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Assessment of Technical Feasibility Based on Thermo-Exergic Analysis for Proposed Binary Cycle Power Plant for Tatapani Geothermal Field

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ABSTRACT - Tatapani Geothermal field is one of the most promising low-enthalpy geothermal fields in central India, located on Son-Narmada lineament in the state of Chhattisgarh, India. A proposed geothermal power plant has been designed for Tatapani Geothermal field which works on Organic Rankine Cycle (ORC). The binary power cycle using ORC has been industry accepted and widely used for exploitation of low enthalpy/low temperature geothermal resources. The complete feasibility study has been carried out using basic principles of ORC thermodynamic cycle along with exergy analysis to access maximum power output and thermal conversion efficiency of the proposed geothermal power plant at Tatapani. The working fluid considered for investigation is isopentane which is proven to provide optimum performance output. Maximum power output and thermal conversion efficiency are the primary goals of ORC thermodynamic analysis. The net work output has been evaluated for different mass flow rates of input brine.

The exergy analysis of proposed geothermal power plant has also carried out along with thermodynamic analysis. Exergy analysis highlights the areas of primary exergy destruction at various plant components and is illustrated in the form of exergy flow diagram. The loss of exergy indicates the potential reasons for the inefficiencies within a process and exergic efficiency as conversion of input heat energy from the brine in to useful work output. The exergic efficiencies are calculated for each component along with exergy destruction. The study conducted validates feasibility of setting up binary geothermal power plant at Tatapani from technical point of view.

Keywords : Geothermal power, Tatapani, ORC, Technical Feasibility, Thermodynamic Analysis, Exergy Analysis, Exergy destruction, Exergic efficiency.

I. INTRODUCTION

India is home to more than 300+ geothermal hot springs across the country. Majority of these geothermal resources are in low to medium temperature range, that is, from 70–150 °C and are suitable for direct heat applications and electric power generation using binary cycle power plant. These hot springs are categorized into seven geothermal provinces, which are as follows:

- Himalayan belt (Puga, Chhumathang)
- Sohana belt in Haryana
- Cambay Graben basin,
- Son-Narmada-Tapi lineament belt (Tatapani)
- West Coast
- Godavari basin
- Mahanadi basin **(Sharma et al, 2013)**

Tatapani is located 95 km NNE of Ambikapur in the state of Chhattisgarh, India. Tatapani thermal signature consists of hot springs (52-97 °C) in marshy ground area and hydro-thermally altered clay zones covering an area of approximately 0.1 sq. km **(Ravishankar,1987)**. Geological Survey of India (GSI) has carried out prospect evaluation by geochemical and geophysical studies along with exploratory drilling & well testing in association with Oil and Natural Gas Corporation Limited (ONGC), India. Total 26 wells drilled, out of which 5 wells were found to be most successful (with cumulative discharge of 1500 lpm). These completed five wells resulted in to hot water discharge temperature of > 100°C at the maximum depth of 350 ft. However, the silica geo-thermometer predicted an average reservoir temperature of around 157 °C. The Na-K geo-thermometer indicated bottom-hole temperature in the range of 180°C to 200°C and hence, the deeper reservoir

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are expected to be having higher than 157°C temperature as concluded by silica geo-thermometer. **(Sarolkar et al, 2015 & Chandrasekharam, 1995)**

The power potential of Tatapani geothermal field was estimated earlier by ONGC & GSI which evaluated around 11 MWe & 18 MWe power potential respectively. The available data indicates higher reservoir temperature may be 170°C to 200° C or more. Considering above, it is estimated that at the depth of 2000m and temperature of 150°C, Tatapani geothermal field expected to sustain power production of 25 MW to 30 MW depending on porosity range of 2% to 10%, by binary cycle or ORC method considering 10% plant efficiency. The power potential will very as per actual plant efficiency. This requires exploring deeper reservoir to assess true potential of the geothermal reservoir. **(Sarolkar et al, 2015)**

As part of this project, a binary cycle power plant is conceptualized based on power potential available by making use of comparative data from similar capacity existing binary cycle geothermal power plants. Certain assumptions are made for the study wherever there is no data available. A lot of exiting binary cycle plant data has been studied as a part of literature review so as to obtain best possible solution to get option power output & efficiency. The focus has been given to Thermodynamic & Exergy analysis which will provide clarity with respect to power output, efficiency & heat lost or exergy destroyed.

The major objectives of this research paper are as follows:

- The estimation of geothermal potential for electricity generation considering different scenarios of porosity %, conversion efficiency %, load factor etc.
- The thermodynamic analysis carried out for the proposed design of a binary cycle geothermal power plant for Tatapani geothermal field with suitable working fluid option. The working fluid type and cycle configuration are the main factors influencing the performance of the proposed plant.
- Evaluate maximum available work generated & efficiency for prospective installation using basic concepts & equations of ORC Thermodynamic cycle along with field geothermal resource potential estimation
- The exergy analysis facilitates plant performance evaluation along with highlight locations of primary exergy destruction. The exergic efficiency of various plant components are calculated to evaluate their individual performances.
- To provide a strong technical basis for the implementation of the proposed binary cycle geothermal power plant at Tatapani. The main contribution of this work will be to reaffirm the technical feasibility of the proposed plant using thermodynamic & exergic analysis. The research will further pave the way for the technical design aspects & economic feasibility of the plant.

