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PLANNING AN OVERHAUL OF THE EXISTING, NON-OPERATING KAPISYA GEOTHERMAL BINARY POWER PLANT (USING PERCHLORO-ETHYLENE) AFTER A PROLONGED DORMANCY PERIOD

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ABSTRACT

In Zambia, a small pilot geothermal Turboden binary power generating plant was constructed, but has remained non-operational for an extended period of time. The plant has been earmarked for reconditioning with a view to improving brine resources and up-rating the electro-mechanical equipment's capacity. With resource evaluations in progress and the plant's surface facility conditions assessed, the plant is set to be operational after equipment overhaul. This study examines the actual and potential overhaul requirements considering both non-operating and operating plant system states in a geothermal environment. The evaluation indicates that a condition-based equipment overhaul can be undertaken, incorporating potential equipment improvements in the system for enhanced performance. Baseline operating reliability maintenance strategy has been proposed by considering the Svartsengi Ormat binary plant standards in Iceland, operating experience and original equipment manufacturers' recommendations. Making geothermal electrical energy as a preferred green energy source calls for an increase in exploration, drilling and plant construction expenses coupled with an effective reliability of plant maintenance and management.

1. INTRODUCTION

Zambia's electrical energy is predominantly hydro-generated. The current total installed generation capacity stands at 1,640 Megawatts (MWe). Only 8 MWe is diesel generated. The national peak demand for 2008 is 1,500 MWe. The annual national demand growth rate for electrical power is 3-4%. For the security of power generation in the event of a drought, the country needs to develop other potential sources of energy, such as the energy stored within the earth's crust.

An inventory of geothermal prospects was carried out to study most of the areas with geothermal surface manifestations to establish their potential to generate electricity for small rural communities far removed from the national power grid. Two sites were targeted for further investigations and development: the Kapisya hot springs and the Chinyunyu areas. The geoscientific studies for the two sites were undertaken with a view to resuscitating and up-rating the existing, non-operating Kapisya geothermal binary power plant which has a nominal capacity of 200 kilowatts (kWe). In 1988, the Turboden binary power plant was installed with the assistance of the Italian government, as a project run by the Geological Survey Department of the Republic of Zambia. The plant has remained dormant since then leading to loss of functional capacity due to equipment degradation.

The installed capacity of the existing binary plant is insufficient to meet the projected power demand for the surrounding areas. The plant is situated in the northern part of Zambia, at the Kapisya hot springs located in the Nsumbu National park, along the western shores of Lake Tanganyika. The country's objective is to utilise renewable energy resources and replace diesel-based power generation where it is in use.

The Kapisya binary plant is based on the organic Rankine thermodynamic cycle (ORC). The ORC technology is a good option with further growth potential for low/medium scale geothermal applications at low-enthalpy geothermal levels (Gaia, 2006). The ORC principle is based on a turbine working similarly to a normal steam turbine but using a secondary working fluid to transform geothermal energy, through heat exchangers, into mechanical energy by expanding through a binary turbine and finally into electric energy through an electric generator. Environmental concerns over climate change and rising oil prices are powerful reasons supporting the explosive growth of this efficient, clean and reliable way of producing electricity.

In view of the need to restore the Kapisya geothermal binary plant functional ability, KenGen – the Kenya Electricity Generating Company was engaged to carry out the necessary assessments. The assessments aim at overhauling, re-commissioning and investigating the possibility of expanding plant capacity. Brine gathering and plant equipment condition assessments were conducted. Geoscientific surveys were also carried out for the Kapisya geothermal fields, in view of power plant capacity expansion. The geoscientific works carried out included geological, geophysical and geochemical investigations. Geochemical surveys involved radon and carbon dioxide (CO_2) gas measurements in soil, sampling of hot and cold springs and borehole water, and geophysical investigations involving the use of the magneto-telluric (MT) and transient electromagnetic (TEM) methods.

The difference in geothermal fields' chemistry characteristics is a major factor in the varying approaches in maintenance methods and management, as they are field specific. The chemistry of most geothermal fluids present maintenance challenges for geothermal power stations as the fluids contain dissolved and suspended elements such as silica, chlorides, carbonates, sulphurs, gases and rock cuttings. Chemical and physical analyses of the brine from the Kapisya field were carried out. The Kapisya geothermal field has an estimated reservoir sodium-potassium ratio and quartz temperature solute geothermometer temperatures of about 124°C (low-enthalpy resource) at the present depth of production (Omenda et al., 2007).

The conceptual model for the Kapisya geothermal system indicates that the reservoir is rift fault controlled and can be tapped by drilling wells up to 500 m depth. The use of downhole well pumps to supply hot water to the heat exchangers would still be required as temperatures are too low to allow for sufficient self-flow to the plant. Five deep wells have been recommended for drilling to confirm the extent and depth of the reservoir and to produce adequate hot water to the power plant. The high resource potential area in Kapisya measures between 0.5 and 1 km^2. There is a high chance (more than 60%) of getting more than 2 MWe using the binary system that is currently installed at Kapisya for generation. Capacity expansion can be achieved by using multiple units. The estimates are based on the volumetric stored heat model (Monte Carlo simulation) which assumed a reservoir temperature range of 120-130°C, a resource area of 0.5-1 km^2, a reservoir thickness of 100-500 m, a porosity of 3-6% and a heat exchanger outlet temperature of 70°C. This is the best model that can be employed for now for these areas due to limited deep drilling data. The Monte Carlo simulation is widely used for geothermal resource estimation because of its realistic estimates (Omenda et al., 2007).

In this study, binary plant equipment and processes are outlined in order to understand actual and potential failure mechanisms, the causes and effects in geothermal operating and non-operating environments. This, combined with a field plant condition assessment, provides the basis for deciding the operation and maintenance management strategy for the Kapisya binary plant. Formal maintenance methods that are commonly used in practice include preventive maintenance (PM), condition based maintenance (CBM) and corrective maintenance (CM). The reliability centred maintenance (RCM), six-sigma and lean formal management methods have a wide application in the power generation industry (Bore Kwambai, 2008). The Svartsengi Ormat binary power plant (Iceland) was identified as a power plant that operates on the same principles with the existing non-operating binary plant in Zambia. The operations and maintenance management strategies for the Svartsengi Ormat binary power plant were studied to better understand operating geothermal binary plant practices.

2. BACKGROUND AND LITERATURE REVIEW

2.1 Organic Rankine cycle

The organic Rankine cycle (ORC) is a practical approach to the ideal Carnot thermodynamic cycle. The heat engine is most efficient when operated on a Carnot thermodynamic cycle. In practice, the Carnot cycle is not feasible because of limitations on the heat transfer characteristics of the condenser units and the heat sink temperature. The maximum temperature has thermodynamic constraints, such as critical temperature and pressure. Practical difficulties in a Carnot cycle give way in a Rankine cycle where the secondary working fluid is completely condensed to saturated liquid and brought to the boiler pressure by a feed pump. Instead of water, the ORC system vaporizes an organic working fluid in a closed loop. Superheat can be introduced into the cycle in order to raise the maximum temperature, thus improving the efficiency of the cycle. In recognition of the inherently low thermal efficiency of basic binary plants, there are several variations on the basic cycle aimed at achieving higher efficiencies. A further improvement can be achieved by adding a reheating stage, where steam expands to an intermediate pressure and is then passed back to the boiler to reach the initial temperature. This results in a higher work output. The cycle also gains in performance when the working fluid to the boiler is preheated by the steam extracted from the turbine outlet, raising the average temperature of heat addition in a process called regeneration, resulting in a higher efficiency than the conventional Rankine cycle.

In its simplest form, a binary plant follows the schematic flow diagram shown in Figure 1. The production wells (PW) are fitted with pumps (P) that are set below the flash depth determined by the reservoir properties and the desired flow rate. Sand removers (SR) may be needed to prevent scouring and erosion of the piping and the heat exchanger tubes. Typically there are two steps in the heating-boiling process, conducted in the preheater (PH) where the working fluid is brought to its boiling point and in the evaporator (E) from which it emerges as a saturated vapour (DiPippo, 2005). The geothermal fluid is everywhere kept at a pressure above its flash point for the fluid temperature to prevent the breakout of steam and non-condensable gases that could lead to calcite scaling in the piping. Furthermore, the fluid temperature is not allowed to drop to the point where silica scaling could become an issue in the preheater and in the piping and injection wells downstream of it.

The organic Rankine cycle can be utilised for heat recovery in bottoming applications with various topping cycles such as a steam turbine. Due to its advantages, power plants based on organic Rankine cycle technology are quickly spreading around the world. The organic Rankine cycle offers many advantages (Gaia, 2006) such as:

- High turbine/thermodynamic cycle efficiency;
- Low turbine mechanical stress;

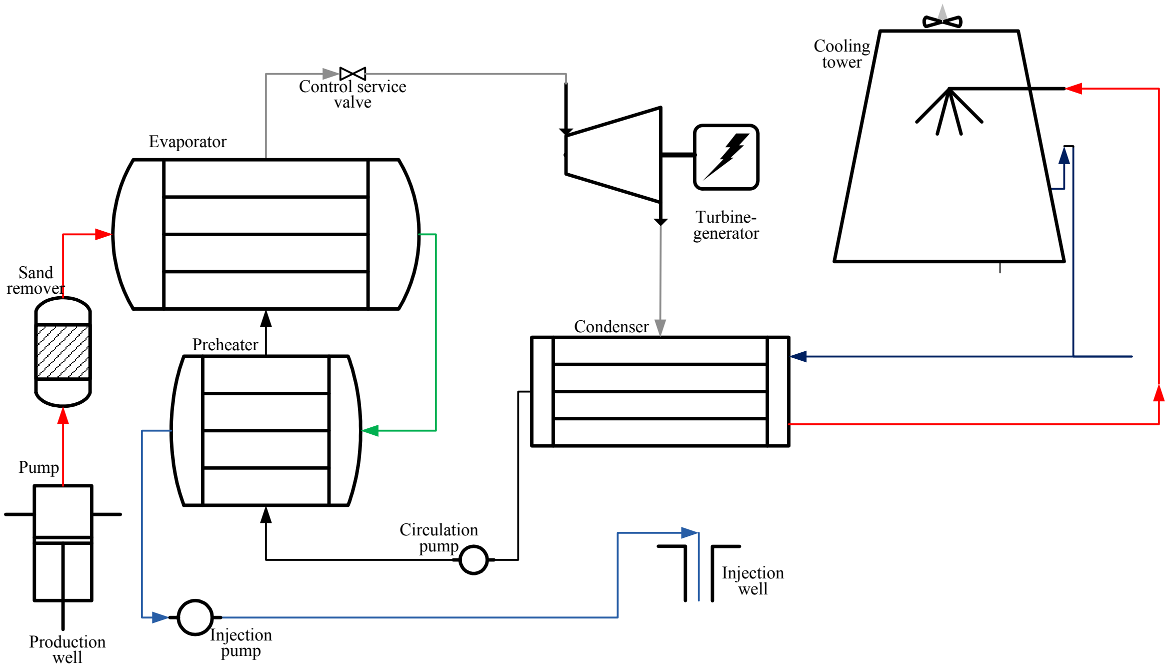

FIGURE 1: Typical schematic diagram for a binary power plant

- Absence of moisture during working fluid expansion;
- Simple start up procedures;
- Automatic and continuous operation;
- Relatively simple maintenance procedures;
- No operator attendance required depending on the level of plant automation;
- Long life of the plant (more than 20 years);
- No need to de-mineralize water.

