



GEOTHERMAL BINARY PLANT OPERATION AND MAINTENANCE SYSTEMS WITH SVARTSENGI POWER PLANT AS A CASE STUDY

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ABSTRACT

Geothermal energy has been developing as an important power source in the world. Utilization of this underground heat source for electric production becomes more and more important. Geothermal binary plants are the best solution for electricity production in low- and intermediate-temperature fields. It is also possible to utilize the waste heat from steam turbines for electricity production. Organic binary plants are the most common geothermal binary plants, which have lower investment and running costs than hydro or coal power plants.

The life of a power plant depends on its availability. Plant capacity must be reliable for a company to stay in business. A smooth operation and maintenance system determines the production capacity of the plant. The control system and manpower skills of a company influence its operation. The simplicity of the motive fluid cycle of organic binary plants aids the operator in running the plant safely. An effective maintenance system allows the plant to be profitable and competitive in the free market. The Svartsengi power plant is located 50 km away from Reykjavik, in Iceland's active volcanic zone. The power station produces both hot water for heating and electricity in five different plants. The seven Ormat units are located in plant no 4. The units produce electricity from waste heat from steam turbines. The control system for the Ormat units is fully automatic and remotely monitored. The plant uses the SCADA system for its operation. The maintenance system of the plant does not directly follow the maintenance approaches shown in the report, being a hybrid of both. However, operators have gained good experience in handling any breakdown.

1. INTRODUCTION

Power plants for generating electricity from hydrothermal resources can be divided into two types: binary and steam. As the word 'binary' (which means two) indicates, there are two cycles in binary plants. Here we will be looking at geothermal binary electric power plants. The two cycles in such plants are the primary cycle with the geothermal fluid and the secondary cycle with the working fluid. The choice of

the working fluid depends on its boiling point, which should be lower than for water. Most binary plants in the world use organic compounds, usually isobutane or isopentane. However, it is also possible to use inorganic compounds. The best example of that is the Kalina binary power plant which uses a mixture of ammonia and water as a working fluid.

Even though commercialisation of geothermal plants started in the early 1900s in Italy, the first installed commercial scale binary plant was the Heber binary power plant in California, USA, that began operation in 1985 (Sones and Krieger, 2000). Binary plants are usually installed in medium-temperature resources which have a temperature range of 100-220°C. Producing electricity using binary plants is advantageous in both low- and high- temperature fields. In low-temperature fields steam turbines cannot be installed; however, binary plants use the advantage of their working fluid (low boiling point) to produce electric power. In high- temperature areas, binary plants use the waste heat from steam turbines to produce electricity. This increases the total efficiency of the plant. This kind of binary plant (in a high-temperature area) is called a combined (hybrid) power plant. In this report, we are going to look at the working system of an iso-pentane binary plant. The plant works with the O.R.C. (Organic Rankine Cycle). Isopentane has definitely a lower boiling point than water. Thus, we can use this system in low-temperature areas.

Most of the operating systems for binary plants are similar to other geothermal power plants. However, in a binary plant, the operator should also consider the organic fluid characteristics. The operation system of Svartsengi binary plant is fully automatic and monitored by the SCADA system. There are different approaches for developing maintenance strategy. In this report we are going to see two of them. These are the business centred maintenance (BCM) approach and the reliability centred maintenance (RCM) approach. In Svartsengi, the maintenance system does not follow any of them, using instead its own designed system.

2. GEOTHERMAL BINARY PLANTS

2.1 General considerations

The first consideration in constructing binary plants is choosing the working fluid. There are many possible working fluids which have different thermodynamic properties. We can use the following characteristics of efficient working fluids to make a choice:

- a) The critical temperature of materials used in plant components must be far below the maximum temperature that can be reached in the cycle;
- b) Saturation pressures at maximum and minimum temperatures should be within a given range, neither involving high pressures as to cause strength-of-material problems, nor low pressures as to give rise to sealing problems against atmospheric infiltrations;
- c) Chemical stability and inertia during temperature changes in the cycle;
- d) Vapour saturation line approximately close to the turbine expansion line; this will avoid excessive humidity at the turbine exit, eliminating superheating, and also allows all or nearly all of the heat rejection to take place at minimum temperatures;
- e) Inexpensive and not difficult to find;
- f) Not toxic;
- g) Non-flammable.

Different studies of binary mixtures of hydrocarbons show that one effective mean to improve performance in binary cycle power plants, designed for low- to moderate-temperature liquid-dominated resources, is to use mixed hydrocarbon working fluids rather than pure hydrocarbons. Significant savings in the cost of power production can be achieved, if hydrocarbon mixtures are used in these plants. The amount of cost reduction increases with the decrease in resource temperature.