CHARACTARISTICS OF TATAPANI GEOTHERMAL FIELD

Tatapani Geothermal field is a promising geothermal reservoir in the state of Chhattisgarh. The Tatapani hot springs are having surface temperature range of 50°C -97°C in marshy ground, and hydro thermally altered clay zones covering an area of about 0.1 sq km (Ravishanker, 1987). Geological Survey of India Tatapani Geothermal field is located 95 km from Ambikapur city and is connected by black top road from Bilaspur. Total 26 wells were drilled by ONGC as part of exploration campaign out of which wells Tat/6, Tat/23, 24, 25 & Tat/26 proved to be highly successful having hot water flow of 100°C on surface at 270 lpm to 425 lpm. The wells Tat/23, 24, 25 and 26 were drilled & completed as production wells with cumulative discharge from these wells of 1500 lpm. The feasibility study of binary geothermal power plant by using stated flow rates was established in collaboration with ONGC **(Pitale et al, 1995).**

Various studies have showed possibility of very high temperature (160° to 190°C) reservoir at deeper level. Geological & reservoir surveys have suggested low resistivity zones at a depth range of 300m to 600m which might relate to deep aquifer. The various survey methods are mentioned below along with indicated temperature range –

Sr. No.	Method of survey	Indicated Temperature
1	Geochemical aqueous Geo-thermometers	160 °C to 200°C
2	Hydrothermal alteration	180°C to 250°C
3	Fluid inclusion study	140°C to 250°C

Table 1

(Sarolkar, 2005)

At Tatapani geothermal field, along with high flow rate, water at near boiling point at atmospheric pressure but in association with a gas-phase of meteoric signature, indicates very well established convective circuit. The effluent water coming out of from proposed binary plant could be utilized for direct heating purposes such as spa and tourism etc. The estimated reservoir power potential is around 11 MWe with base temperature of 140°C covering an area of 2 sq km to 18 MWe with base temperature of 112°C over an area of 7.2 sq km at the estimated depth of 1500m. **(Pitale et al, 1995)**

II. SOLUTION METHODOLOGY

Estimation of Stored Heat (Geothermal Power Potential)

In this method, it is assumed that we are extracting the heat from a specific volume of rock, by cooling it down from its original state to a certain base temperature. The based considered is basically the lowest temperature at which it is viable to produce electricity commercially. However

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practically it is not possible to tap the heat resources contained in the rock fully due to uneven distribution of permeability & porosity of the rock. Due to this reason only, the stored heat is multiplied by a factor called recovery factor. The recovery factor varies between 10-50%, where average value of 25% for hydrothermal resources & 40% for enhanced geothermal resources depending upon the local geological conditions.

The estimation of geothermal potential for electricity generation is evaluated based on below equation:

Stored Heat $E_s = [(1-\emptyset).\rho_r.C_r + \emptyset.\rho_w.C_w].V.(T_r - T_b)$ Eq. 1

Recoverable Heat $E_r = E_s.R$ Eq. 2

Installed Power $N = \frac{E_r.n}{f.t}$ Eq. 3

(Mendrinos et al, 2008)

Table-2 represents the values of various geological parameters required for geothermal resource calculations based on previous works by **Sarolkar et al, 2015** & **Pitale et al, 1995**. These values are used to evaluate geothermal power potential in this study.

Parameter	Assumed Values
Area at the reservoir , m2	8000000
Reservoir Thickness, m	500 & 1000
Rock Heat Capacity , KJ/Kg °C	0.79496
Rock density, kg/m³	2660
Water heat capacity, kJ/kg°C	4.186
Water density, kg/m³	916
Rock Volume Estimated, m³	4000000000
Rock natural state temperature, °C	150
Base temperature, °C	74
Recovery factor, %	0.33

Table 2

Binary Power Cycle Concepts

As the name suggests, Binary means two working fluids are used in the power generation cycle. The primary fluid is high temperature geothermal fluid coming out of the well & the secondary fluid is basically working fluid (Hydrocarbon or Refrigerants) which circulates in the closed cycle is also called as power fluid.

The selection of cycle is based on the geothermal fluid temperature range. If the geothermal fluid temperature is between 130 to 180 °C ORC is preferred where if it is below 130 °C Kalina cycle is more suitable. ORC mainly uses various hydrocarbons as working fluid where as Kalina cycle works on a mixture of water-ammonia as working fluid. **(Valdimarsson, 2011)**

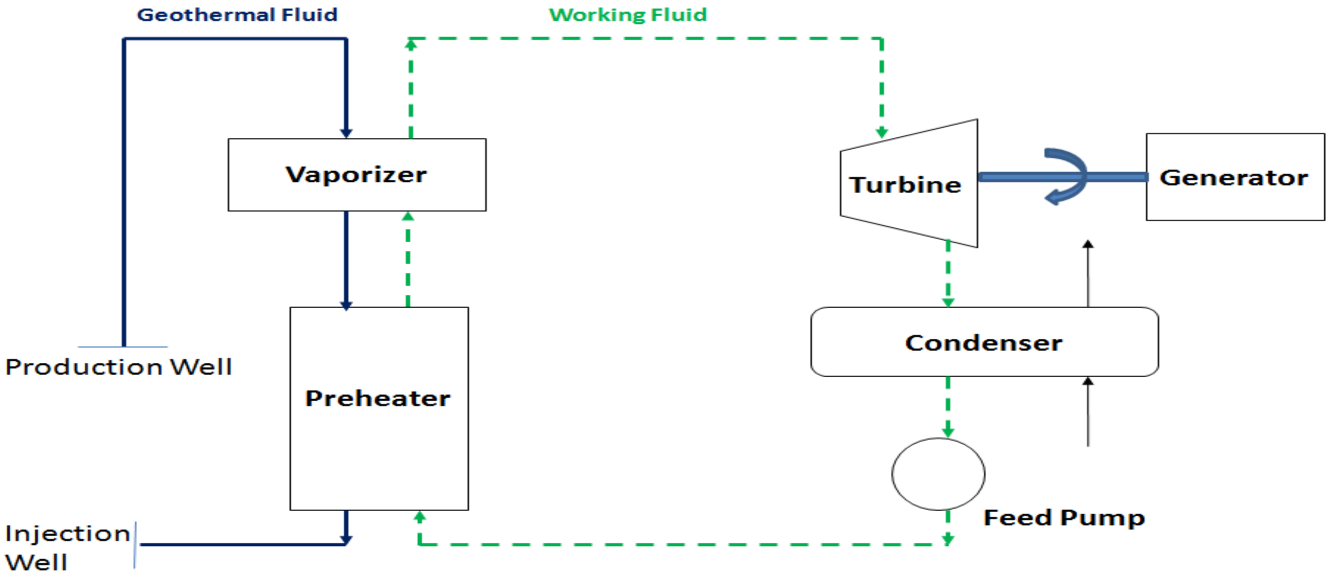

Figure: 1, Basic Binary Power System

In basic binary power system there are two closed loop systems; first heat transfer cycle is of geothermal fluid & second is of the ORC for working fluid. There is no direct contact of geothermal fluid with working fluid; hence heat transfer takes place by means of heat exchangers. The selected working fluid takes heat from geothermal fluid & evaporates, this evaporated vapor than falls on turbine at high pressure & temperature to produce mechanical work. The working fluid is discharged to a condenser where it is again converted into liquid phase using cooling medium such as air or water. The condensed liquid working fluid then pumped using a feed pump to the evaporator again & hence completes the cycle.