2.2 Binary cycle working fluids

Various binary working fluids other than water have been proposed for the Rankine cycle based plants. The choice of working medium types depends on the constraints that relate to the thermodynamic properties, health, safety and the environment. Another objective in finding a suitable working fluid is cost effectiveness. This design decision has great implications for the performance of a binary plant.

Thermodynamic properties:
All the usual working fluids have critical point (refer to Figure 2) temperatures and pressures far lower than pure water. Since the critical pressures are reasonably low, it is feasible to consider supercritical cycles for the hydrocarbons as this allows a better match between the brine cooling curve and the working fluid heating-boiling line, reducing the thermodynamic losses in the heat exchangers. These losses arise through the process of transferring heat across a large temperature difference between the

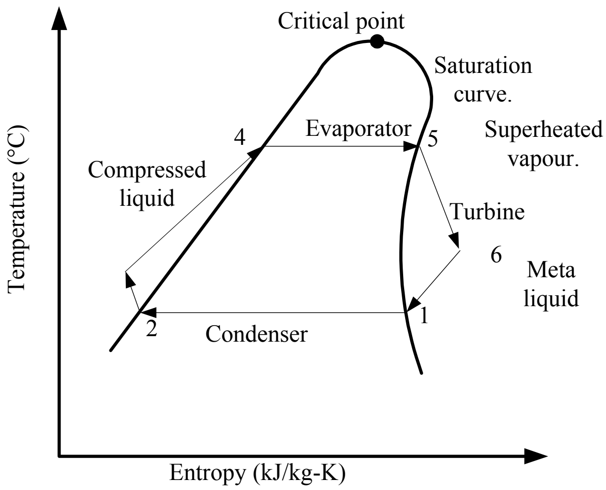

FIGURE 2: Temperature-entropy diagram for a retrograde working fluid

hotter brine and the cooler working fluid. By maintaining a closer match between the brine cooling curve and the working fluid heating/boiling curve, these losses can be reduced. Binary mixtures of these working fluids have also been studied for use in geothermal binary plants. In particular, the thermodynamic properties of 90% i-C_4H_{10} (iso-butane) and 10% i-C_5H_{12} (iso-pentane) are in application as a working fluid. The Kalina cycle was proposed where a mixture of ammonia and water is used to provide a better match between the temperature of the hot and cold flows (Wall et al., 1989). Binary mixtures evaporate and condense at variable temperatures, unlike pure fluids that change phase at a constant temperature. The working fluid mixtures can be tailored to match the characteristics of the geothermal resource brine and the limitations imposed by the power conversion cycle. There is also a possibility of changing the composition of the working fluid in response to long-term variations in the available geothermal resource temperature. This means that subcritical pressure boilers for mixed fluids can be better matched to the brine cooling curves, in a manner similar to, but not exactly like, supercritical pure fluids. The thermodynamic properties for some working fluids are outlined in Table 1.

TABLE 1: Thermodynamic properties of some working fluids (DiPippo, 2008)

Fluid	**Formula**	**Tc (°C)**	**Pc (MPa)**	**Ps@300K (MPa)**	**Ps@400K (MPa)**
Propane	C_3H_8	96.95	4.236	0.9935	n.a.
i-Butane	i-C_4H_{10}	135.92	3.685	0.3727	3.204
n-Butane	C_4H_{10}	150.8	3.718	0.2559	2.488
i-Pentane	i-C_sH_{12}	187.8	3.409	0.09759	1.238
n-Pentane	C_sH_{12}	193.9	3.240	0.07376	1.036
Ammonia	NH_3	133.65	11.627	1.0161	10.3
Water	H_20	374.14	22.089	0.003536	0.24559

Also shown in Table 1, Ps is the saturation pressure, with Tc corresponding to the fluid temperature. Another important characteristic of binary fluids is the shape of the saturated vapour curve as viewed in temperature-entropy coordinates; refer to Figure 2. The saturation curve for water has a negative slope everywhere, but certain hydrocarbons and refrigerants show a positive slope for portions of the saturation line. That is, there exists a local minimum in the entropy at some low temperature point, and a local maximum in the entropy at a higher temperature. Retrograde fluids include normal- and iso-butane and normal- and iso-pentane. Since the low temperature point is lower than any temperatures encountered in geothermal binary plants, for practical purposes these fluids can be taken as having saturated vapour lines similar to that shown in Figure 2. This has major implications for Rankine cycles. On the one hand, normal fluids such as water require considerable superheat, to avoid excessive moisture at the turbine exhaust. On the other hand, retrograde fluids allow expansion from the saturated vapour line into the superheated region, process 5-6, avoiding any moisture during the turbine expansion process. It has been shown that it is possible to run a supercritical cycle in which the turbine inlet state lies above the critical point and the expansion line lies inside the wet region for a portion of the process, emerging into the superheated region (without suffering any wetness penalty in efficiency).

Apparently, the fluid remains in a metastable vapour state while passing through the wet region by staying on the dry side of the Wilson line.

In the Kapisya plant it was envisaged to operate two 100 kW turbo generators at an optimum temperature of 95°C. The plant is designed to operate on the principle of the ORC thermodynamic cycle using perchloro-ethylene (C_2Cl_4) as a working fluid. Perchloro ethylene is non-flammable but concerns have been raised on its toxicity and global warming effects.

The advancement of drilling technology, the development of efficient heat exchangers and the deployment of binary fluids with better thermodynamic properties contribute to the useful application of a low-enthalpy energy resource on a much wider scale (Chandrasekharam, 2008). At a medium-temperature level, steam remains the most suitable fluid, since it is an inexpensive, readily available, non-toxic and well-known medium. The organic Rankine cycle, based on chlorofluorocarbons (CFC) or other fluids with a low critical temperature, proves to be a workable one at a low temperature level.

Health, safety and environmental considerations
The environmental, safety and health properties of working fluids must be considered when deciding on the type to be applied. These include flammability, toxicity, ozone depletion potential (ODP) and global warming potential (GWP). Table 2 summarizes these properties for the fluids plus two chlorofluorocarbons that used to be considered candidate working fluids. The ODP is normalized at 1.0 for refrigerants, R-11 and R-12, which are the worst in this regard. The GWP is normalized at 1.0 for carbon dioxide. Owing to their very high ODP and GWP, both R-12 and R-114 have been banned from use by the Copenhagen Amendment.

TABLE 2: Working fluid environmental and health properties

Fluid	Formula	Toxicity	Flammability	ODP	GWP
R-12	CCl_2F_2	Non-toxic	Non-flam.	1.0	4.500
R-114	$C_2Cl_2F_4$	Non-toxic	Non-flam.	0.7	5.850
Propane	C_3H_8	Low	Very high	0	3
i-Butane	i-C_4H_{10}	Low	Very high	0	3
n-Butane	C_4H_{10}	Low	Very high	0	3
i-Pentane	i-C_sH_{12}	Low	Very high	0	3
n-Pentane	C_sH_{12}	Low	Lower	0	3
Ammonia	NH_3	Toxic	Lower	0	0
Water	H_20	Non-toxic	Non-flam.	0	-

2.3 Main systems and components of the Kapisya geothermal binary power plant

2.3.1 General binary power plant equipment

To make improvements in the effectiveness of operations and maintenance, one must understand the details of the embedded binary plant system. The plant system has several components that are interconnected and require maintenance for proper functioning. The major equipment found in a geothermal binary power plant is listed below (DiPippo, 2008):

- Brine gathering system:
    - Downhole well pumps and motors;
    - Wellhead flow control valves and controls;
    - Brine (mainly single-phase) piping, insulation and supports;
    - Brine flow meters;
    - Pressure relief valves;
    - Sand remover system.
- Brine/working fluid heat exchanger:
    - Preheater – horizontal cylinder, liquid-liquid, shell-and-tube with brine on tube side and working fluid on the shell side;
    - Evaporator/superheater: horizontal cylinder, liquid-liquid, shell-and-tube with brine on tube side and working fluid on the shell side.
- Turbine-generator and controls:
    - Working-fluid turbine;
    - Brine inlet devices;
    - Generator and protection system;
    - Control system;

  - Oil and air system.
- Transformer and transmission line.
- Working-fluid condenser, accumulator and storage system:
  - Condenser;
  - Dump tank and accumulator;
  - Evacuation pumps to remove working fluid to storage during maintenance;
  - Working fluid feed pump system;
  - Condensate pumps and motors;
  - Booster pumps (as needed).
- Heat rejection system:
  - Wet cooling system;
  - Condenser heat exchanger;
  - Cooling water pumps and motors with induced draft fans and motors – cooling water treatment system (as needed);
  - Dry cooling system – air-cooled condensers with manifolds and an accumulator.
- Back-up system:
  - Standby power supply (diesel power generator or grid supply).
- Brine disposal system:
  - Brine return pumps and piping;
  - Injection wells for brine re-injection.
- Fire protection system (if working fluid is flammable):
  - High-pressure sprinkler system;
  - Flare stack.

Geothermal binary power plants are among the most benign of all power plants regarding environmental impact. The binary plant flow diagram shows that the only impact on the environment takes place at the heat rejection side of the plant. This is because the geofluid is pumped from the reservoir and returned entirely to the reservoir after passing through the heat exchanger; the potentially harmful geofluid never sees the light of the day. The cycle working fluid is contained completely within pipes, heat exchangers and the turbine, so that it too never comes into contact with the environment, either chemically or physically (DiPippo, 2008). The only possible form of pollution from a binary power plant might be called thermal pollution, i.e., the amount of heat that must be rejected from the cycle in accordance with the laws of thermodynamics. Even this effect can be minimised if the there is a beneficial use for the waste heat such as greenhouse and swimming pool heating.

2.4.2 Equipment list for the Kapisya geothermal binary power plant

Only the major Turboden binary power plant components are discussed for the purpose of this study. The existing brine supply system has thirteen shallow production wells that were drilled in the vicinity of the power plant to estimated depths ranging from 150 to 200 m. The wells were fitted with downhole line-shaft pumps driven from surface-mounted electric motors. Five of the wells are either not self discharging or have little discharge. The Kapisya geothermal field is a low-enthalpy field, as such the artificial lift of geothermal fluids from the production wells is necessary to increase the flow and maintain the same production since the reservoir pressure drops with production. Three of the wells are connected to the plant brine/working fluid heat exchanger through single-phase flow piping. Pipe insulation and some supports were either not installed or are missing. For brine disposal purposes, there is no re-injection; instead, surface evaporation ponds are used. For environmental and reservoir pressure drawdown reasons, re-injection will be introduced during the plant expansion drilling project phase.

The binary turbine-generator unit transforms thermal energy into mechanical energy and finally into electric energy through electric generators using perchloro-ethylene organic working fluid in a closed loop. The specialised maintenance of the turbine wheel is very critical since it has a direct bearing on the desired power plant output and working fluid mass flow rate. For the brine-working fluid heat transfer regulation, the evaporator is fitted with brine inlet and outlet devices. The 2 × 100 kW, 50 Hz, 400 V, 3-phase synchronous electric generators used to convert (from rotation) mechanical energy into electrical energy are directly coupled to the binary turbine.

