	**62**	**96**	
Casa Diablo							Aka Mammoth
	MP-I	1984	Binary	3.5	2	7	
	MP-II	1990	Binary	5	3	15	
	PLES-I	1990	Binary	3.3	3	10	
				Totals	**8**	**32**	
Honey Lake	Wineagle	1985	Binary	0.35	2	0.7	
	Amedee	1988	Binary	0.8	2	1.6	
				Totals	**4**	**2.3**	
United States: Nevada, Utah, Hawaii, Idaho and Alaska							
Plant		**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Nevada	Wabuska 1	1984	Binary	0.5	1	0.5	
	Wabuska 2	1987	Binary	0.7	1	0.7	
	Desert Peak 2	2007	Binary	6	2	12	
	Empire	1987	Binary	0.9	4	3.6	Aka San Emidio
	Steamboat I	1986	Binary	0.86	7	6	
	Steamboat IA	1988	Binary	0.55	2	1.1	
	Steamboat 2	1992	Binary	7	2	14	
	Steamboat 3	1992	Binary	7	2	14	
	Burdette	2006	Binary	10	2	20	Orig. Galena 1
	Galena 2	2007	Binary	10	1	10	
	Soda Lake 1	1987	Binary	1.2	3	3.6	
	Soda Lake 2	1991	Binary	2	6	12	
	Stillwater I	1989	Binary	0.93	14	13	
	Brady II	2002	Binary	3	1	3	
				Totals	**48**	**113.5**	
Utah	Cover Fort 1	1985	binary	0.5	4	(2)	Inactive
				Totals	**0**	**0**	
Hawaii	Puna PGV-1	1992	Flash-Binary	2.5	10	25	
				Totals	10	**25**	

Idaho	Raft River	1981	Binary	5	1	(5)	Dismantled, 1982
	Raft River Phase 1	2007	Binary	13	1	13	
				Totals	1	**13**	
Alaska	Chena Hot Springs	2006	Binary	0.2	2	0.4	
				Totals	2	**0.4**	
Australia							
Plant		**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Mulka	Unit 1	1986	Binary	0.02	1	(0.02)	Inactive
Birdsville	Unit 1	1992	Binary	0.15	1	0.15	
				Totals	**1**	**0.15**	
Austria							
Plant		**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Blumau: Rogner Hotel & Spa		2001	Binary	0.25	1	0.25	
Altheim	Unit 1	2002	Binary	1	1	1	
				Totals	**2**	**1.25**	
Costa Rica							
Plant		**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Miravalles	Unit 5	2004	Binary	9.5	2	19	
				Totals	**2**	**19**	
El Salvador							
Plant		**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Berlín	Bottoming Unit	2007	Binary	9.3	1	9.3	
				Totals	**1**	**9.3**	
Germany							
Plant		**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Neustadt-Glewe	Unit 1	2003	Binary	0.2	1	0.2	
				Totals	**1**	**0.2**	
Guatemala							
Plant		**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Zunil	Orzunil Unit 1	1999	Flash-Binary	3.5	7	24.6	
Amatitlán	Unit 1	2007	Flash-Binary			20	
				Totals	**7**	**44.6**	
Kenya							
Plant		**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Olkaria III	Phase I	2000	Flash-Binary	6	2	12	Aka West Olkaria Flower Company
Oserian	Unit 1	2004	Binary	1.8	1	1.8	
				Totals	**3**	**13.8**	
Nicaragua							
Plant		**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Momotombo	Unit 3	2002	Binary	7.5	1	7.5	
				Totals	**1**	**7.5**	

Portugal						
Plant	**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Ribeira Grande Phase A	1994	Binary	2.5	2	5	
Phase B	1998	Binary	4	2	8	
			Totals	**4**	**13**	
Thailand						
Plant	**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Fang Unit 1	1989	Binary	0.3	1	0.3	
			Totals	**1**	**0.3**	
Turkey						
Plant	**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Salavath Dora 1	2006	Binary	7.4	1	7.4	
			Totals	**1**	**7.4**	
Argentina						
Plant	**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Copahue Unit 1	1988	Binary	0.67	1	(0.67)	Retired in 1996
Ethiopia						
Plant	**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Langano Unit 1	1998	Flash-Binary	3.9,4.6	2	(8.5)	Inactive
Zambia						
Plant	**Year**	**Type**	**MW-rated**	**N° Units**	**MW-Total**	**Comments**
Kapisya	1986	Binary	0.1	2	(0.2)	Not Connected to transmission line