The major components of a binary cycle power plant are as follows:

1. Evaporater (Heat Exchanger)
2. Turbine
3. Condenser (Heat Exchanger, water cooled or air cooled)

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4. Feed pump
5. Pre-heater (Heat Exchanger)
6. Generator

Selection of Working Fluid

Selection of the working fluid is of foremost consideration in designing the geothermal power system. There are various factors must be considered in selecting the working fluid. The proper choice of working fluid has got direct impact on the performance of the unit. Due to low temperature of the heat source, irreversibilities within the heat exchangers are very detrimental to the overall efficiency of the cycle. These irreversibilities are highly dependent on the thermodynamic properties of the working fluid. The thermodynamic properties of the working fluid as critical pressure, critical temperature, boiling point, toxicity etc mainly influence the performance of the system. Other essential criteria include the influence of the working fluid on overall cost, Health, safety and environmental effects.

Fluid	Formula	Critical Temp (°C)	Critical Pressure (bar)	Toxicity	Flammability	Molecular Wt.
i-Pentane (iC5)	i-C5 H12	187.8	34.09	Low	Very high	72.15
n-Pentane (nC5)	C5 H12	193.9	32.40	Low	Very high	72.15
i-Butane (iC4)	i-C4 H10	134.9	36.85	Low	Very high	58.12
n-Butane (nC4)	C4 H10	152.0	37.18	Low	Very high	58.12
Propane (C3)	C3 H8	96.6	42.36	Low	Very high	44.1

Table 3

Past studies concluded that the highest net power output & thermal efficiency is obtained from the isopentane working fluid for the similar temperature range among the hydrocarbon working fluids for a binary ORC **(Ahangar, 2012)**. Hence isopentane has been selected as working fluid for this project.

III. THERMODYNAMIC & EXERGIC ANALYSIS

The proposed binary cycle geothermal power plant diagram is designed based on the previous works done by various researchers on this subject in order to carry out detailed thermodynamic & exergic analysis. The basic data has been taken based on actual realistic numbers from previous works and suitable assumptions are made wherever applicable or in case of data unavailability.

i. Thermodynamic Analysis Methodology

In 1961, Harry & Lucien developed a method for make use of low boiling temperature organic fluid as the working fluid for power turbines for producing electricity. Conventionally, electrical power is generated using Rankine power cycle using water as working fluid.

In an Organic Rankine Cycle using an organic fluid as working fluid instead of water. It facilitates heat recovery from lower temperature resources such as industrial waste heat, geothermal heat, solar ponds, etc. The low temperature heat is than converted into useful work that can be converted into power.

The working principle of the Organic Rankine cycle is very much similar to Rankine cycle. In ORC, there is a heat source in the form of hot water coming out of geothermal well instead of boiler.

In the ideal ORC cycle include primarily four processes as explained below w.r.t below figures 2 & 3 as examples:

1. **Isobaric Evaporation (1–4)**. It means that there is no pressure change in the heat exchanger. It can be further divided into three catagories: preheating (1-2), evaporation (2-3) & superheating (3-4).

2. **Isentropic Expansion (4–5)**. Isentropic expansion is an adiabatic (during the process there is no heat exchange with the environment) and is reversible (No pressure drops, no fiction losses or nil leakages).

3. **Isobaric Condensation (5–8)**. It can be subdivided into the de-superheating (5-6), condensation (6-7) and sub-cooling (7-8) processes.

4. **Isentropic Pump (8–1)**. For an isentropic compression on a liquid, dS = dT =0.

Where as in the real cycle, due to the presence of irreversibility's reduces the cycle efficiency. Irreversibility's mainly occur due to below:

- **In the expansion:** In the real expansion process, only a part of energy is converted in to useful work. The remaining part is converted into heat and lost to the surroundings.

- **In the heat exchangers:** The pressure drops across the heat exchanger causes reduction in power recovery.

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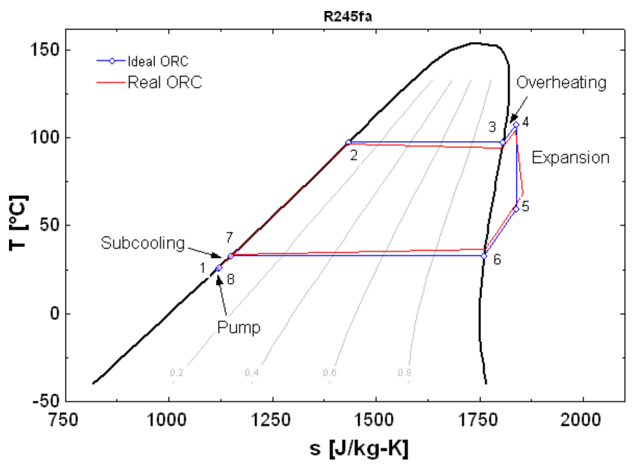

Figure: 2

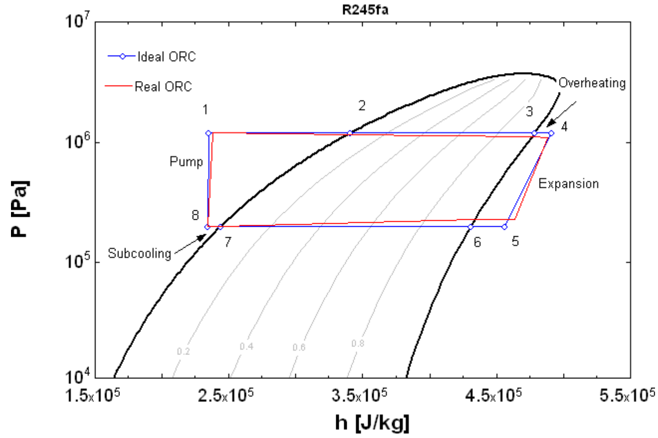

Figure: 3

- **In the pump**: This includes internal leakages & electro-mechanical losses.