The vaporised working fluid flows through a water-cooled condenser, where it is cooled and condensed back into a saturated liquid. The horizontal shell-and-tubes, water-cooled heat exchangers are connected to two wet cooling towers (Figure 3) for heat rejection into the atmosphere through twin induced-draft counter flow cooling towers. Water circulation pumps are fitted for cooling the water flow. The cooling system components require condition inspection and maintenance during the plant overhaul including the draft fans and motors in the cooling towers (provided with galvanized walls for corrosion protection); their proper function is critical to the working fluid condensation. The feed pump in the working fluid closed-loop raises the working fluid pressure from the condenser to the evaporator pressure. The power cabinets house all circuit breakers, contactors, and metering instruments for the power generating system.

FIGURE 3**:** The Kapisya binary power plant

The control cabinet houses the control and protection systems for the well equipment and the turbine-generator units. Auxiliary equipment also includes the electro-pneumatic control system that operates the control valve actuators and provides air pressure supply to the pneumatic components in operation in the governing system. The turbine and generator bearing oil systems supply lubricating oil to the turbine bearing and generator bearings for lubrication and cooling. The turbine mechanical seal oil system is designed to supply oil to the turbine mechanical seal for pressure sealing against working fluid leakage and cooling during operation. The stand-alone binary plant is provided with a standby diesel generator power supply for start-up and emergency plant control system.

3. MAINTENANCE AND MANAGEMENT METHODS

3.1 General information

Any operating equipment can fail by means of a complete breakdown, operational malfunctioning or a decreased performance rating. The types of maintenance activities required will depend on the type of actual or potential failures, the effects of the failure on the equipment and the entire system, the costs of repairs, safety and environmental concerns and other failure consequences. Maintenance aims to preserve the function of equipment by keeping equipment in its present or design condition.

While correcting equipment failures effectively and efficiently is important, anticipating and heading off failures is also a major part of maintenance management through concepts known collectively as operating reliability maintenance (Palmer, 1999). The term reliability maintenance management in industry refers to specific programmes that maintenance management undertakes with regard to keeping equipment from failing, such as reliability centred management (RCM) or preventive maintenance optimisation, six sigma and lean management. Even with varying terminology these methods seem to revolve around three major activities: preventive maintenance, condition-based maintenance or predictive maintenance, and corrective maintenance.

3.2 Preventive maintenance

Preventive maintenance (PM) is described as scheduled preventive tasks intended to reduce the probability of failure of operating equipment (August, 1999). The preventive tasks are undertaken on a time or machine based scheduling process, usually monitored by a computer system, human memory or wall charts. The interval counters include calendar time, operational running hours, operational cycles or production and seasons in the machine life span. Preventive maintenance possesses a planned scope of work, time estimates, material estimates, and other elements. What is significant is that the activities are not based on a particular noticed problem, but an expectation that regular maintenance will reduce or prevent the appearance of problems.

Most preventive maintenance activities are set up based on experience from past failures, equipment characteristics and vendor recommendations (lubrication, filter change, etc). Preventing past failures from reoccurring decides many preventive maintenance procedures. If catastrophic failures are not prevented, the number of failures will tend to rise. Equipment characteristics such as age, type, or the criticality of plant production may also cause the plant to set up preventive maintenance procedures. Newer equipment is prone to infant mortality and may justify routine checks of operating conditions after initial installation or overhaul. Finally, equipment manufacturers or vendors usually recommend routine maintenance procedures to keep equipment in good working order, often excessively recommending their equipment. By performing the preventive maintenance as the equipment designer envisioned, equipment life will be extended closer to its design life span. It is often said that if a plant spends a lot of time on breakdown maintenance, then the plant does not spend enough time on preventive maintenance.

There is a valid concern of preventive maintenance including excessive or unneeded maintenance with the potential of incidental damage to components due to reassembling error inherent in rebuilding equipment. A review system needs to be in place to reduce or otherwise adjust PM frequencies as the plant gains experience with failure patterns. The benefit of preventive maintenance is active involvement with equipment on a routine basis and a reactive mode where maintenance only quickly fixes breakdowns after a failure occurs.

Corrective maintenance resolves deficiencies after they are found so that plant operations have no problems with an actual breakdown. Therefore, preventive and corrective maintenance go hand in hand to reduce breakdowns and increase plant reliability.

3.3 Corrective maintenance

Corrective maintenance (CM) is a maintenance strategy in which equipment is allowed to run until it fails after which maintenance is scheduled and executed. It is also referred to as run-to-failure or no scheduled maintenance. According to reliability solutions (Plucknette and Latino, 2002), the run-to-failure strategy is suitable in conditions where:

- Failure has no or limited consequences on safety and production costs; the cost of repair of the failed component is cost effective.
- Failure cannot be prevented by predictive maintenance activity.
- Failure cannot be predicted by predictive maintenance such as when failure occurs too quickly to be predicted by a diagnostic mechanism.

- Failure cannot be eliminated by redesign (by project maintenance task) such as where the component has been in service for several years without failures.

The advantages of corrective maintenance are that the maintenance strategy requires fewer staff and less initial investment. If dealing with new equipment, minimal incidents of failure would be expected until the equipment fails or breaks. Since during this period there are no associated maintenance costs, it may be viewed as actually saving money. However, the downside of this approach is in its realities. This approach raises future capital expenditures because, while waiting for the equipment to break down, the life of the equipment is actually shortened. This results in more frequent equipment replacement and higher capital equipment costs. Furthermore, additional costs may be incurred when the primary equipment failure causes failures in associated secondary devices.

The total maintenance costs in the corrective approach may easily be higher than those incurred if a more proactive approach had been taken. The labour costs associated with unplanned repairs may be higher than normal because the failure may require more extensive repairs than would have been required if the equipment had not been run until it failed.

3.4 Predictive maintenance

A predictive maintenance (PdM) or condition-based maintenance programme goes far beyond normal, frequency-based preventive maintenance. Techniques such as vibration monitoring, oil analysis, ultrasonic and thermography are applied to detect early warnings of serious equipment problems from a real-time assessment. Predictive maintenance involves comparing the trends of measured physical parameters against known engineering limits for the purpose of detecting, analysing and correcting problems before failure occurs. In addition, the knowledge learned from analysing the equipment facilities leads to the use of new alignment, rebuilding, or other techniques to dramatically extend the trouble-free running times of equipment. Condition-based maintenance is a technology that strives to identify incipient faults before they become critical which enables accurate planning and an efficient execution of preventive maintenance tasks. Predictive maintenance analysis also delays much routine servicing and allows the plant to alter the routine overhaul strategy as well, thus completely avoiding the significant potential of reassembling error inherent in rebuilding equipment. Near the end of the equipment's expected life, predictive maintenance might pronounce the equipment in good health. Routine servicing can rationally be delayed to reduce the potential of infant mortality after servicing.

Predictive maintenance also implements continuous monitoring systems that reduce the need for travelling predictive maintenance routes. Some of the issues involved in using predictive maintenance techniques are the placement of sensors and the proper interpretation of data by predictive maintenance personnel. Plants want to do predictive maintenance rather than react and recover from breakdowns.

3.5 Project maintenance

The most important time to seek to identify a project is when the plant loses capacity. Any event that causes the plant to lose capacity should be scrutinised for a project. Certain plants assign a cross-functional team appropriate to the failure to address it and to find the root causes of any specified events. These specified events might include any capacity loss and certain types of regulatory or safety concerns. The cross-functional team not only searches for the root causes, but also recommends any future work needed to provide permanent repair beyond the initial one already in place. Some plants go further by applying root cause analysis to the plant. These plants fill out a root cause analysis sheet after certain failures even if they are not directly tied to capacity losses. Much project maintenance is essentially the repair of a failed mechanism beyond its original capability such as using better material or a different type of component for the service. On the other hand some project maintenance calls for significant changes to plant design and may also be costly. By modifying the design, the project work tends to improve plant reliability.

Reliability maintenance also includes project maintenance work which makes up an important part of the maintenance strategy. The project maintenance work tends to make the plant, or the involved equipment, better on a one-time basis with the addition or modification performed. Project maintenance aims to preserve the function of the plant by improving the equipment (Palmer, 1999). If a particular piece of equipment has inherent features that lessen its reliability, perhaps the equipment can be modified to make it more reliable.

If maintenance acknowledges that certain equipment and system designs are inherently more reliable than others, then maintenance must spend adequate time with the equipment issues before procurement and installation. Maintenance must establish equipment and vendor standards, assign certain maintenance supervisors or planners to spend time with corporate groups on specific projects, and give a review of the proposed project specifications. Any work order that modifies equipment or restores equipment to superior performance may be considered a project. The plant should continually be evaluating project ideas for making the plant more reliable.

3.6 Non-operating reliability maintenance

While most of the literature focuses mainly on the operating reliability of equipment, the non-operating state requires attention from maintenance and management teams, and system designers. Large portions of safety critical embedded systems, such as a missile defence system in times of peace or safety equipment spend the majority of their life in the non-operating state (Inacio, 1998). The non-operating environment is characterized by parts or systems that are connected to a functioning device where there is a reduction or elimination of the physical and electrical stresses compared to the operating condition. Systems designed for high operating reliability do not necessarily perform well (or at all) after long periods of exposure to the non-operating environment. For proper handling of the non-operating environment (factors associated with each different target environment), issues relating to non-operating failures need to be taken into consideration from the design stage of the lifecycle. In order for non-operating systems to work flawlessly when needed, designers need to consider the effects of the non-operating environment closely and compensate for them early in the design phase. The equipment is in a dormant state when it is in its normal operational configuration and connected, but not operating. Storage is defined as the state in which the system, subsystem, or component is totally inactive and resides in a storage area. The product may have to be unpacked and connected to a power source to be tested.

A system may be situated in numerous non-operating environments throughout its lifetime; some may be of concern due to the possibility of causing harm to a system while others may be of negligible importance. Systems may lay inactive in the field (subject to possible harsh environmental factors) or elsewhere (possibly en route for maintenance). During these times, systems may come into contact with numerous environmental stresses which may be natural (such as adverse weather) or manmade (such as mishandling or abuse). If it is known what can go wrong in a system, then it is possible to design around such faults right from the early stages of a project.

3.7 Management strategies

The procedures and methodologies for assessing and assigning maintenance activities into maintenance methods constitute a maintenance management system. The reliability centred maintenance, six-sigma, and lean formal management methods which have a wider application in the power generation industry, are mentioned in this study. Other management methods in practice include total quality management (TQM), total production maintenance (TPM), and good-to-great (G2G) among others, with wide application in the manufacturing and service industries.

Reliability centred maintenance is a maintenance perspective in an operational context which involves understanding plant goals, needs, and equipment (for instance how equipment operates, ages, and fails), and then developing a maintenance strategy to optimise outcomes in the context of your goals. Reliability centred maintenance recognises the joint roles of operators in the maintenance process and maintenance in operations. When we understand and quantify roles in the maintenance process and understand maintenance limitations (where and when to involve design engineering), we get better in all ways (August, 1999). Applied reliability centred maintenance helps develop a general philosophy of how operations and maintenance best work together. It prevents functional losses by managing failures. It leads to process improvement. The overall objective is meeting mission goals, usually in the form of costs, safety, and risk.