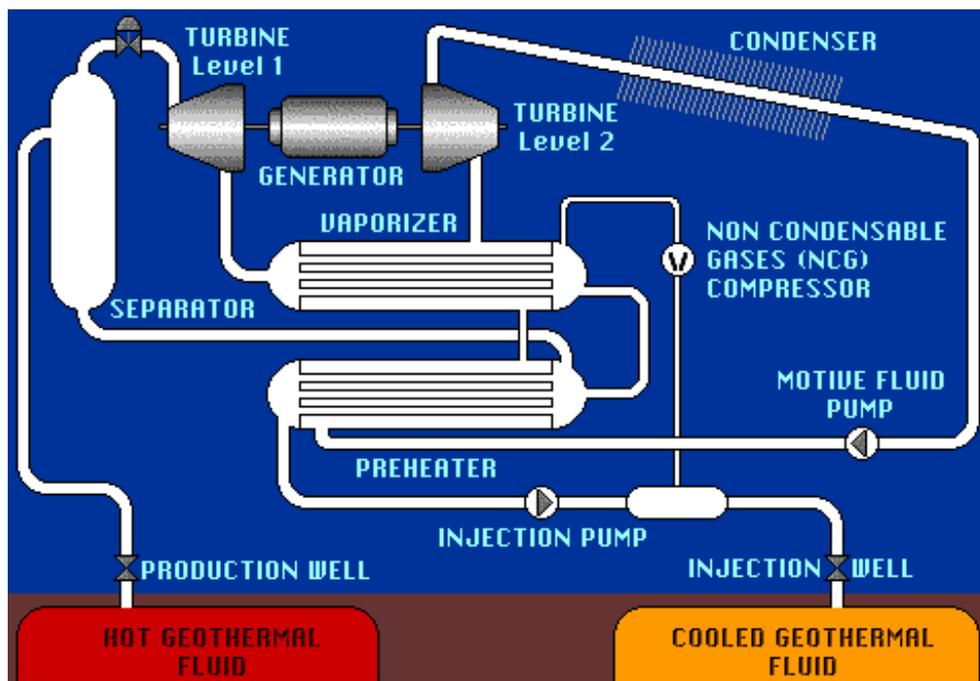


FIGURE 1: Flow diagram for a geothermal binary power plant (Ormat, 2002)

For a two phase flow of “brine and steam”, a binary plant may consist of the following components (Figure 1):

- Separator, one or more;
- Pipe lines - for both the steam and the brine and for the re-injection system;
- Heat exchanger including pre-heater, vaporiser and recuperator (working fluid to working fluid heat exchanger);
- Turbine and its accessories;
- Generator and its accessories;
- Condenser;
- Auxiliaries such as compressors, pumping units, fire fighting system, HVAC system, cooling system, drainage system, H₂S detecting system etc.;
- Control system;
- Electrical units, such as switch gears, bus bars, transmission lines, etc.;
- Stand by diesel generator, for emergencies.

For lower quality resource temperatures below about 175°C, flash plants lose their efficiency; then it is more efficient to transfer heat from the geothermal fluid to a volatile working fluid that vaporizes and is passed through a turbine. Because all of the geothermal fluid is returned to the reservoir, binary-cycle plants do not require mitigation of gaseous releases and reservoir fluid volume is maintained. Because larger binary plants typically comprise small modules, maintenance can be done on one module at a time, thus minimizing the impact on plant output.

2.1 Organic Rankine Cycle

The principle of an organic cycle is not complicated. It is a practical approach to the Carnot cycle. The organic compound is vaporized by the steam or hot water in the boiler/vaporizer at low temperature. The organic vapour then drives the turbine to produce electric power at the generator. The outlet motive fluid from the turbine is taken to water or air cooled condensers. The feed pump will drive the working fluid to the pressure of the vaporizer. The main components of the total system for the circulation of the working fluid are: Boiler/vaporizer, pump, turbine and condenser. Figure 2 shows the simple Rankine cycle, and Figure 3 a temperature-entropy diagram for a Rankine cycle.

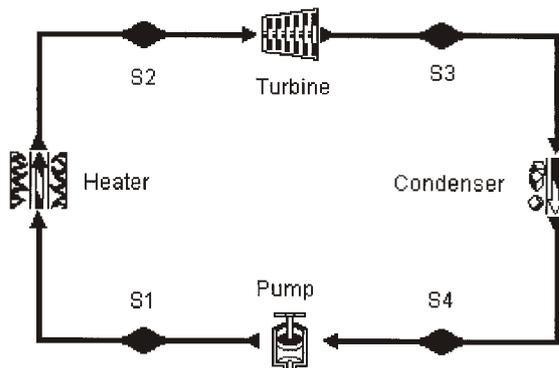
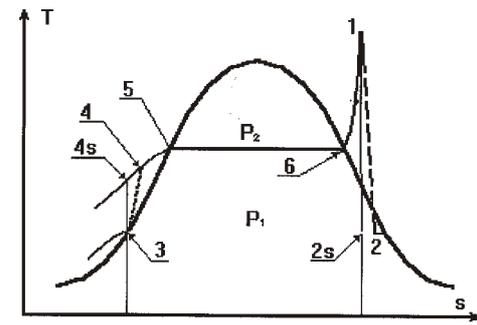


FIGURE 2: Simple Rankine cycle



T-s diagram for a Rankine cycle.