The expansion work can be given by:

- From the T-s diagram, (assuming the vapor is a perfect gas):

  $w_{exp} = c_p * (T_4 - T_5)$ Eq. 4

- From the p-h diagram,

  $w_{exp} = h_4 - h_5$ Eq. 5

The diagrams show that the irreversibility's considerably reduces the amount of useful work that can be recovered. **(Quoilin, 2008)**

ii. ORC Cycle efficiency

The cycle efficiency is basically net work (the work turbine minus the work of the pump) divided by the amount of heat supplied.

Pump Work: $w_{pump} = h_1 - h_8$ Eq. 6

Heat Supplied: $q_{boil} = h_4 - h_1$ Eq. 7

In order to get the powers, the intensive variables must be multiplied by the mass flow rate:

$\dot{W}_{exp}\ [W] = \dot{M}\,.\ w_{exp}$ Eq. 8

$\dot{W}_{pump}\ [W] = \dot{M}\,.\ w_{pump}$ Eq. 9

$\dot{Q}_{boil}\ [W] = \dot{M}\,.\ q_{boil}$ Eq. 10

The ORC cycle efficiency:

$$\eta = \frac{\dot{W}_{exp} - \dot{W}_{pump}}{\dot{Q}_{boil}} = \frac{w_{exp} - w_{pump}}{q_{boil}} = \frac{(h_4 - h_5) - (h_1 - h_8)}{h_4 - h_1} \qquad \text{Eq. 11}$$

Above equation is only valid for adiabatic expansion and compression. In the case of a heat exchange between the Turbine (or pump) and the surroundings, a heat balance will be shown by:

$\dot{W}_{exp} = \dot{M}\,.\ (h_4 - h_5) - \dot{Q}_{amb,exp}$ Eq. 12

$\dot{W}_{pump} = \dot{M}\,.\ (h_1 - h_8) - \dot{Q}_{amb,pump}$ Eq. 13

Where Q_{amb} is the heat exchanged between the turbine (or the pump) and the ambiance.

The cycle efficiency becomes:

$$\eta = \frac{\dot{W}_{exp} - \dot{W}_{pump}}{\dot{M}\,.\ (h_4 - h_1)} = \frac{[\dot{M}\,.\ (h_4 - h_5) - \dot{Q}_{amb,exp}] - [\dot{M}\,.\ (h_1 - h_8) - \dot{Q}_{amb,pump}]}{\dot{M}\,.\ (h_4 - h_1)} \qquad \text{Eq. 14}$$

(Quoilin, 2008)

iii. Exergy Analysis Methodology

The first law of thermodynamics deals with the quantity of energy and implies that energy cannot be created or destroyed. This law hardly serves as an important tool for the recording of energy during a process and offers no challenges to the engineer. However, the second law deals with the quality of energy. More precisely, it is concerned with the degradation of energy during the process, the entropy generation, and the opportunities lost to do useful work; and it offers plenty of room for improvement. **(Cengel et al, 5th Edition 2017)**

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The exergy, which is a property, implies regarding total useful work available, which is also known as availability or available energy. The rest of the energy, which is wasted or discarded to the surroundings & not useful, is termed as unavailable energy.

Exergy analysis is a powerful tool for assessment of a thermodynamic system & focus on wastage of energy at various states of a system. This enables us to determine useful work output for a given state & also for an entire system.

The exergy analysis provides below information regarding a system -

- Provides amount of useful work available & lost/discarded to the surroundings
- Pin points the area of low efficiency or high wastage of energy
- Provides information of overall efficiency of a process

Ignoring kinetic and potential energy changes, the specific flow exergy of geothermal fluid at any state (at geothermal plant location) can be evaluated from below formula

$$e = h - h_0 - T_0(s - s_0) \qquad \text{Eq. 15}$$

The exergy rate can be obtained by multiplying specific exergy by the mass flow rate of the geothermal fluid,

$$\dot{E} = \dot{m}\,.\,e \qquad \text{Eq. 16}$$

Pre-heaters, Evaporators or vaporizers, and condensers in the plant are essentially heat exchangers designed to perform specific tasks. The exergy efficiency of a heat exchanger can be measured by the increase in the exergy of the cold stream of fluid divided by the decrease in the exergy of the hot stream of fluid. That is;

$$\dot{E}_{vap\ (A)} = \frac{\dot{E}_{10}-\dot{E}_9}{\dot{E}_1-\dot{E}_2} \qquad \text{Eq. 17}$$

Exergy distruction is basically difference between the numerator and denominator in above Eq. for a heat exchanger. That is,

$$\dot{I}_{vap\ (A)} = (\dot{E}_1 - \dot{E}_2) - (\dot{E}_{10} - \dot{E}_9) \qquad \text{Eq. 18}$$

Exergy efficiency and exergy destruction relations for Level-A vaporizer-preheater system as

$$\varepsilon_{vap-pre\ (A)} = \frac{\dot{E}_{10}-\dot{E}_8}{(\dot{E}_1-\dot{E}_2)-(\dot{E}_3-\dot{E}_4)} \qquad \text{Eq. 19}$$

$$\dot{I}_{vap-pre\ (A)} = (\dot{E}_1 + \dot{E}_3 + \dot{E}_8) - (\dot{E}_2 + \dot{E}_4 + \dot{E}_{10}) \qquad \text{Eq. 20}$$

The exergetic efficiency of the condenser is calculated as explained above. However, the exergy destruction in the condenser is expressed by the exergy drop of isopentane across the condenser.