4. KAPISYA BINARY PLANT OVERHAUL REQUIREMENT ASSESSMENT

4.1 Overhaul requirements for binary power plants

The outdoor installed Kapisya binary power plant constructed in 1988 by Turboden of Italy has two binary turbine-generator units, each rated at 100 kWe. The plant was only partially commissioned since the plant was not connected to any electricity reticulation. The plant and auxiliary equipment has been in its normal operational configuration and connected, but not operating since the partial commissioning. During the dormant period, the equipment has not received any form of system on-and-off cycling for testing purposes or maintenance attention.

The overhaul of the plant comprises a comprehensive inspection and restoration of the system in order to maintain it in good operating condition or to restore its ability to function as per design. Activities include such things as disassembly, cleaning, lubricating, adjusting, parts inspection or replacement and testing.

Planning for an overhaul of the power plant and brine gathering equipment requires the consideration of a number of factors. The factors are associated each with a different target of non-operating and operating environments. Issues relating to failures after long periods of exposure to the non-operating environment need to be taken into consideration. The operating plant reliability issues after overhaul are cardinal to the operation of the equipment. The Kenya Electricity Generating Company carried out a field equipment condition assessment targeting the overhaul and re-commissioning of the plant and brine gathering equipment. The brine gathering and plant equipment condition assessment details are outlined in Tables 3 and 4.

The assessment also involved disassembling some power plant and brine gathering equipment for visual inspection and carrying out some non-destructive tests and measurements against engineering standards. Obviously, acquiring this data from the equipment is a time consuming task, and attention is focussed on components that directly affect plant functions and operations. Because of the difficulty of acquiring equipment field data, for some components alternate data sources or other operating plant data was used. Upon completion of the assessment, the information available for overhaul was limited to the plant's major equipment's condition, operations and maintenance-related material requirements and maintenance activity recommendations. Some scanty equipment nameplate data was obtained. The equipment operations and maintenance manuals, the original bid specifications and purchase orders detailing the original equipment specifications were not available. The success of a plant's overhaul relies on equipment condition data that may not exist or be out of date for the intended application. Understanding the details of specific components (for instance how it operates, ages, and fails) to ensure accuracy in deciding overhaul requirements and management

TABLE 3: Brine gathering system assessment

Section	Equipment	Material/ model/type	Condition	Recommendations
Well head	Line shaft pumps (including motors)	Caprari (manufacturer)	Corroded	Replace with new and service existing. Sand removal system
	Control and service valves of various sizes	Carbon steel	Leaking due to corrosion	Remove and replace
Brine transmission pipeline	Pipe supports and bearing bars	Carbon steel pipes	Corroded and missing	Remove and replace
	Insulation	Fibreglass	Not installed	Install
	Insulation cover	Aluminium	Not installed	Install

should be established. To work with a high degree of accuracy, the equipment condition acquired by observation, experience, or measurements must be used. The extent and type of maintenance activities will be based on the evidence of need for maintenance obtained from the actual assessment of the equipment condition.

The brine gathering equipment, particularly the well head components, while inactive in the field were subject to possibly adverse brine chemistry and weather effects for an extended period. Some of the effects are clearly visible on the wellhead equipment as shown in Figure 4. The figure shows one of the wellhead's equipment heavily corroded and leaking. The brine's chemical and physical composition presents a number of maintenance challenges. The pipeline's insulation and expansion joints and bearings were not installed. Line insulation is necessary to reduce heat loss to the environment resulting in power loss. The expansion joints and supports are necessary to handle thermal expansion due to temperature fluctuations of the brine and the weight carrying capacity of the pipes.

Observed corrosion effects on equipment
Corrosion problems in concrete structures such as wellhead concrete degradation and the attack on steel exposed to hydrogen sulphide have been widely observed. Most failures have been due to corrosive effects worsened by the non-operation of the existing plant and a lack of plant maintenance. Corrosion and calcite scaling were found to be the major causes for most of the components requiring repair, or replacement maintenance on the brine gathering equipment, particularly the wellheads. Much of the corrosion effects were mainly localised to the wellhead equipment due to brine leakages.

FIGURE 4: Corroded wellhead equipment in Kapisya

Lack of plant information
There is no historical record of any maintenance work being performed in the commissioning report**.** Having equipment information is a necessary tool for effective maintenance. Equipment information as a tool basically consists of the existence of plant equipment files. This tool helps the plant base the proper maintenance required on knowledge rather than on memory, or trial and error. This knowledge

TABLE 4: Condition of plant equipment and operations, and maintenance related material requirements

System/ function	Equipment	Material/ model/type	Condition	Maintenance activity
Cooling tower	Screen	Carbon steel	Corroded	Remove and replace
Evaporator	Working fluid	Perchloro ethylene	Properties lost	*Replace*
Oil and air system	Cable trays	Painted Carbon steel		
	Elbows with nuts	Stainless steel	Leaking	Remove, replace
	Oil filters	Stainless steel	Unknown	Remove, replace
	Pressure switch	0.1-1Bar		Remove, replace
	Turbine oil	Caltex R&0 32 or equivalent	Expired	Remove, replace
	Hosepipes	“	Worn	Remove, replace
Electro-pneumatic control syst.	Air compressor hose pipe	Nylon ($^3/16$)	Missing	Replace
Evaporator, condenser and turbine	Temperature element	Type - Pt: 100	Faulty	Remove, replace
	Pressure switch (0.1-1Bar)	As per original	Faulty	Remove, replace
Turbine/generator protection or control boards	Gen. over voltage, under voltage, under frequency, ground over volt. protection relays	As per original specifications	Relays missing	Replace
	Selector actuator key type	As per specifications Complete with mounting adapters, and contactors	Start keys missing for unit 1&2	
	Standby batteries	With 12V cells, 30AH, sealed type lead acid		Remove, replace
	220/110V power transformer	300VA, air cooled wire wound power transformer	Faulty	
Bore field power supply board	Selector actuator, Indicator Lamps (switch) knob type Push-button actuator switch	Complete with adapter and lamps for 220V	Possible hydrogen sulphide (H_2S) attacks	Replace faulty ones
Circulation pumps	Pump supply cable	Steel armoured p.v.c. Insulated 3core, 4mm^2 copper cable		
	Pump control cable	Steel armoured p.v.c. Insulated 2core, 1.5mm^2 copper cable		
Control system	Control cables	Single core 2.5mm^2 copper cable		
	Power Cables – Single Core	Single core 35mm^2 copper cable		

comes from recording and referencing equipment data or specifications and is the result of previous maintenance actions. The lack of information affects planning for the correct maintenance actions for the present and the future (Palmer, 1999). In many cases, original equipment manufacturers assist greatly in maintenance decision making.

The turbine equipment consists of the turbine rotor, turbine wheel and rotor bearings, the casing and the mechanical seals. The auxiliaries include inlet valves and lubrication and mechanical seal oil systems. According to the field equipment condition assessment undertaken, the major components requiring maintenance are listed in Table 4. For the observed actual failures, the maintenance activity's recommendations have been outlined which include component repair and replacement. It is envisaged that by carrying out the condition based maintenance activities, the operating plant reliability will be fully restored.

4.2 Geothermal fluid composition

4.2.1 Fluid chemistry

The geothermal fluid's chemical and physical properties affect the way the fluids can be used, the type of design and the maintenance needs of the geothermal power plants. Geothermal power plants have specific maintenance challenges related to the nature of geothermal fluids. Different resources have different brine chemistry and temperature. In general, the chemistry of most geothermal fluids present maintenance challenges for geothermal power stations because the fluids contain dissolved and suspended elements such as silica, chlorides, carbonates, sulphurs, gases and rock cuttings which are responsible for maintenance problems such as corrosion, erosion, scaling, acid attacks and fouling in the plant and fluid transmission lines. A geochemical survey is undertaken to collect all the relevant chemical information, which can be used in identifying a geothermal reservoir with desirable chemical characteristics for the intended use. The chemistry of geothermal fluids is a useful tool in predicting the potential of mineral deposition and corrosion effects in the entire operation of a geothermal cycle. These problems require a maintenance strategy specific to a geothermal field to address them and to ensure plant availability and utilization. Geochemical surveys for Kapisya involved the collection of water samples and soil gas surveys for CO_2 and radon.

From the chemistry of the hot water samples collected from a total of eight hot springs and thirteen drilled shallow wells, which are all clustered within a radius of a few metres, it is evident that the samples derived from a similar source. The relatively low level of dissolved solids indicates the geothermal waters in this reservoir are quite dilute with total dissolved solids (TDS) values ranging from 432-509 ppm. The chloride (Cl) levels are also relatively low with a range of 182-233 ppm. The pH value ranges between 8.1-8.3, as measured at sampling temperatures, and 7.99-8.34 as measured at laboratory conditions as indicated in Table 5. All other parameters show clear similarities in value; this is an indication that all the shallow wells and the hot springs are tapping from a common source, preferably from a single aquifer. The relatively high levels of fluoride in the spring and the well water in Kapisya make it unsuitable for drinking purposes. For every water point sampled, four different types of elements were analysed, including the conservative constituents Cl, B, HCO_3 and F. Acidified samples were collected for the analysis of metal species (Na, K, Ca, Mg, Li, Cu, and Fe) (Omenda et al., 2007). An analysis for sulphates (SO_4) and amorphous silica in the hot water samples was also undertaken. Unstable species and parameters that included pH, TDS, H_2S and conductivity were also analysed.

4.2.2 Mineral deposition potential

The potential for mineral deposition has been assessed for the hot well fluids of the field so that the usability of the fluids could, in turn, be assessed. The mineral deposition potential was worked out by the aid of a computer programme called WATCH (Arnórsson and Bjarnason, 1994; Omenda et al., 2007). This was achieved by working out the saturation indices of the common mineral phases known to pose deposition problems in geothermal systems when subjected to the dynamic changes of pressure and temperature expected in such systems during production. The mineral phases considered were calcite, anhydrite and amorphous silica that were suspected to be present as deduced from the chemical analysis of the hot water discharge from both the shallow wells and the hot spring. The average figures for saturation indices for water samples are shown in Table 5. The saturation indices were calculated by considering both the thermodynamic data and the analysed chemical data from the water samples.

TABLE 5: Average saturation indices for water samples

Mineral phase	Saturation index	Saturation state
Anhydrite	-1.070	Under saturated
Calcite	0,213	Slightly oversaturated
Amorphous silica	-0,823	Under saturated

The saturation state depicts the equilibrium conditions in the reservoir between the hot water and the secondary mineral assemblages present. When the waters are under saturated with respect to a certain mineral phase, it implies that there is no possibility of the deposition of that particular mineral and vice versa for the oversaturation state. From the chemical analysis of the reservoir water from Kapisya, all the samples indicated under saturation with respect to amorphous silica and anhydrite minerals. However, calcite was slightly oversaturated in almost all the well waters, at least for the assumed temperature conditions in this system of about 124°C.

Corrosive attacks on metals can occur in several of the following forms: uniform, pitting, crevice, stress corrosion cracking, sulphide stress cracking, and hydrogen blistering. Materials and methods of mitigating corrosion include the use of inhibitors and biocides. Calcite deposition removal is possible by drilling out and using hydrochloric acid (HCl) treatment (but care is needed). Control can be achieved by inhibition using organic phosphates and synthetic polymers (for instance polycarboxylic acids) as stated by Ármannsson (2009). Some of the strategies used in monitoring the deposition include coupon fitted brine gathering equipment. Improved chemicals for injection for dual function for scale/corrosion inhibitions are also in use.