FIGURE 3: T-s diagram for a Rankine cycle

Energy is added to the system at the heater and it is rejected in the condenser. The working fluid expands isentropically in the turbine to give useful work. The pump is used to increase the condensed fluid pressure to match that of the boiler. The net power output of the system is the difference of work at the turbine and at the pump.

The advantage of a binary organic cycle is an increase in the total efficiency of the system. In a binary cycle, waste heat from steam turbines is used or the low heat content from low-temperature areas. There is no doubt that it can increase the thermal efficiency of a plant. From the T-s diagram in Figure 3, we can determine the thermal efficiency of the working fluid as follows:

$$\text{Thermal efficiency} = \frac{\text{Net power out}}{\text{Heat in}}$$

$$\eta'_{th} = \frac{W_{net}}{Q_{in}} = \frac{(|W_T| - |W_P|)}{Q_B}$$

In an ideal Rankine cycle, the parameters are a) Isentropic pump compression; b) Isentropic turbine expansion; c) Isobaric boiler heat addition; and d) Isobaric condenser heat removal. Hence

$$|W_T| = m(h_1 - h_{2s}) \quad \text{and} \quad |W_P| = m(h_{4s} - h_3)$$

$$Q_B = m(h_1 - h_{4s})$$

For an irreversible Rankine cycle the following applies:

$$|W_{TA}| = m(h_1 - h_2) \quad \text{and} \quad |W_{PA}| = m(h_4 - h_3)$$

$$Q_{BA} = m(h_1 - h_4)$$

The isentropic turbine and pump efficiencies (η'_T and η'_P) can then be calculated as follows:

$$\eta'_T = \frac{W_{TA}}{W_T} \quad \text{and} \quad \eta'_P = \frac{W_{PA}}{W_P}$$

or

$$\eta'_T = \frac{h_1 - h_2}{h_1 - h_{2s}} \quad \text{and} \quad \eta'_P = \frac{h_4 - h_3}{h_{4s} - h_3}$$

The following definitions are used in the equations:

η_{th}	= Thermal efficiency;
η_T	= Turbine efficiency;
η_p	= Pump efficiency;
h	= Enthalpy;
Q_B	= Ideal boiler heat addition;
Q_{BA}	= Actual boiler heat addition;
W_P	= Ideal pump work;
W_{PA}	= Actual pump work;
W_T	= Ideal turbine work;
W_{TA}	= Actual turbine work;
m	= Mass of working fluid.

Using a preheater can increase the efficiency of the Rankine cycle. Usually the preheater is a separate heat exchanger which is used to heat up the working fluid before it goes to the vaporizer. The vaporizer itself can serve as a reheater for the outlet fluid from the high-pressure turbine before it goes to the low-pressure turbine. This is to prevent the turbine blades being eroded by wet fluid.

2.3 Advantages of a vapour-turbine cycle using isobutene or similar fluids

The vapour-turbine cycle using isobutane or other suitable fluids has many advantages over flashed steam or indirect steam heating cycles (Kruger and Otte, 1973):

1. Water pumped from the reservoir at pressures above saturation reaches the surface at nearly maximum well temperature, whereas water lifted by steam suffers severe temperature losses.
2. Since water at full pressure retains its gases in solution, the gases can be returned to the ground without danger of atmospheric pollution.
3. If steam and dissolved gases were permitted to escape from the water, the chemical composition of the water would change, very likely causing precipitation of solids out of solution, and plugging of wells.
4. Keeping water at constant high pressure in the heat exchangers helps to minimize heat-exchanger tube stresses. The possibility of stress corrosion, which is often the chief cause of failure in high-temperature hot water heat exchangers, is thereby reduced.
5. A vapour turbine incorporates fewer stages, and the vapour volume change through the turbine is not as great, therefore the vapour turbine generally offers more efficiency than a steam turbine.
6. Wheel speed in vapour turbines is lower than that in steam turbines, therefore design problems are simpler and blade stresses are much less severe.
7. The vapour turbine cycles can be relatively quiet; flashed-steam cycles require costly noise-abatement measures.
8. Organic compound turbines operate above atmospheric pressure throughout the cycle. The possibility of air and oxygen getting into the turbine and causing corrosion and explosive mixtures is eliminated. Air entering the system under vacuum is a major cause of corrosion in steam systems.
9. Organic compounds and other such fluids are relatively simple.
10. Organic compound turbines are much smaller and therefore less costly than steam turbines of the same power output.
11. Organic compounds remain dry throughout its expansion through the turbine, thus eliminating the erosion of blades by water droplets that are so common in steam turbines.
12. Organic compounds are compatible with oil, so internal bearings can be used in the turbine, yielding a turbine much more rugged and lower in cost, and requiring only a single shaft seal at the coupling end of the turbine.
13. Since organic compounds are non-corrosive, there should be no need for expensive stainless steels which is often required in various parts of a turbine in a flashed-steam cycle.