Similarly, The exergetic efficiency of a turbine:

$$\varepsilon_{turb(A)} = \frac{\dot{W}_{turb\ (A)}}{(\dot{E}_{10}-\dot{E}_{11})} \qquad \text{Eq. 21}$$

The exergy destruction in the turbine:

$$\dot{I}_{turb\ (A)} = (\dot{E}_{10} - \dot{E}_{11}) - \dot{W}_{turb\ (A)} \qquad \text{Eq. 22}$$

The exergetic efficiency and exergy destruction for the Level-A pump:

$$\varepsilon_{pump(A)} = \frac{\dot{E}_8-\dot{E}_7}{\dot{W}_{pump\ (A)}} \qquad \text{Eq. 23}$$

$$\dot{I}_{pump\ (A)} = \dot{W}_{pump\ (A)} - (\dot{E}_8 - \dot{E}_7) \qquad \text{Eq. 24}$$

The exergetic efficiency of Level-A isopentane cycle can be determined as below:

$$\varepsilon_{level(A)} = \frac{\dot{W}_{net\ (I)}}{(\dot{E}_1-\dot{E}_2)+(\dot{E}_3-\dot{E}_4)} \qquad \text{Eq. 24}$$

Total exergy distruction in Level-A cycle can be determined by

$$\dot{I}_{level(A)} = \dot{I}_{pump\ (A)} + \dot{I}_{vap\ (A)} + \dot{I}_{pre\ (A)} + \dot{I}_{turb\ (A)} + \dot{I}_{cond\ (A)} \qquad \text{Eq. 25}$$

The exergetic efficiency of the plant, ***based on total brine exergy drops across the vaporizer-preheater systems of Level-A and Level-B cycles*** (i.e. total exergy inputs to Level-A and Level-B cycles), can be given as below

$$\varepsilon_{plant} = \frac{\dot{W}_{net\ plant}}{(\dot{E}_1-\dot{E}_2)+(\dot{E}_3-\dot{E}_4)+(\dot{E}_2-\dot{E}_3-\dot{E}_5)+(\dot{E}_5-\dot{E}_6)} \qquad \text{Eq. 26}$$

The First Law thermal efficiency of the plant, *can be* calculated from

$$\eta_{plant} = \frac{\dot{W}_{net\ plant}}{\dot{m}_1(h_1-h_2)+\dot{m}_3(h_3-h_4)+\dot{m}_2(h_2-h_5)+\dot{m}_5(h_5-h_6)} \qquad \text{Eq. 27}$$

Where the terms given in the denominator are heat transfer rates in vaporizer A, preheater A, vaporizer A, and preheater A, respectively**. (Kanoglu, 2002 & Koroneosa et al, 2017)**

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IV. PROPOSED GEOTHERMAL POWER PLANT

A binary cycle geothermal power plant diagram has been designed for Tatapani Geothermal field based on reference research works across the globe based on suitability of application, reference temperature range & flow rates/discharge of geothermal fluid. A lot of assumptions have been made in the analysis based on actual geothermal power plant conditions for the operational power plants worldwide. The proposed geothermal power plant works in closed loop & there is zero environmental discharge.

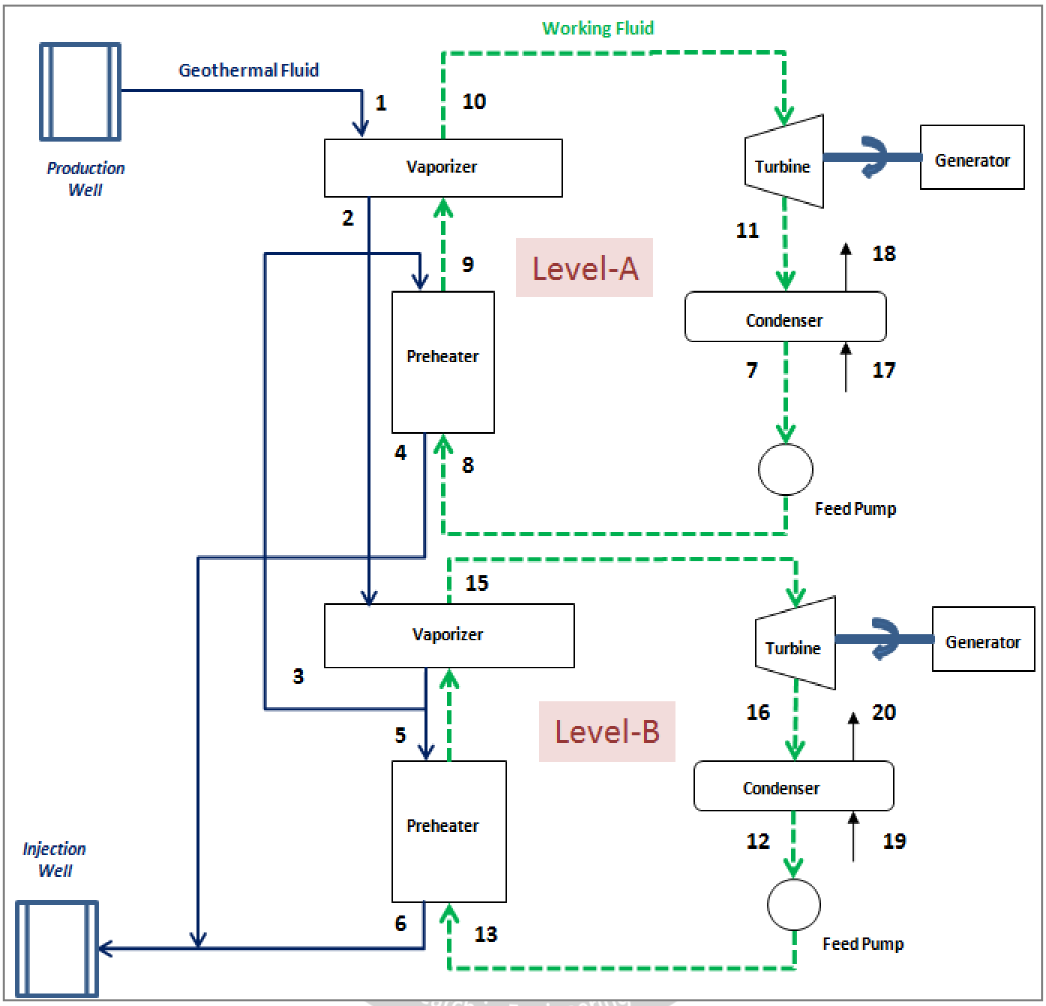

Figure: 2 Proposed Binary cycle power plant

The plant diagram is designed such that the geothermal fluid passes through two levels i.e; Level-A & Level-B. The brine which exits level-A vaporizer is directly fed to level-B vaporizer where the brine further transfers heat energy to isopentane cycle. The brine is then equally divided in to equal quantity & diverted to preheaters of level-A & Level-B respectively so that further heat transfer takes place. The brine leaving from preheaters is diverted to the injection well. **(Kanoglu, 2002**)