5. OVERHAUL APPROACH FOR SVARTSENGI ORMAT BINARY PLANT

5.1 General information

The Svartsengi power plant has combined electricity generation and hot water production for district space heating. The total installed production capacity of the power station is 76.4 MWe and 150 MWth. The effluent brine from the power station is used for spa facilities at the nearby Blue Lagoon, popular among tourists. The heating plant supplies hot water to nine towns and the Keflavik International Airport. The Svartsengi geothermal area is close to the town of Grindavík, Iceland, on the Reykjanes peninsula and is part of an active fissure swarm, lined with crater-rows and open fissures and faults. The Svartsengi power station was developed in six successive phases since 1978.

The power plant has three 1.2 MWe Ormat binary turbine/generator units which are water-cooled, utilising steam which had previously flowed unharnessed from the chimneys of the power station. The binary units' condensers, which are water cooled, preheat water for district heating. The station also has another four 1.2 MWe Ormat binary turbines which are air-cooled, adding up to 8.4 MWe generating capacity from binary turbine units. There are a total of five steam turbines installed at the Svartsengi power station, outlined as follows:

- Two AEG back pressure turbines with a capacity of 1 MWe each;
- One Fuji back pressure turbine with a capacity of 6 MWe – the back-pressure steam is transferred to the Ormat units in Plant IV;
- Two Fuji condensing turbines, each with a capacity of 30 MWe.

The instrumentation, control and protection systems serve to monitor and communicate plant operating parameters. The measuring instruments include pressure gauges, temperature gauges, vacuum meters, and flow meters, etc. The control function is important to ensure that the geothermal power plant operates within the required limits. The control system receives measured parameter signals and uses the value of the signals to generate control signals to keep the performance within what is desired. The Svartsengi power station control system is the supervisory control and data acquisition (SCADA) system. The protection systems include all the systems installed to ensure that the plant components are protected. They include the protection relays for the generator, transformers and turbine protection. Because of the criticality of these systems, their sound operation is necessary for the operation and safety of the plant.

Due to the high level of salinity and the high temperature, geothermal brine cannot be utilised directly for district heating as has been the case in Reykjavík and most places in Iceland. On cooling, silica deposits from the brine resulted in some equipment becoming inoperable after a short time (Lienau, 1996). As a result, a double-flash (at high and low pressures) plant system is utilised resulting in minimal depositions. Heat exchangers are applied to facilitate the utilisation of geothermal energy in organic Rankine plant units and for district space heating.

The station's operations and maintenance staff consists of fourteen men, who undertake both the operations and maintenance of the Svartsengi and Reykjanes power stations. For the power plants' control and monitoring systems equipment maintenance, there are three technicians under the operations and maintenance team. One electrician is in charge of general electrical maintenance work assisted by the fourteen operations and maintenance staff, most of whom are trained electricians as well. At the top of the power stations' hierarchy are the power station and maintenance managers who are responsible for the operations and maintenance management of both power stations. The Reykjanes power plant has 2×50 MW steam turbines installed which are also maintained by the same team. The steam gathering equipment is maintained by a staff of two who are assisted by one fabricator and two sheet metal and air-conditioning maintenance staff. Figure 5 shows the operations and maintenance organisational structure.

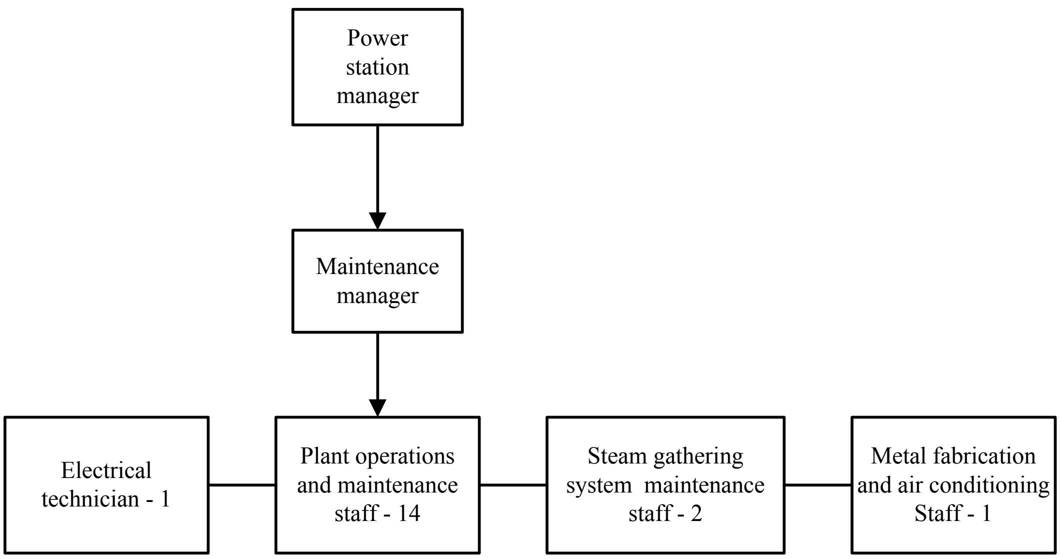

FIGURE 5: Svartsengi plant operations and maintenance structure

The steam turbine overhaul maintenance periods are based on predictive inspections that include both real-time online and planned shutdown inspections carried out periodically on equipment for the steam gathering and turbine/ generator systems. The predictive methods applied include thermograph, vibration analysis, stroboscope and penetrant crack checks. The power output parameters are monitored as part of the predictive methods. The high temperature, depositions and scaling related signs of impeding failures are the main focus of the inspections. Critical rotating part checks are equally part of the predictive maintenance inspections. On the other hand, the overhaul maintenance periods for the Ormat units is scheduled every 4-5 years of operation depending on the condition inspections of the equipment.

5.2 Maintenance types at Svartsengi power station

Applied RCM helps to develop a general philosophy of how operations and maintenance best work together. It prevents functional losses by managing failures. It also leads to process improvement. The overall objective is meeting mission goals, usually in the form of costs, safety, and risk (August, 1999). This practice is the basis of the maintenance management approach for the Svartsengi power station.

Preventive maintenance
To ensure the proper operation of the system, the maintenance team carries out periodic inspections and maintenance on various subsystems of the plant. The maintenance activities are repeated at a predetermined frequency on daily, weekly, monthly, six month and yearly periods. The biannual maintenance is more comprehensive involving the disassembling of the turbine, the replacement of seals, and pump performance tests. Inspections and maintenance are also carried out on the gearbox and the generator. Most preventive maintenance activities are set up based on experience from past failures, equipment characteristics and original equipment manufacturers' recommendations. Recommendation of maintenance manuals assume equipment is operated according to design conditions which may not be true in some cases. The criticality of equipment to plant production also determines the amount of preventive maintenance a piece of equipment receives.

Corrective maintenance
Preventive and corrective maintenance go hand in hand at the power plant to reduce breakdowns and increase plant reliability. The breakdown maintenance is applied where equipment is actually broken down or fails to operate properly. The practice of the operations and maintenance staff working as one unit at the station makes the initial breakdown maintenance strategy more precise. Reactive jobs by their nature are urgent. The plant desires to do more preventive, predictive and project work maintenance, and do less reactive work.

Non-operating reliability maintenance
The station carries out reliability tests on protection and monitoring systems at start-up after maintenance on the turbine system to ensure their proper functioning. Over speed and steam separator water level protection systems are the most vital tests carried out at start-up. The standby machines or non-used machines in normal operation are also checked at each proper interval so that they are in working order whenever they must be operational. These include the oil coolers and the protection systems.

Predictive maintenance
Predictive maintenance is practiced at the station by the application of vibration analysis, infrared thermograph analysis, oil analysis, visual inspection, insulation tests, and power output parameter measurements. This is undertaken to determine the health of the plant's systems for the purpose of detecting, analysing and correcting incipient equipment failures. During my attachment to the Svartsengi power plant, I was privileged to be part of the team that carried out predictive inspections on the NCG system. The non-destructive liquid penetrant testing (PT) method was applied on non-

condensable gas nozzles, which led to the detection of surface breaking discontinuity failure due to thermal stresses in operating conditions. If that had not been diagnosed, it would have led to a failure. Predictive maintenance diagnosis might detect the problem within a week as predictive maintenance personnel monitor equipment on a routine check. The combination of these predictive instruments and visual inspections helps the maintenance management to decide the overhaul needs for the steam turbines.

Near the expected equipment overhaul period, predictive maintenance might pronounce the equipment in good health. Routine servicing can rationally be delayed to reduce the potential of infant mortality after an overhaul. Application of non-destructive testing for incipient failure contributes massively to plant reliability and maintenance cost cuts. The station maintenance management has incorporated some of the manufacturer's maintenance manual recommendations in the station's maintenance management approach.

Routine testing and full-scale performance tests to assess the performance of all plant equipment, as well as the overall plant is undertaken after the initial start-up. Full power and inlet/outlet steam conditions tests are carried out as part of turbine performance tests on completion of the overhaul work. This is done against the baseline plant performance. Key plant parameters are adjusted to ensure the plant conforms to performance expectations, including the calibration and testing of the rotor and turbine balancing and control system. The records of adjustments are kept for future maintenance reference.

Project maintenance
Project maintenance is practised at the Svartsengi station if a particular piece of equipment has inherent features that lessen plant reliability. For instance, at the time of this report, an extra moisture trap was being fitted on to a steam supply line to improve steam quality to the turbine. Modifications to the binary turbines' heat-rejection systems, changing from air cooling to wet cooling for binary plants could be carried out to improve the systems' reliability and raise performance levels.

5.3 The Svartsengi Ormat binary plant layout

5.3.1 General description of the Ormat binary unit layout

For the purpose of this study, emphasis was placed on the 1.2 MWe binary power plant maintenance practices at the Svartsengi power station. The Ormat energy converter (OEC) binary unit, was designed to generate electrical power by using a geothermal heat source for the following main subsystems (Figure 6): vaporiser (evaporator), power skid, oil systems, electro-pneumatic control system, organic motive fluid piping system, heat source inlet/outlet system, air-cooled (or water-cooled) condenser, power and control cabinets, purge system, and instrumentation.

The vaporiser is a horizontal, gas-liquid tube-and-shell heat exchanger with a straight flow tube bundle, sheet metal shell and fixed tube sheets. The geothermal steam flowing through the vaporiser tubes heats up the motive fluid, which flows through the vaporiser shell side. The liquid separator is installed on the upper side of the vaporiser, designed to retain the droplets of liquid carried over with the vapour and, thus, prevent the impinging of droplets on turbine blades.

The power skid consists of a binary turbine coupled to an asynchronous generator. The turbine is a double-stage impulse type designed to operate with organic working fluid. The turbine assembly also contains the bearing lubrication and mechanical seal oil systems. The asynchronous air-cooled type generator is 3-phase, 1,300 kW, 600 V and 50 Hz. The functions for the turbine and generator bearing oil system are to supply oil to the turbine bearing and generator drive end bearing for lubrication and cooling. The turbine mechanical seal oil system is designed to supply oil to the turbine mechanical seal for pressure sealing against working fluid leakage and cooling during operation.