14. Condensed organic compounds have lower density and lower latent heat than steam, therefore cavitation damage should not occur in the boiler feed pump.
15. Corrosion problems are less severe and the organic compound boiler feed pump can be made from cheaper materials than a conventional water feed pump.
16. Because organic compound turbines have much lower rotating inertia than steam turbines of the same power, the short-circuit torque problem from the drive couplings is virtually eliminated.
17. Organic compound turbines can be designed to utilize lower condensing temperatures, thus, cycle efficiencies are improved and water rates are reduced below those of steam turbines.
18. With no air or non-condensable gas in the condensers, organic compound condensers can be made 100 percent effective; with steam condensers, gas in the steam reduces condenser efficiency by increasing condensing pressure.
19. Steam turbines can require substantial gas removal equipment unlike those using organic compounds.
20. The organic Rankine cycle (ORC) permits efficient transfer of heat from well water down to quite low temperatures; water can be discharged from the generating plant at temperatures as low as 50°C. In contrast, steam cycles can rarely be economic at water-discharge temperatures below 100°C.

Some of the disadvantages are the following: Binary plants tend to have higher equipment costs than flash plants. Because they transfer heat from the geothermal fluid and return all the geothermal fluid to the ground, they do not have condensed steam available as cooling water. Thus, they must use a separate water source or air-cooled condensers. The working fluid is also expensive and flammable. The number of the working fluid providers is small in the world. The air cooler is dependent on the outside temperature. The lifetime of a turbine shaft seal is small and the seal is expensive.

2.4 Organic binary power plant operation

The simplicity and small number of components in an ORC binary power plant allow the operator to run the plant safely. The power availability of the plant depends on its successful operation. Today, the use of sophisticated operating systems, computer control programs and automation make it possible for most plants to operate with fewer personnel. The ability and knowledge level of operators are the most significant factors affecting the smooth operation of a plant. Today, almost all ORC plants are using SCADA (Supervision, Control And Data Acquisition) system for plant operation.

The following is vital for plant operation (Woodworth, 1988):

- a) **Operator training.** The operation personnel should understand the operating system. Even if modern power plants are remotely controlled, the ability and knowledge of the operators determine the smooth operation of the machinery. If the operators are not well trained in the equipment they operate, the use of modern technology has no meaning. To be competitive, training should be continuous and up-to-date with the latest technology. The plant management should not hesitate to train them, since it will not lose from the outcome. And it is essential for the plant to train its personnel before it starts to operate.
- b) **Technology.** Nowadays a plant can be controlled and operated remotely with a few well trained personnel using a SCADA system. The plant should up-date its equipment to the latest technology periodically for better production.
- c) **Operation manual.** A manual is a guidebook for an operator. It gives full information about the operating and control systems of the plant. The manual should be understandable and simple to follow by the operator. It must be clear enough to all operating personnel. The operation manual gives all the necessary steps required to start up, shut-down and normal operation of the plant.

The plant start-up procedure contains all the steps that the operator should follow to put the plant into operation. The manual should describe all the options that lead the plant into operation, that is to say, all the necessary steps for manual, mechanical, automatic and remote start-up. Here, all the preconditions,

before the start-up button is pressed, should be well stated. Auxiliary systems like lubrication, cooling, draining, ventilation, etc., should be ready. Gauges, sensors and other measuring devices in the plant which need check-ups before start-up should be mentioned. Normal operating evolutions tell the operator what he should do during normal operation. All data and inspections like water sampling, and the condition of the equipment should be well described. Normal shutdown stops the plant producing electricity for maintenance or other reasons. All the necessary steps to cool down the machines safely should be clearly defined here. Auxiliary equipment that should be operated before the turbine rests are to be described here. The cooling and lubrication systems of the rotating parts should be given special attention by the manual. Alarms and automatic shutdown of the plant must be described in the manual. The operator should know what immediate action should be taken during alarms, and what procedures to follow during automatic shutdown of the plant. He also should know how to identify and solve observed problems.