Key Assumptions:

- ✓ Geothermal Brine thermodynamic properties are considered as water
- ✓ The effect of non-condensable gases & salts present in the geothermal fluid are negligible and hence are ignored
- ✓ Geothermal fluid passes through two levels, level-A&B
- ✓ Mass flow rate - 150 kg/s
- ✓ Geothermal Fluid Temperature from the well - 150 °C
- ✓ The condition of isopentane at turbine inlet is considered to be saturated vapor
- ✓ Brine Re-injection Temperature – 60 °C
- ✓ Heat losses & Pressure drops across various components of the plant are neglected
- ✓ Working fluid – Isopentane

Based on previous works, it has been concluded that the Isopentane as working fluid tends to prove more efficient & suitable for Binary cycle geothermal power plants as compared to other working fluid options such as Isobutane, n-pentane & n-butane. **(Ahanger, 2012)**

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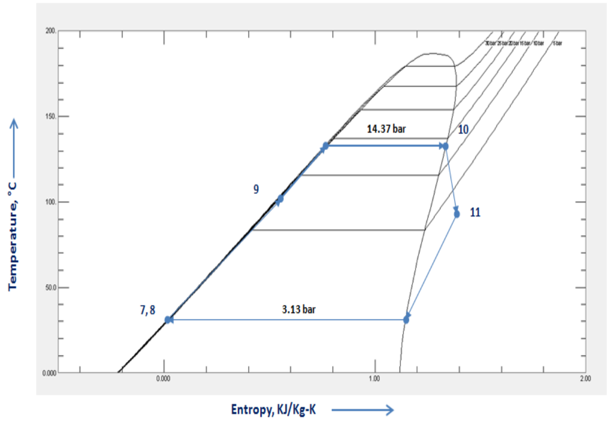

Figure: 3 P-H Diagram of Level-A Isopentane Cycle

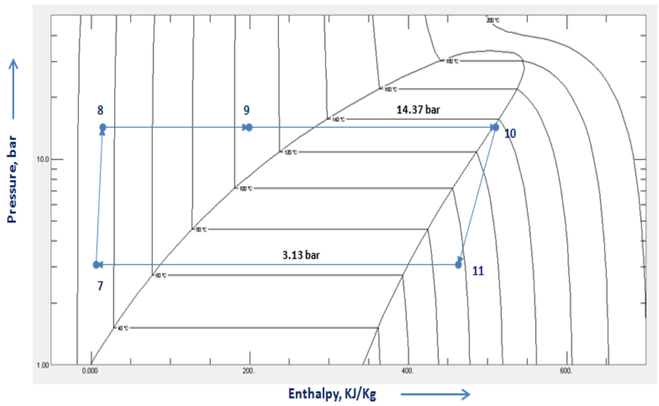

Figure: 4 T-S Diagram of Level-A Isopentane Cycle

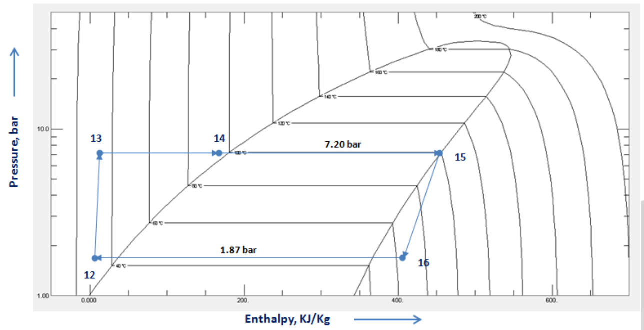

Figure: 5 P-H Diagram of Level-B Isopentane Cycle

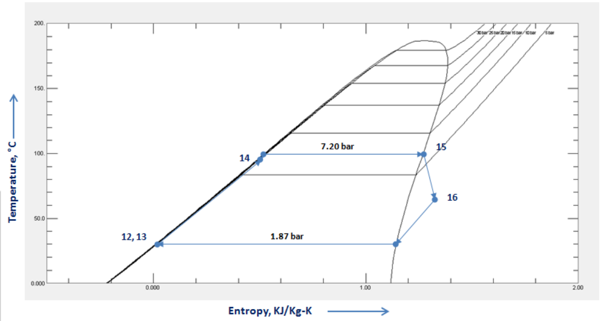

Figure: 6 T-S Diagram of Level-B Isopentane Cycle

Tools/Hardware/Software Used:

- Thermodynamic property values for Isopentane are taken from **REFPROP**, NIST standard reference database 23, version 8.0
- Thermodynamic properties of water are used in place of geothermal fluid from standard Steam Table.

RESULTS & DISCUSSION

Using equations given in methodology section, the Tatapani geothermal Field potential based on different porosity, conversion or plant efficiency and load factor is evaluated using equations 1, 2 & 3 as below:

Case-1: Rock natural state temperature - 150°C, Base temperature - 74°C, Reservoir thickness - **500m**

Sr. No	Assumed Porosity	Power Potential at 10% plant efficiency, MWe		Power Potential at 7.5% plant efficiency, MWe		Power Potential at 4.84 % plant efficiency, MWe (As obtained by thermo-exergic analysis)	
		95 % Load	*100% Load*	*95 % Load*	*100% Load*	*95 % Load*	*100% Load*
1	**0.1**	**38.3**	**36.4**	**28.7**	**27.3**	**18.5**	**17.6**
2	**0.05**	**36.8**	**35**	**27.6**	**26.2**	**17.8**	**16.9**
3	**0.02**	**36**	**34.1**	**27**	**25.6**	**17.4**	**16.4**

Table 4

Hence, Best case scenario – 38.3 MWe, Worst Case scenario – 16.4 MWe

Case-2: Rock natural state temperature - 150°C, Base temperature - 74°C, Reservoir thickness - **1000m**

Sr. No	Assumed Porosity	Power Potential at 10% plant efficiency, MWe		Power Potential at 7.5% plant efficiency, MWe		Power Potential at 4.84 % plant efficiency, MWe (As obtained by thermo-exergic analysis)	
		95 % Load	*100% Load*	*95 % Load*	*100% Load*	*95 % Load*	*100% Load*
1	**0.1**	**76.6**	**72.7**	**57.4**	**54.5**	**37.1**	**35.2**
2	**0.05**	**73.7**	**70.0**	**55.3**	**52.5**	**35.7**	**33.9**
3	**0.02**	**72.0**	**68.4**	**54.0**	**51.3**	**34.8**	**33.0**