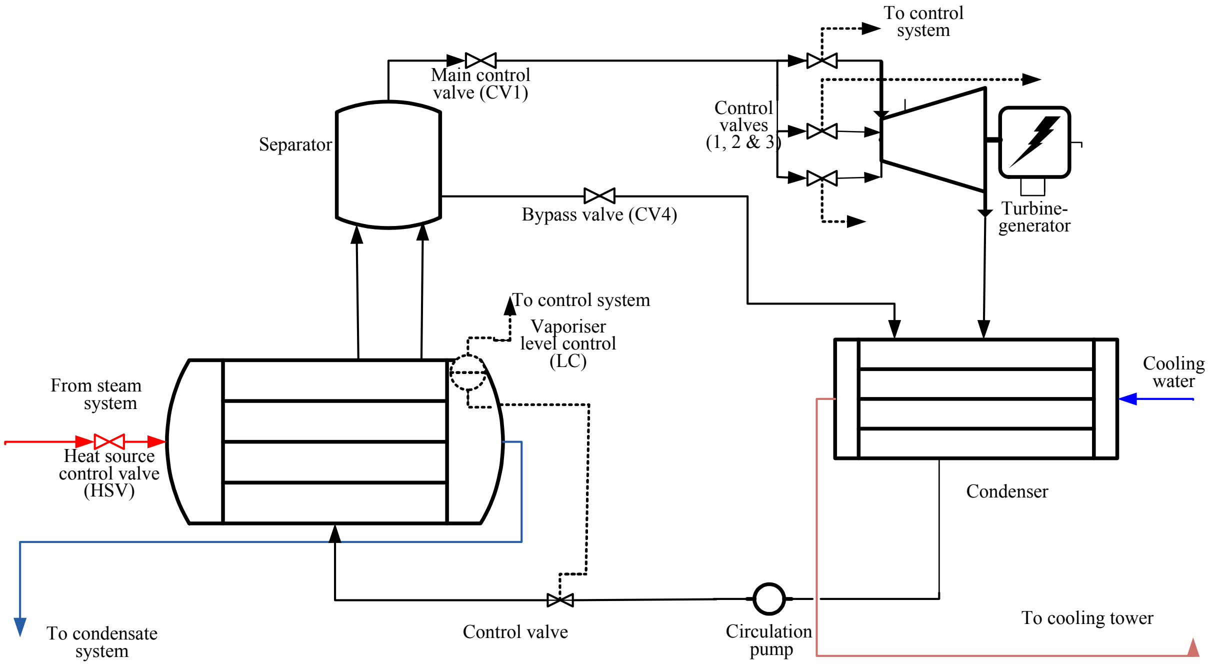

FIGURE 6: Ormat unit single line diagram

The electro-pneumatic control system operates the control valve actuators and provides air pressure supply to pneumatic components. The pneumatic control panel is fed by the air supplied, and is required for the operation of the pneumatic equipment. The feed pump, motive fluid strainer, valves (bypass, injection, control and inlet) and piping expansion joints make up the organic working fluid piping system.

The geothermal inlet and outlet system comprises the following equipment:

- Vaporiser inlet nozzle at the vaporiser inlet head;
- Condenser outlet nozzle at the vaporiser outlet head;
- Two non-condensable gas (NCG) removal nozzles, one at the vaporiser outlet head upper part, and the second at the condensate pot at the bottom part of the vaporiser outlet head.

The vaporised organic motive fluid passes through an air (or water) cooled condenser, where it is cooled and transformed back into organic liquid. The air-cooled condenser is a horizontal air-cooled heat exchanger which comprises fans driven by electric motors. A purge system is installed on the upper side of the condenser outlet boxes. The system is designed to purge the OEC condenser from the NCG, consisting mostly of air. The purge system has been manually operated for many years. A multistage centrifugal feed pump transfers the motive fluid from the condenser to the vaporiser.

The power cabinets house all circuit breakers, contactors, transformers and metering instruments for the power generating system. The control cabinet houses the OEC control and protection systems. The instrumentation system includes all the parameters needed for the proper operation of the OEC unit, such as pressure, temperature, voltage, current, and power, etc., measured by the appropriate measuring instruments.

The feed-back control system (Figure 6) comprises the closed-loop circuit of the vaporiser level control (LC) system and the turbine injection and bypass valves. The main control valve (CV1) is designed to regulate the motive fluid flow from the vaporiser to the turbine for proper functioning. The turbine injection valves (1, 2 and 3) are designed to control the organic motive fluid flow to the turbine during start-up and synchronisation, thus controlling the turbine/generator speed at a synchronous speed. In the event of failure, all three valves will close and will back up the turbine main valve to block the vapour flow to the turbine. The turbine bypass valve (CV4) is provided to protect the vaporiser against an excess pressure condition (shell side). Under start-up and synchronisation, and during normal operation, the turbine bypass valve is activated to close the valves. The fluid level control system function is to maintain the motive fluid in the vaporiser at a constant level, thus ensuring optimal power output of the Ormat energy converter.

The heat source control system is designed to control the heat source flow through the vaporiser in order to control the vaporiser pressure and turbine/generator output power below their limitations. The heat source control system is based on two control valves: the heat source control valve (HSV), and the non-condensable gas removal valve. Under start-up conditions, before synchronisation, the heat source control valve is partially opened to allow for heating at a low rate and to maintain the vaporiser pressure at a pre-set value. In the event that the vaporiser pressure or the generator output is above limitations, the HSV will be partially closed by the control system. Closing the valve will reduce the Ormat energy converter heat load, thus reducing the vaporiser pressure and the generator output power.

The function of the non-condensable gas removal valve is to allow the removal of gases from the vaporiser tube side with the minimum of pressure build-up in the vaporiser tube side; on the other hand, gas removal should be done with minimum steam venting. Excessive steam venting will result in power loss.

The operations instruction manual details the unit start-up procedure, normal operation, heat removal procedure, normal shutdown procedure, automatic shutdown procedure, and emergency shutdown procedures. Operations status is graphically displayed on the control and indication panel at the control cabinet. During all procedures the Ormat unit is monitored by system software for failures and warnings. In the event of a failure, the relevant operating procedure will be terminated and a shutdown procedure initiated.

5.4 Ormat binary plant overhauls

The Ormat binary unit overhaul is scheduled for every four to five years of operation. The station attributes the long overhaul period to strict adherence to the high standards of the lubricating systems, periodic maintenance, and fitted micro-filtration based on predictive maintenance. The other contributing factor is that manufacturers of the equipment trained the operating and maintenance crew at the Svartsengi power station. All operations and maintenance activities are undertaken by the operations and maintenance crew based at the station and supervised by the maintenance manager.

The unit overhauling and/or inspection of each turbine are generally based on several principles. Regular periodical inspections on equipment are undertaken every year. And to better achieve maintenance goals, a partial inspection is done every half year, when important parts must be overhauled and a check is conducted. While all equipment is operated under good conditions, the station plans call for an overhaul or inspection after stopping a unit. In order to prevent any trouble from occurring, the generating units' equipment undergoes overhaul periodically. As a precaution, all overhauling and inspections are done while referring to installation records and test records. All necessary tools and auxiliary materials are provided before overhauling maintenance work commences. The necessary spare parts that are provided are in reference to the last inspection records. Any trouble, damage, or unusual matters observed (or not) during the overhaul maintenance is recorded. In general, the following are replaced in addition to other system components:

- O-rings and oil seals;
- Bearings (both on the turbine and the generator).

Due to the fluid chemistry of the Svartsengi geothermal fluids, the steam gathering equipment inspections are part of the predictive inspections carried out periodically. The borehole components are inspected for silica deposition and corrosion. During overhaul periods, the heat exchangers (condenser and vaporiser) are maintained to avoid the accumulation of deposition resulting in turbine power loss.

The high knowhow among maintenance manpower has been the key to a successful maintenance program at the station. When carrying out turbine-generator maintenance, one of the strongest resources available for the station is the skilled and industry experienced people trained by the original equipment manufacturers (OEMs). Other attributes are the experienced technical maintenance and station managers, and high safety awareness. Nearly all turbine-generator overhaul tasks are executed by the O&M team in adequately equipped station maintenance workshops. These aspects allow the turbine-generator set to be back on-line on time. Only some of the welding and cleaning work is outsourced. This is the reason for the reduced costs for overhaul and maintenance in general.

6. THE KAPISYA BINARY PLANT OVERHAUL APPROACH TO IMPROVEMENT

6.1 Review of the overhaul facilities

It is necessary to be on familiar terms with the resources required to attain successful plant rehabilitation. The resources should be related to the projected results. Some of the resources include the supervision, logistics, industry experienced technical foremen, skilled craft labour and wide-ranging tools. The facilities within the limits of vicinity and cost should be established except where overriding reasons prevail.

The maintenance facilities like the maintenance workshops should be planned to provide for the projected power plant expansion, and not only for the existing plant overhaul. A provision should be made for the installation of basic maintenance facilities at the power plant and projected for the expected plant expansion. Currently the plant has no such facilities. A possible alternative for facilities based on economics and the use of improved facilities, including modernised equipment, is necessary to consider. The reconditioning team on-site will need to be equipped with a complete field office trailer and tool trailer stocked with wide ranging turbine-generator overhaul and testing tools.

A centralized logistics office is critical to on-site team support from knowledgeable technical managers for on-time schedule delivery. Unlike the Svartsengi power station, the Kapisya overhaul logistics office is located over 1,000 km away from the station. The remote geographic location of the plant, off the national power grid, calls for extensive planning in transportation and plant accessibility requiring a long lead time. In this case, the majority of the involved costs are actually not related to plant work but to logistics and conveyance. The reason for this is that the power plant is off the grid and located in a remote and rural area which is not well connected to the supplier or service providers located in urban areas. A number of geographically variable cost factors affect the total work cost. In the absence of service by utility companies, temporary amenities are required to be in place for the purpose of serving the staff on-site.

When carrying out turbine-generator overhaul maintenance, one of the strongest resources available is skilled and geothermal industry experienced people to carry out the work. Due to the lack of such within the Zambian power utility, a contractor with exposure in the field has been engaged to undertake the overhaul and carry out on-site training of the operations and maintenance staff. The operations and maintenance team to be trained were initially hydro and diesel power plant trained. The education and training of the maintenance and management staff by the original equipment manufacturers is also important in cost reduction.

Neither the Kapisya area nor nearby small towns have the trained/skilled manpower needed to be employed for operations and maintenance work. However, these areas have a high demand for electricity due to lakeshore activities such systems fisheries, lodges, nearby settlements and districts. The Kapisya project site is located in a remote area, which is difficult to access, has bad roads and no communication networks. The implementation of the project in such a remote area and the O&M afterwards becomes prohibitively expensive due to the high cost of transport and conveyance. Due to the low volume of the market, manufacturing firms or service companies cannot afford to have extended facilities in the area.

6.2 The Kapisya binary power plant failure mode and effect analysis (FMEA)

The failure mode and effect analysis (FMEA) is a stepwise, in-depth method for identifying potential failure sites and the failure mechanism effects of failures. Failure modes define the ways in which the failure of the equipment occurs and the circumstance associated with that failure. The causes of failure refer to the likely originators of the failure while the effects of failure define what happens if and when failure occurs. The effects of failure include functional, safety, operational, environmental and economic consequences. The four main classes of failure mechanisms are mechanical, electrical, corrosion, and radiation. Radiation effects cause both mechanical and electrical degradation. Mechanical defects cause properties of materials to be altered. For instance, such defects could alter the mechanical, optical, thermal and electrical properties of metals. The effects of the potential failure affect the maintenance approach to be adopted for the particular equipment, whether to prevent the failure from happening or to correct the failure after it happens. In doing a failure mode and effect analysis for a binary power plant, the main equipment was grouped into these main subsystems: the brine gathering and disposal system, the turbine and auxiliaries system, the generator and auxiliaries system, the heat exchangers and auxiliary systems and the control, instrumentation and monitoring system.