2.5 Maintenance system

The term maintenance can be defined as the combination of all technical and associated administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function. The origin of maintenance came with the industrial revolution. Before that, machines were designed, built and operated by their users. The industrial revolution separated product users from makers. This resulted in machine operators and maintainers doing different jobs. Maintenance cannot correct fundamental design errors but design change maintenance can be applied, if maintenance cost is expensive. Maintenance can be reactive (corrective), i.e. failure response; or preventive, i.e. time based.

Preventive maintenance is carried out at pre-determined intervals, or corresponding to prescribed criteria, and intended to reduce the probability of failure or the performance degradation of an item. Preventive maintenance is planned and scheduled (or carried out on opportunity). If preventive maintenance is initiated as a result of knowledge of the condition of an item derived from periodic, routine or continuous monitoring, it is called condition-based maintenance.

Corrective maintenance is carried out after a failure has occurred and is intended to restore an item to a state in which it can perform its required function. If corrective maintenance is necessary immediately in order to avoid serious consequences, it is called emergency maintenance. Thus, emergency maintenance cannot be scheduled. In some cases, however, ensuring that decision guidelines have been prepared and necessary resources are available it can be planned. Nowadays, there are different approaches to maintaining of a plant. The management body of the plant should choose the best approach which satisfies the objective of the plant. Two of them are discussed here.

2.5.1 Business centred maintenance (BCM)

Business centred maintenance is a methodology or framework of guidelines for deciding maintenance objectives, formulating equipment life plans and plant maintenance schedules, designing the maintenance organisation and setting up appropriate systems of documentation and control. It has been formulated by Dr. Anthony Kelly of Manchester University (Kelly, 2002). This approach springs from and is driven by the identification of a business objective, which is then translated into maintenance objectives and underpins the maintenance strategy formulation. This approach considers every maintenance activity and procedure from a business point of view. Since every industry passes through a competitive environment, the approach is quite reasonable. We can see from Figure 4 how he tackles the maintenance procedures of an organization.

The following is a brief discussion of some elements of the methodology in order to understand this approach.

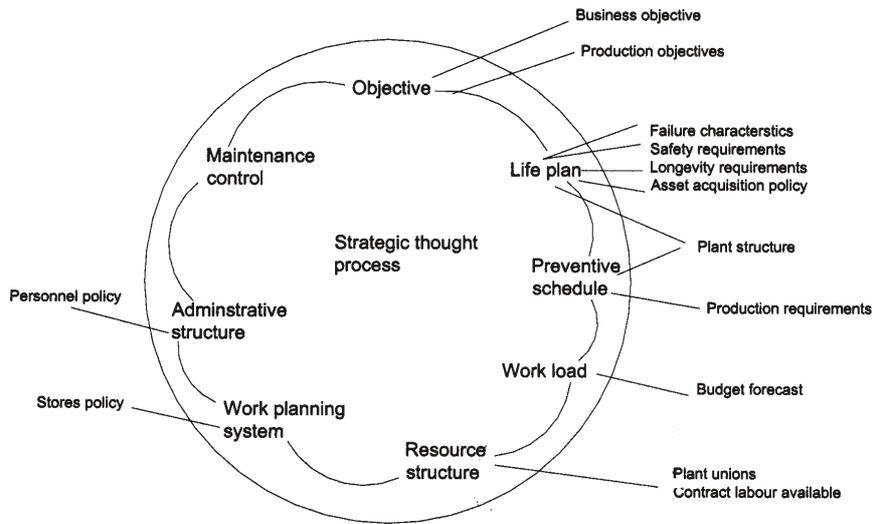


FIGURE 4: Business centred maintenance methodology (Kelly, 2002)

Life plan can be defined as the programme of preventive maintenance work to be carried out on a plant over its entire life. It is influenced by the following factors:

- Failure characteristics;
- Plant structure;
- Asset acquisition policy; and
- Safety policy.

Three main steps are used to determine the life plan of a plant (Figure 5) (Kelly, 2002).

1. Understanding the plant structure and the characteristics of its operation;
2. Establish maintenance life plan for each unit;
3. Establish a maintenance schedule for the plant.