Table 5

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Hence, Best case scenario – 76.6 MWe, Worst Case scenario – 33. 0 MWe

Exergy rates & other properties at the binary power plant at various locations based on proposed power plant layout are calculated using equations 4-14 as following:

State No	Fluid	Phase	Temp, T (^{0}C)	Temp, T (K)	Pressure, P (Bar)	Enthalpy, h (KJ/Kg)	Entropy, S (KJ/Kg ^{0}C)	Mass Flow rate, ṁ (Kg/s)	Specific Exergy, e(KJ/Kg)	Exergy Rate, Ė (KW)
0	Brine	Dead state	13	286	1.013	54.69	0.20	-	-	-
0	Isopentane	Dead state	13	286	1.013	-33.36	-0.11	-	-	-
1	Brine	Liquid	150	423	-	632.27	1.84	150	106.85	16028.20
2	Brine	Liquid	120	393	-	503.90	1.53	150	67.82	10173.10
3	Brine	Liquid	100	373	-	419.25	1.31	75	46.87	3515.08
4	Brine	Liquid	60	333	-	251.26	0.83	75	14.51	1088.46
5	Brine	Liquid	100	373	-	419.25	1.31	75	46.87	3515.08
6	Brine	Liquid	60	333	-	251.26	0.83	75	14.51	1088.46
7	Isopentane	Liquid	30	303	3.1386	5.16	0.02	61.57	1.44	88.64
8	Isopentane	Liquid	30.6	304	14.37	7.40	0.02	61.57	3.30	203.32
9	Isopentane	Liquid	105	378	14.37	194.64	0.57	61.57	33.30	2050.03
10	Isopentane	Sat. Vapor	135	408	14.37	507.40	1.34	61.57	124.45	7662.23
11	Isopentane	Sup. Vapor	95	368	3.1386	460.80	1.37	61.57	69.87	4301.72
12	Isopentane	Liquid	30	303	1.8733	5.06	0.02	44.06	1.24	54.59
13	Isopentane	Liquid	30.3	303	7.2	6.10	0.02	44.06	2.12	93.48
14	Isopentane	Liquid	95	368	7.2	167.23	0.50	44.06	25.87	1139.81
15	Isopentane	Sat. Vapor	100	373	7.2	455.42	1.27	44.06	92.91	4093.39
16	Isopentane	Sup. Vapor	68	341	1.8733	412.04	1.29	44.06	44.49	1960.19
17	Water	Liquid	13	286	1.013	54.69	0.19	394.38	0.63	247.15
18	Water	Liquid	30	303	1.013	125.82	0.43	394.38	2.62	1033.27
19	Water	Liquid	13	286	1.013	54.69	0.19	252.09	0.63	157.98
20	Water	Liquid	30	303	1.013	125.82	0.43	252.09	2.62	660.48

Table 6

Exergy destruction, exergic efficiencies & first law efficiencies for various plan components for level A & B are evaluated using equations 15 – 27 as following:

Component	Exergy destruction (KW)	Exergic Efficiency (%)	Heat Transfer or power (KW)	First law efficency (%)
Vaporizer A	242.90	95.85%	19255.50	
Vaporizer B	189.38	93.97%	12697.50	
Preheater A	579.91	76.10%	12599.25	
Preheater B	1380.28	43.12%	12599.25	
Condenser A	4213.08	18.66%	28052.35	
Condenser B	1905.60	26.37%	17931.50	
Turbine A	491.52	85.37%	2868.99	

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Turbine B	221.89	89.60%	1911.30	
Pump A	23.47	83.01%	138.15	
Pump B	7.11	84.54%	46.00	
Net Level A Cycle	5550.87	32.97%	2730.84	**8.57%**
Net Level B Cycle	3704.27	33.49%	1865.30	**7.37%**
Net Combined Level A-B	9255.14	33.18%	4596.14	**8.04%**
Overall Plant (based on exergy input to isopentane cycle)	9255.14	30.29%	4196.14	**7.34%**
Overall Plant (based on exergy input to the plant)	9255.14	26.18%	4196.14	**4.84%**

Table 7

Net work output:

Net Work output , Level-A	2730.84 KW
Net Work output , Level-B	1865.30 KW
Net Work output , Combined Level-A & B	4596.14 KW
Net Work output (Plant)	**4196.14 KW**

Table 8

Note: Assumed parasitic power is 400 KWe which includes auxiliaries' power consumption. *Total plant work output will be difference of total work net minus parasitic power.*

Exergy Flow Diagram:

Based on above calculations in Table-7, we obtain below flow diagram given as the percentage of brine exergy input in below figure. This clearly represents the amount of exergy lost in various components as well as net power output.

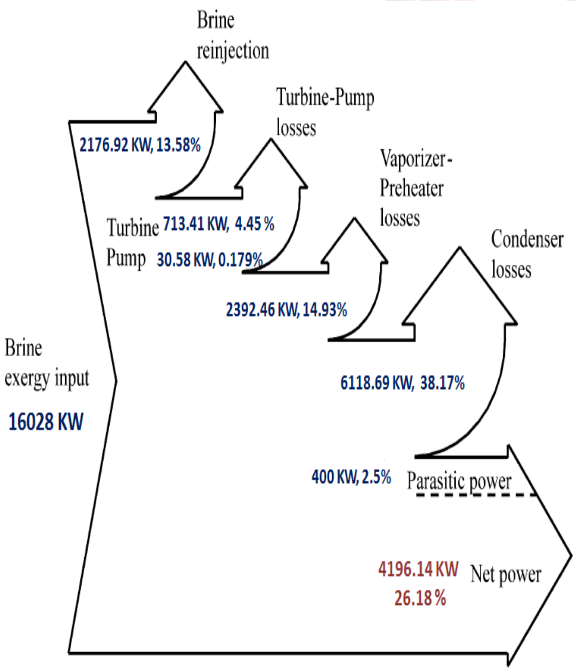

Figure: 7 Exergy Flow Diagram

1. The project validates feasibility of setting up binary geothermal power plant at Tatapani from technical point of view based on geothermal potential calculations, thermodynamic & exergy analysis. The estimated power potential ranges from minimum **16.4 MWe** to maximum **38.3 MWe** considering reservoir thickness of 500m. Hence considering **4.1 MWe** output from one unit, minimum four such units can be installed in the field to tap full geothermal potential. However, considering reservoir thickness of 1000m, the estimated power potential ranges from minimum **33.0 MWe** to maximum **76.6 MWe**.