The Kapisya binary power plant's critical embedded systems have spent the large majority of their life in the non-operating state from inception. The non-operating environment in this case is characterized by parts or systems that have had a reduction or elimination of the physical and electrical stresses compared to the operating condition. Parts of the non-operating environment may be of concern due to the possibility of causing harm to a system while other parts may be of negligible effect (Pecht, 1995). For testing purposes, equipment in a dormant state may be cycled on and off.

The Kapisya plant's systems are not in a controlled environment because of their outdoor installation; therefore, factors such as moisture from condensation and daily temperature fluctuations may have consequences. During installation, the removal of some of the system's components' protective coverings exposed the system to an uncontrolled environment. This is a location where environmental stresses such as thermal, biological, and humidity stresses are to be found. Human abuse factors such as destruction and criminal damage of the equipment can be considered, though there is little evidence of vandalism. The equipment is in a dormant state when it is in its normal operational configuration and connected, but not operating.

Ideally, the failure mode and effect analysis begins during the earliest conceptual stages of design and continues throughout the life of the product or service. Besides the non-operating environment, one has to be concerned with the extent to which the designed system will be inactive in the target field environment. For the purpose of this study, data acquisition included a variety of data sources: observed maintenance practices at the Svartsengi power station, the Ormat plant manufacturer's recommendations and a literature review.

Failure mode and effect analysis for the brine gathering equipment

The failure mode and effect analysis for the main equipment for this system is illustrated in Table 6. It shows the potential failures, possible causes, effects and possible maintenance solutions.

TABLE 6**:** Cause and effect analysis for brine gathering and disposal systems

Function/ Component	Potential failure	Potential cause(s) of failure	Potential effect(s) of failure	Possible maintenance solution
Brine pipeline	Burst, Leaking, Insulat. damage (not installed), Scaling Corrosion	Fracture, coating failure. Solid particle eros. High calcite scalin. Water hammer. Excessive pressure. Environm. damage. Un-insulated pipeline installed.	Blocked or restricted pipe. Changed flow characteristics. Cost of repair and generat/power loss. Wasted resources. Safety and environment.	Replace/repair pipe. Repair/install insulation/ supports and expansion bellows. Audio-visual check. Use inhibitors. Redesign the system to flow requirements. Monitoring /control flow parameters.
Service/ control valves	Scaling. Wear/damage of valve disc. Leakage through glands.	Calcite scaling. Corrosion (all forms). Solid particle eros. Excessive pressure. Worn/loose packin. Wrong valve/ material selection. Coating failure. Wear (all forms).	Stuck valve. Uncontrolled brine flow. Lost valve disc. Changed flow/ output characterist.	Use inhibitors. Replace/repair valve. Coating replacement. Redesign valve. Monitoring/control flow Visual check.
Lineshaft pump and motor	Solid particle erosion. Scaling. Wear/damage of impeller. Leakage through glands. Vibration/noise. Bearing failure.	Clogged. Impeller failure. Motor failure. Corrosion. Wrong specific. or installation. Human abuse of the equipment.	Loss of well or power output. Loss of brine/well. Loss of vacuum.	Sand remover check/replace. Repair/replace pump or motor. Use inhibitors. Motor insulation test. Redesign the system to flow requirements. Vibration analysis and monitoring. Audio-visual check. Replace bearing.
Wellhead concrete structure	Yielding Well growing	H_2S attack. High wellhead pressure. Microbiologically influenced corros.	Brine leakage. Concrete degradation.	Improved cement quality. Rebuild. Re-enforcements.
Injection pump	Scaling. Corrosion fatigue. Wear/damage of impeller. Leakage through glands. Vibration/noise. Bearing failure.	Coating failure Wear (all forms). Clogged. Motor failure. Impeller failure. Corrosion. Wrong specification or installation.	Loss of reinjection efficiency. Loss of vacuum. Environmental (surface disposal).	Repair/replace pump/motor Use inhibitors. Motor insulation test. Redesign the system to injection requirements. Vibration analysis and monitoring. Audio-visual check. Replace bearing.

Failure mode and effect analysis for turbine and auxiliaries

A summary of the failure mode and effect analysis for a turbine and auxiliary system is illustrated in Table 7 where the possible failures are given, along with the possible causes and effects.

TABLE 7**:** Cause and effect analysis for turbine and auxiliary systems

Function/ Component	**Potential failure**	**Potential cause(s) of failure**	**Potential effect(s) of failure**	**Possible maintenance solution**
Casing	Blocked blades. Loss of inter-stage seals (in multistage turbine).	Fracture. Solid particle erosion. Excessive pressure.	Blocked or restricted turbine by-pass valve. Changed flow characteristics. Wasted resources. Safety and environment.	Replace/repair casing. Visual check. Redesign the system to flow requirements. Monitoring/control flow parameters.
Inlet valves	Wear/damage of valve	Solid part.erosion. Excessive press. Worn/loose pack. Wrong valve/ material selection. Wear (all forms).	Changed flow/output characteristics. Loss of control. Safety.	Replace/repair valve. Redesign valve. Monitoring/control flow parameters. Visual check.
Turbine	Worn blades. Bearing failure.	Corrosion. Poor alignment. Fatigue and fract. Temperature recycling. Vibrations and shock	Vibration of rotor. Loss of control. Reduced efficiency. Safety.	Online vibration monitoring and analysis. Turbine–generator alignment. Replace/repair turbine. Turbine inspection.
Lube oil pumps	Wear/damage of gears. Leakage through glands. Vibration/noise. Bearing failure.	Clogged pump. Pump failure. Corrosion. Wrong settings.	Loss of oil press. Gen-turbine bearing failure.	Replace oil sieve. Repair/replace pump or motor shaft mounted pump. Redesign the system to lube or sealing needs. Audio-visual check. Replace bearing. Recalibrate. Lube oil redundancy.
Mechanical seal	Seal wear out or damage.	Wrong specific. or installation. Contact, heat or corrosion. Seal hardening. Reduced oil pressure. Vibrations and shock.	Power loss. Environmental Safety. Gas leak.	Repair/replace pump or motor. Correct specifications. Vibration analysis and monitoring. Visual check. Replace seal.

Failure mode and effect analysis for the heat exchangers and auxiliaries
A summary of the failure mode and effect analysis for a turbine and auxiliary system is illustrated in Table 8 where the possible failures are given, along with the possible causes and effects.

FMEA for the generator and auxiliaries system
The generator main components considered are the generator rotor and stator, the rotor bearings, and the excitation system. Table 9 illustrates the failure, cause, and effect analysis for the generator and auxiliaries system.

TABLE 8**:** Cause and effect analysis for heat exchangers and auxiliary systems

Function/ Component	Potential failure	Potential cause(s) of failure	Potential effect(s) of failure	Possible maintenance solution
Evaporator	Burst, leaking. Insulation damage. Scaling. Corrosion.	Fracture, coating failure. Solid particle eros. High calcite scalin. Water hammer. Excessive pressure. Environmental damage.	Blocked or restricted pipe. Changed flow characteristics. Cost of repair and generat./power loss Wasted resources. Safety and environment.	Replace/repair by-pass valve. Redesign the system to flow requirements. Monitoring/control fluid level.
Wet cooling tower (in-direct, induc. draft).	Scaling. Fouling of fills. Fan blade fail. Reduced water level.	Calcite scaling. Corrosion. Vibration. Excessive evaporat. Micro-organism growth and solid deposition.	Reduced heat transfer rate. Changed inlet/outlet temperatures. Power loss.	Cooling water treatment. Circulation pumps and motors check. Monitoring/control flow parameters. Visual check. Make up water dampers used.
Condenser	Corros. of tubes. High condenser pressure. Tube fouling.	Wrong operation. Malfunction. Poor condenser configuration.	Reduc. power output. Low heat transfer coefficient. Poor condensation. Loss of vacuum.	Cooling water treatment. On-line monitoring of fluid condition. Moisture separator. Clean biologic growth/ material/deposits

TABLE 9: Failure, cause, and effect analysis for the generator and auxiliaries system

Function/ Component	Potential failure	Potential cause(s) of failure	Potential effect(s) of failure	Possible maintenance solution
Generator stator.	Stator over heating. Arcing.	Loosened wedges. Poor cooling. Corona effects. Copper dusting. Core insulation failure.	Windings damage. Insulation loss. Over/under voltage output.	Alignment. Stator parameter monitoring. Tighten wedges. Calibrate protection equipment. Penetrating epoxy use.
Generator rotor.	Vibration. Bearing rubbing.	Misalignment. Poor lubrication. Loosened wedges. Fatigue and fracture.	Bearing and rotor damage. Windings damage.	Alignment. Replace bearing. Monitor and analyse vibrations online. Refurbish rotor.
Excitation system.	Under/over voltage. Vibration. Overloading.	Mis-operation of excitation system. Loss of excitation. Misalignment. ESD and lightning.	Winding overheating. Loss of power output.	Monitoring excitation parameters. Proper operation.
Air-cooled stator.	Blocked air inlet. Damaged generator fan.	Wrong enclosure specification. Particulate accumulation. Vibrat. and shock. Misalignment.	Loss of insulation. Misalignment. Core melting.	Inspection of windings. Alignment. Condensation and particulate removal. Replace enclosure.
Fire protection system.	Clogged.	No service.	Safety concerns. Penalties.	Replace with high pressure sprinkler system. Service flare.

FMEA for the instrumentation, control and protection system

The supervisory equipment, instrumentation, control, and protection, are very important parts of a power plant. Abnormal turbine-generator operating conditions will cause damage to the plant and possibly to personnel if the supervisory system fails. The instrumentation covers a wide variety of instruments installed in the geothermal power station. The instruments serve the purpose of monitoring and communicating the performance parameters of the plant. The instruments include pressure gauges, temperature gauges, flow meters and protection relays. The control function is important to ensure the plant operates within the set limits. The control and monitoring functions depend on received measured parameters. The turbine and generator protection system which ensures that the plant components are protected spends most of its time in a non-operating state. A failure mode cause and effect analysis for the control, instrumentation and monitoring system is presented in Table 10.

TABLE 10: Cause and effect analysis for the control, instrumentation and monitoring system

Function/ component	Potential failure	Potential cause(s) of failure	Potential effect(s) of failure	Possible maintenance solution
Control and monitoring system.	Wrong signal. No signal. Damaged integrated circuits (ICs).	Damaged cable. Poor calibration. Faulty sensors. Extreme temperat. fluctuations. Electrostatic discharge (ESD) and lightning.	Loss of control (overspeed, governor failure, lube oil failure, excessive vibration) and monitoring. Safety risks.	Recalibrate. Replace/repair/install sensors. Enclosure re-specification.
DCS.	Loss of power supply. H_2S damage. Damaged integrated circuits (ICs).	H_2S attack Damaged cable Extreme temp. fluctuations (non-op)	Loss of monitoring. Machine damage.	Safety risks. H_2S remover/filter. Redundancy.
Relays.	Wrong parameters. No input parameters. Solder joints break.	Poor calibration. H_2S damage. Temperature cycling. No protective coverings degradation.	Loss of control and monitoring. Safety risks.	Monitoring excitation parameters. Proper operation. Replace relays.
Instrumentation for supervisory, efficiency, auxiliary, protection & condition monitoring.	Wrong or no signal for plant & brine system. Wrong protection measurements.	Faulty temperature, pressure, speed, vibrations, output probes. Loss of calibration.	Loss of operating efficiency. Safety hazards. Loss of control and monitoring.	Re-calibrate probes. Replace probes.