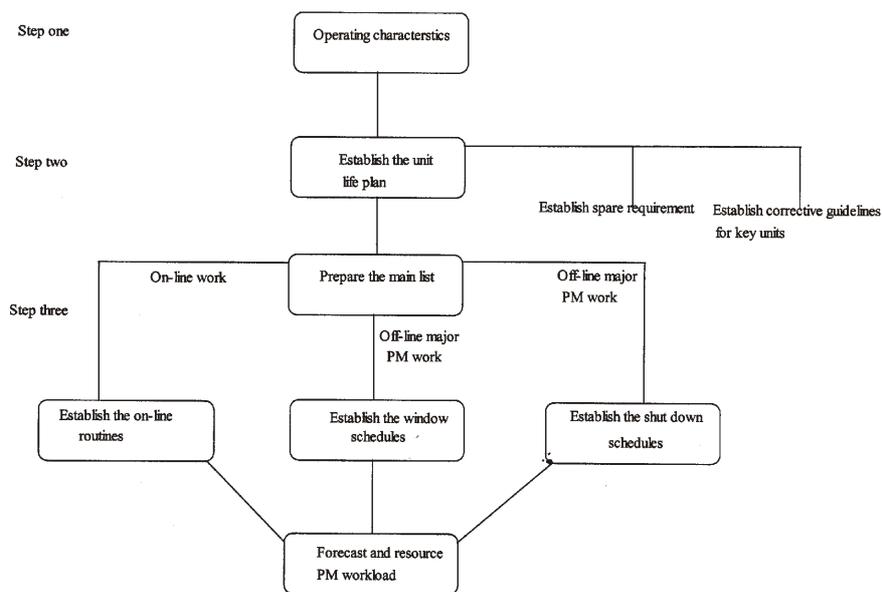


FIGURE 5: Flow chart showing steps for building a life plan for a plant (Kelly, 2002)

Workload can be defined as categorizing maintenance work for the whole of a plant by its planning and scheduling characteristics. It is the largest single influence on organizational design in BCM. The shape and constitution of workloads vary across different power plants. Maintenance shift work is not usually required. Table 1 shows a categorization system used for a general maintenance workload in a plant.

TABLE 1: Categorization system for a general maintenance workload in a plant (Kelly, 2002)

Work level	Category	Description
Typical first line work	A	Required to be done when it arises.
	B	Required to be done within 24 hours.
	C	Minor corrective work that does not fall into categories A and B but does not require planning and is of relatively short duration.
	D	Minor routine preventive work, e.g. 500 hr service that does not require a high degree of skill and carried out on a routine basis.
Typical second line work	E	Major corrective work that starts as a category A or B job.
	F	All corrective jobs that benefit from some form of planning and have a scheduling lead time > 24 hrs. Such jobs do not require a major influx of resources.
	G	Modification work that has the same planning characteristics as category F.
	H	Preventive maintenance work that has the same planning characteristics as category F, e.g. this would include all services other than major outages.
Typical third line work	I	Work that might involve some planning and scheduling efforts in terms of job methods and major spare part resourcing. In addition, it involves an influx of labour to resource peaks or has a specialist skill content.

Work planning: can be defined as the way in which maintenance work (preventive, corrective, and modification) is planned, scheduled, allowed and controlled. The function of work planning is to ensure the 'five rights' i.e. 1) To get the right resource; 2) To the right place; 3) At the right time; 4) To do the right job; and 5) Do it in the right way.

Doc Palmer (1999) sets maintenance planning into six principles in his "Maintenance planning and scheduling handbook".

1. The planners must be organized in a separate department to that of maintenance crews;
2. The planning department concentrates on future work;
3. The planning department maintains a simple, secure file system;
4. Planners use personal experience and file information to develop work plans;
5. The planning department recognizes the skill of the crafts;
6. Wrench time is the primary measure of work force efficiency and of planning efficiencies.

Maintenance control is a mechanism for controlling the overall maintenance effort of a plant to run according to the designed maintenance system. That means, to control the following items:

- Maintenance cost;
- Maintenance effectiveness;
- Organizational efficiency.

2.5.2 Reliability centered maintenance (RCM)

In this kind of maintenance system approach, we are biased to make the plant reliable for production, and to keep the plant in operation. F. Stanley Nowlan and Howard F Heap evolved this maintenance system

in the airline industry during the 1960's and 70's (August, 1999). The logic of RCM is based on three questions

- How does a failure occur?
- What are its consequences for safety or operability?
- What good can preventive maintenance do?

The RCM procedures are:

1. System definition and acquisition of operational and reliability information;
2. Identification of "maintenance significant items" (MSI); i.e. items the failure of which would significantly threaten safety or increase cost (because of loss of production and/or high direct repair cost);
3. For each MSI, determination of failure modes, their likely causes, and whether they can be detected (and if they can be, the way in which this might be done);
4. For each significant failure mode, selection of the maintenance task, or tasks most appropriate for reducing its likelihood of occurrence or mitigating its consequences;
5. The formation of the task list into a workable plant-wide schedule;
6. Implementation of the schedule and sustained feedback of in-service data for periodic review and update.