2. Complete thermodynamic & exergy analysis conducted using basic concepts & equations provides very strong support to idea of establishing **4.1 MWe** capacity binary geothermal power plant with only single unit working on two level cycles considering brine input temperature of 150°C with brine flow rates of 150 kg/s. Even with half the flow rate i.e., 75 Kg/s, it is capable of producing & sustaining 1.8 MW of power. The study re-affirms the earlier evaluation by **Sarolkar and Das (2015)** to be able to sustain power potential of 28 MW to 30 MW depending upon porosity considering 10% plant efficiency & 17 MW to 18.1 MW at 6% plant efficiency provided deeper reservoirs are explored & exploited.

3. The thermodynamic cycles were constructed based on stated assumptions & data considered for isopentane as working fluid for ORC as shown on P-H & T-S diagrams for level-A & level-B cycles. The data was than evaluated based on thermodynamic equations & net work output & thermodynamic efficiency for the plant was calculated.

4. The exergic efficiency obtained for the power plant based on isopentane organic rankine cycle is 30.2% whereas the exergic efficiency based on energy input from brine (at level-A vaporizer) to the plant is 26.1%. The exergy flow diagram obtained from the analysis clearly shows that 71.3 % of the total exergy input to the binary power plant is lost. Out of remaining 28.6 %, only 26.1% is converted to work output, whereas 2.5% is consumed by the parasitic loads in the plant.

5. The exergic efficiency obtained in previous works by **Dipippo & Marcille (1984)** has been calculated to be 20% & 33.3% based on exergy input to the plant & rankine cycle respectively with 140°C input brine temperature. **Kanoglu (2002)**, obtained exergic efficiencies of 29.1% & 34.2 % based on exergy input to the plant & rankine cycle respectively with 162°C input

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brine temperature. Based on comparison done by **Koroneos (2017)**, the exergic efficiency for binary geothermal power plant ranges from 20% to 50%. Hence our results of exergic efficiency for proposed binary cycle geothermal power plant i.e.; 26.1% & 30.2% based on exergy input to the plant & rankine cycle respectively with 150°C input brine temperature assumption are within the acceptable range; however it can further be improved by reducing the amount of exergy destruction.

6. The first law efficiency for the proposed power plant is calculated to be **4.8%** & **7.3%** based on exergy input to the plant & based on input to the isopentane rankine cycle respectively. This implies that more than 90% of the input energy is lost as waste heat. This can be treated as a justification for the use of geothermal heat for district heating whenever suitable & economically viable.

V. CONCLUSION & FUTURE SCOPE

1. The proposed geothermal power plant design came out as sensible & practical design assuming various plant data with suitable working fluid. Considering base temperature of 150°C, the power potential resulted to be equivalent to 4.1 MWe from one prospective unit having two levels. However based on this study, further analysis can be easily carried out for different geothermal fluid temperatures inputs to evaluate equivalent power potential. Also various working fluids can be evaluated for improvement in power output and efficiency.

2. The aim of thermodynamic & exergy analysis was to have clear view of overall plant performance, identify points of exergy destruction and evaluate scope to improve further along with verifying technical feasibility of plant. There seems a great scope in improving efficiencies of both the pre-heaters and condensers. Additionally condensers can be evaluated further for air as cooling medium to analyze if it adds value.

3. The study utilizes concepts & data from existing/operational geothermal power plants given in various research papers, which makes the analysis extremely reliable, however the overall plant efficiency can further be increased by minimizing points of exergy losses or making use of most efficient heat exchangers/turbines. The heat exchanger sizing is a major influencing factor in the design of the power plant. The choice of heat exchanger depends upon the value of pinch point temperature difference. Smaller pinch point temperature difference value represents expensive heat exchanger whereas high pinch point temperature difference corresponds to less expensive heat exchangers. As a rule of thumb, the pinch should be around 5 to 10 K to have economical or optimal design. In this project, we have maintained the value of pinch above 5K in all the heat exchangers and hence the results are realistic & practical.

4. Geothermal energy has the potential to play a very significant role in improving quality of life of millions of people in region. It is one of the few renewable power technologies which are capable to supply continuous, base-load power to an electric grid. The Binary geothermal plants have the capability to ramp up or down production multiple times each day ranging from 100% to as low as 10-15%. The unit cost of electricity from geothermal plants is also becoming increasingly competitive with respect to conventional energy resources. As a source of heating, for millions of homes and businesses at any location makes its future even brighter.

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NOMENCLATURE

$\emptyset$	Porosity, (%)
ρ_r	Rock density, kg/m³
ρ_w	Water density, kg/m³
C_r	Rock heat capacity, kJ/kg°C
C_w	Water heat capacity, kJ/kg°C
V	Rock Volume, m³
T_r	Rock natural state temperature, °C
T_b	Base temperature, °C
R	Recovery factor
n	Conversion efficiency
f	Load factor
t	Commercial life span of the plant, msec
E_s	Stored Heat, KJ
E_r	Recoverable Heat, KJ
N	Installed power, MWe
P	Pressure, bar
T	Temperature, °C
h	Specific Enthalpy, KJ/Kg
s	Specific Entropy, KJ/Kg-K
$\dot{W}$	Power, KW
η	First Law Efficiency, %
$\dot{I}$	Exergy destruction, KW
ε	Exergic Efficiency, %
$\dot{E}$	Exergy Rate, KW
$\dot{m}$	Mass flow rate, Kg/s
e	Specific flow exergy, KJ/Kg

SUBSCRIPTS

0	Dead state
A	Level-A
B	Level-B

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Cond	Condenser
Pre	Pre-heater
Turb	Turbine
Vap	Vaporizer

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