Table 11 outlines some of the O&M related corrosion problems on geothermal power plant components (Marita, 1998). According to the survey, when making materials selection, prior experience was often the basis coupled with an in-house evaluation and a combination of different factors. The maintenance approach for most of the O&M related corrosion problems would be by designing around the failure mechanisms, achieved through the selection of materials that are more corrosion resistant in a geothermal environment.

The binary turbine is expected to have a long operational life to due to the characteristics of the working fluid that, unlike steam, is non-eroding and non-corroding for valve seats, tubing and turbine blades.

TABLE 11: Causes of failures and components affected by the specific problems

Causes of failure	Components affected
Corrosion (all forms).	Turbine blades/valves/rotor, expansion bellows, NCG pipelines, wells, fluid collect. & disposal systems, valves, condensers, evaporator syst.
Scaling.	Wells, pipelines, reinjection pumps, evaporator and condenser tubes, valves, control valves at well heads, lineshaft pumps.
Stress corrosion cracking.	Piping, pipe elbows, heat exchangers, valves, wherever 300 series stainless steel is used, duplex stainless steel, some higher Ni alloys, condensers, valve shafts.
Microbiologically influenced corrosion.	Cooling towers (incl. concrete above vapour space), heat exchangers, pipelines, tube and shell main condenser, condenser tubes, valves.
Fatigue	Turbine blades/rotor, pipelines, heat exchangers, rotating equipment.
Corrosion fatigue	Turbine blades/rotor, pipelines, condensers, cond. tubes, rotating parts.
Solid particle erosion	Turbine blades/rotor/seals, pipelines, well components.
Wear (all forms)	Turbine blades/rotor, valve stem, mechanical seals, valves, brine equipm.
Coating failure	Turbine casing, pipelines, well & line valves, epoxy coating on mild steel condenser, structural steel, Teflon linings, circulating water pipes.
Creep	Teflon linings.
Yielding	Wells.
Fracture	Well casing, turbine blades, pipelines, welds.
Combination	Turbine blades.
H_2S attacks	Exposed copper for switchgears, transformers, motors, control systems.

Generator major overhaul (every 8 to 10 years):
The electrical and mechanical tests that are required (Kiameh, 2002) include the following:

- Perform insulation resistance and polarization index tests.
- Investigate causes of partial discharge.
- Check the tightness of the stator wedges (re-wedging may be required)
- Determine if there is any loosening in the core laminations or deterioration in the core insulation. Apply penetrating epoxy if the insulation is degrading.
- Perform casing pressure, and stator pressure and vacuum decay tests.
- Refurbish the rotor, inspect radial pin and end caps (ultrasonic and dye penetrant testing), vacuum test, slip ring refurbishment, and check for copper dusting.
- Calibrate protection equipment.

6.3 Summary of maintenance needs for the Kapisya binary power plant

The stepwise approach for the overhaul of the Kapisya binary power plant requires a definition of the main power plant and brine gathering subsystem components. The components which are critical have functional, safety, economical, environmental and operational impacts. The next step is the definition of the system operation and usage in a geothermal environment. The maintenance approaches for most of the O&M-related corrosion problems have a great influence on plant reliability because of the chemical and physical properties of the geothermal fluids. From the identification of potential failure sites and failure mechanisms for the subsystem components, maintenance activities can be drawn. The types of maintenance activities required depend on the type of actual or potential failures, the effects of the failure on the equipment and entire system, the costs of repairs, safety and environmental concerns and other failure consequences. The actual or potential causes of failures are also considered in deciding the maintenance approaches that need to be taken. A summary of preventive and corrective maintenance activities for each failure mechanism in the Kapisya binary power plant are listed in Tables 6, 7, 8, 9, and 10. The executed strategy of the overhaul maintenance activities will depend on the management method applied. The management of the life cycle of the power plant will rely on the outlined maintenance strategies determined.

Increasing the competitiveness of geothermal electrical power energy requires a reduction of costs ranging from exploration and drilling to plant operations and maintenance (O&M). There are several options that could assist with the reduction of O&M costs associated with material problems. These include, among others, the optimisation of the currently available materials and technologies, the life extension of existing equipment and a service life prediction (Marita, 1998).

6.4 Potential improvements to existing power plant facilities

The Kapisya power plant and brine gathering equipment were installed over twenty years ago. With age some of the systems may need upgrading to current geothermal power plant technological levels of performance. The overhaul period should be seen as providing a magnificent opportunity to introduce process improvements, new equipment, a certain amount of automation, and so forth. The potential for improvement to the existing non-operating power plant are of two general types: resource supply and surface facilities. The project maintenance aims to preserve the function of the plant by improving equipment.

The difference between the most-likely geothermal resource capacity and the electro-mechanical capacity of an existing plant shows the amount of incremental power output that could be achieved by a combination of plant improvements, construction of a new binary plant coupled with further geothermal explorations (Lovekin et al., 2006). The improvements that can be considered include surface facilities, the well field and gathering system improvements and plant equipment. Table 12 provides an overview of the potential improvements that may be considered for this study.

TABLE 12: Potential plant and brine resource equipment improvements

Potential improvements to resource supply	Potential improvements to power plant
Upgrading brine gathering system facilities	Modifications to binary turbines
Drilling make-up production wells	Modifications to heat exchanger systems
Performing workovers or stimulations of existing shallow wells	Modifications to process configuration (such as working fluid)
Drilling larger-diameter or directional wells	Reduction of parasitic power consumption (station load)
Controlling scaling or corrosion problems	Better plant equipment monitoring and control system
Increasing the setting depth of downhole production lineshaft pumps	Better mitigation and monitoring of scaling and corrosion
	Improvements in plant operation and maintenance (O&M) procedures

The working fluid mixtures can be tailored to match the characteristics of the geothermal resource brine and the limitations imposed by the power conversion cycle. There is also a possibility of changing the composition of the working fluid in response to long-term variations in the available geothermal resource temperature (DiPippo, 2005). When a cycle has an efficiency of say 10%, an improvement of only one percentage point represents a 10% improvement, and this may make the difference between an economically viable project and one that is not.

Some failures can be eliminated by redesign (by project maintenance task). The applicability and costs of these possible improvements to the Kapisya power plant clearly need to be evaluated on a case-by-case basis. Improvement of existing facilities and the idea of abandoning some old facilities need to be approached with caution (Edmund and Schmidt, 1966). The improvement of equipment should be preceded by the development of a preliminary general power lay-out on the basis of using only geothermal field proved equipment. All the improvements require review on the basis of plant performance and engineering. This can be followed by establishing the overhead gains.

7. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1 Discussion

The outsourced field assessment of the Kapisya binary power plant and brine gathering system conditions sets the stepping stone for the overhaul and further plant and resource improvements. The field assessment coupled with an analysis for failure sites, failure mechanisms and effects of failures for both extended non-operating and operating plant states will broaden the overhaul scope. The study considered wide ranging natural and geothermal environments in which the systems are located. This survey suggests that the approach will introduce aspects associated with both plant operating reliability and potential equipment improvements. For system process performance enhancements, potential areas of improvements are of two general types: increased brine supply and raised plant generating equipment performance.

Considering that a newly overhauled and operating plant will be prone to infant mortality and require a reliability maintenance strategy, setting a baseline maintenance approach may be justified. A baseline maintenance approach was derived from:

- Svartsengi power station standards, operations and maintenance experience of the Ormat plant; develop a general philosophy of how operations and maintenance best work together.
- Outlined plant and brine gathering equipment overhaul and improvement needs.
- Commonly applied maintenance managements such as reliability centred maintenance methods in power production.

The maintenance strategy and associated maintenance activities that would provide the baseline approach for the reconditioned plant are summarised in Figure 7. The proposed approach will

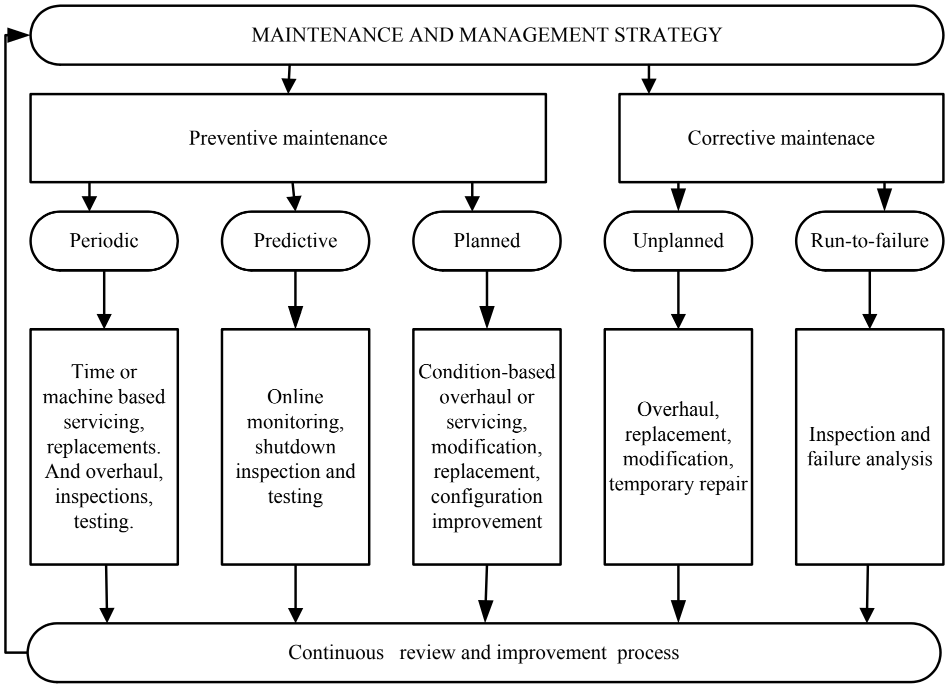

FIGURE 7: Relationship of maintenance and management strategy and activities

establish a continuous process for assessment, review and improvement of the maintenance programme to ensure that the maintenance strategy is effective, meets its objectives and has been implemented in line with observed design requirements, the Svartsengi power station standards, and operating experience.

7.2 Conclusions

Effective planning for the overhaul of the Kapisya binary power plant and associated facilities requires consideration of varying engineering, operational, maintenance, environmental, safety, and cost aspects in a geothermal energy setup. Once all aspects are taken into account and evaluated, a successful reconditioning can be achieved.

Systems designed for high operating reliability do not necessarily perform well (or at all) after long periods of exposure to the non-operating environment.

7.3 Recommendations

The applicability and costs of the potential upgrades to the Kapisya power plant brine supply and plant generating equipment to enhance performance clearly need to be comprehensively evaluated on a case-by-case basis to establish the potential gains.

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NOMENCLATURE

ODP	Ozone depleting potential
GWP	Global warming potential
O&M	Operation and maintenance
PM	Preventive maintenance
CBM	Condition based maintenance
RCM	Reliability centred maintenance
FMEA	Failure mode and effect analysis
SCADA	Supervisory control and data acquisition

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