Figure 6 shows a flowchart for a critical streamlined RCM approach.

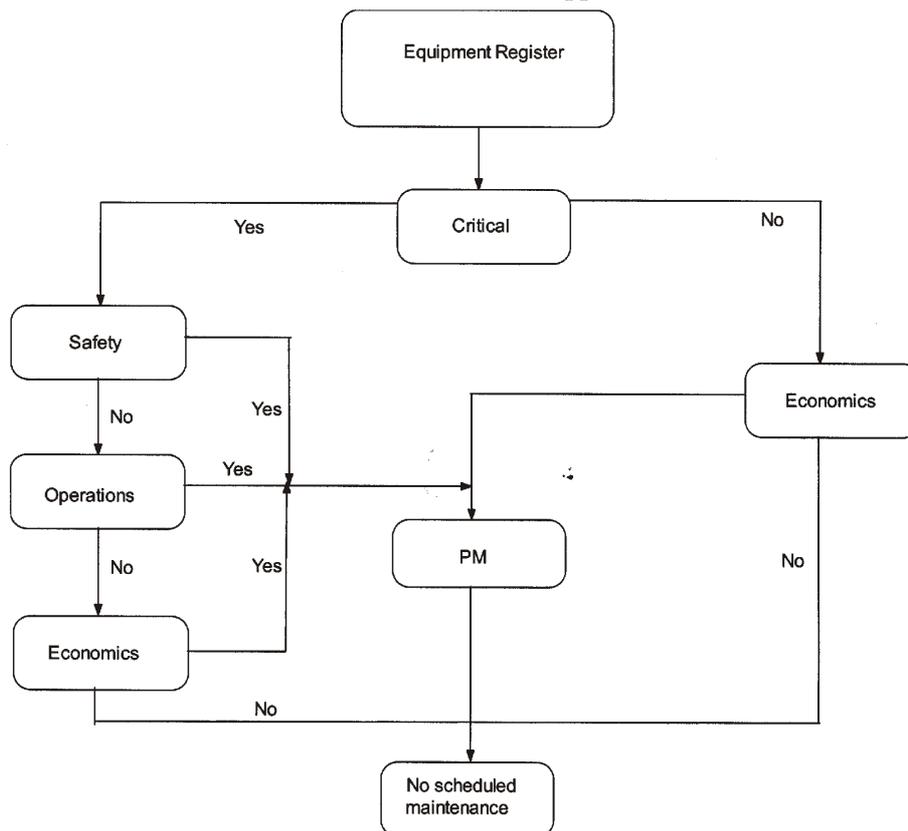


FIGURE 6: Critical streamlined RCM approach

2.6 Computerized Maintenance Management System (CMMS)

Utilizing a modern computerized system has an important role for plant maintenance. However, we should note that they are not the ultimate remedy to one's maintenance troubles. The documentation and planning activities especially need this vital tool. Management can use it to control maintenance activities through maintenance reports and future work plans. The maintenance group can better visualize, determine and manage its backlog with its resources using a computer maintenance system.

There are plenty of software applications today for maintenance systems. It is essential to know what type of computer system is involved and who created the software. Selections of a system are influenced by a specific operating platform, the potential of the provider company in business, specific industry experience or geographical closeness for support. The system should be friendly to all users. Access for upgrading the program most conveniently and training staff are basic factors when selecting CMMS. We should not presume that a CMMS must be installed fully at once. It may never need full installation. The planners might initialize the planning module gradually as they become familiar with the CMMS.

The advantages of a CMMS are (Palmer, 1999):

1. Computerizing the inventory system produces the overwhelmingly largest value-added benefit;
2. Providing easily obtainable reports to the maintenance group;
3. Prevention of work order loss and determination of current work order status;
4. Automization of the mini-files linking history, parts, maintenance procedures, safety data, tools and other information related to specific equipment;
5. Providing similar data for everyone throughout the network system;
6. Automating the PM generation of work orders.

3. SVARTSENGI POWER PLANT

The Svartsengi power plant is located on the Reykjanes Peninsula about 50 km away from Reykjavik in a high-temperature geothermal field. The geothermal field is near the town of Grindavik. Today it supplies electricity to the inhabitants in the region and contributes a considerable amount of electricity to the national grid, although the power plant was initially constructed for a heating utility. The rise of oil prices in the world greatly influenced the geothermal exploration in the area. Hitaveita Sudurnesja (HS) runs the plant. All data and information used in this report on the Svartsengi power plant is by the courtesy of Hitaveita Sudurnesja.

Drilling of geothermal wells for heating in this high-temperature area started in the early 1970s. The results of extensive exploration and studies were promising, so the Hitaveita Sudurnesja company was established in 1974. When the company was established, 40% was owned by the national government and 60% by the seven local municipalities. The state participated for the sake of the Keflavik International Airport district heating system. Today, the national government owns only 15.5% and seven municipalities own the rest.

The Svartsengi high-temperature field has a uniform reservoir temperature of 240°C below 600 m. The high temperature and salinity of approximately 2/3 seawater hinders utilizing the hot water directly. Therefore, the power plant uses heat exchangers to heat up fresh groundwater. The total flow from the production wells is varied over the two seasons. It is 200 kg/s during summer and 250-260 kg/s during winter. A summary of the project development of the Sudurnes Regional Heating System is as follows:

- **1971-72:** The first two wells drilled. They disclosed a reservoir temperature of about 235°C and highly saline water with total dissolved solids of about 20,000 to 30,000 ppm, not usable directly in a district heating system.
- **1972-73:** Orkustofnun published a feasibility report for a district heating system for the region. Production cost of heating with geothermal energy estimated at about 1/3 that of oil-fired heating.
- **1974:** A pilot plant built by Orkustofnun. Two wells drilled (HSH-4/1713 m; HSH-5/1519 m). Hitaveita Sudurnesja or Sudurnes Regional Heating Company established, owned 60% by regional municipalities and 40% by the Icelandic state.
- **1976-77:** A preliminary power plant of 3 MWth commissioned. Power plant I of 12.5 MWth commissioned.
- **1978:** First 1 MWe turbo generator commissioned. A second unit of power plant I of 12.5 MWth commissioned. Well HSH-6 drilled (1734 m).

- **1979-80:** Third and fourth units of power plant I of 2 x 12.5 MWth commissioned. A second 1 MWe and a third 6 MWe turbo generator units commissioned. Wells HSH-7 (1438), HSH-8 (1603 m), HSH-9 (994 m), HSH-10 (425 m) and HSH-11 (1141 m) drilled.
- **1981:** Power plant II of 75 MWth commissioned. Well HSH-12 (1488 m) drilled for injection tests.
- **1989-92:** Seven binary power units of a total 8.4 MWe commissioned.
- **1999-2000:** Power plant V opened, producing 75 MWth, replacing Power plant I, and 30 MWe from a steam turbine.

Today the Svartsengi Power Plant has five main power stations:

- **Plant I:** The oldest plant, commissioned in 1977, produces both electricity and hot water. Four units with a capacity of 12.5 MWth each (to heat cold water from 5 to 125°C). Two AEG back pressure turbines, capacity 1 MWe each.
- **Plant II:** Commissioned in 1981, produces only hot water. Three units with a capacity of 25MWth each (to heat cold water from 5 to 125°C).
- **Plant III:** Commissioned in 1980, produces only electricity. One Fuji back pressure turbine with a capacity of 6 MWe, the waste heat is transferred to Ormat units.
- **Plant IV:** Commissioned in 1889-1992, produces only electricity. Seven Ormat organic turbines, 1.2 MWe each.
- **Plant V:** The latest power station, commissioned in year 1999-2000 to replace plant I. Produces both hot water, 75 MWth, and electricity in one Fuji condensing turbine with a capacity of 30 MWe.

3.1 The Ormat binary plant in Svartsengi

All of the Ormat units in the Svartsengi power station are found in plant IV. The total number of turbines for electricity production in the power station is now eleven. The organic turbines are seven of these, identified as turbines number 4 to 10 in the power station. All of the Ormat units take the exhaust steam from plant III with the backpressure Fuji turbine as a heat source. The working fluid in these turbines is isopentane. The temperature of waste steam from the 6 MW turbine is 103°C. The steam goes to each unit in a separate pipe. Four of the Ormat units are air-cooled and the other three are water-cooled. The working fluid is heated to 95°C in the boiler by the steam. The boiler is of the shell and tube type, which allows for an indirect heat exchanging system. The vaporized isopentane gas leaves the boiler and passes to the separator. The separator pressure is 6.2 bars.

The main components of the plant and their characteristics are the following (Ormat, 1992a):

1. **Vaporizer:** Shell (for isopentane) and tube (for steam) type.
Separator is welded on the top of it to remove droplets of liquid, also fitted with a safety valve.
Normal operating parameter are
Heat source inlet temperature 103°C.
Heat source outlet temperature 95°C.
Flow rate 18720 kg/hr.
2. **Turbine:** Single-stage, impulse type organic turbine.
Turbine wheel and shaft assembly are on the low-pressure side.
The high pressure side is divided into three chambers for regulating the output.
The bearings and shaft seals are lubricated by an outside lubrication system.
The turbine drives the generator via a gear transmission.
Normal operating parameters are
Vapour inlet pressure 6.2 bar.
Vapour inlet temperature 95°C.
Speed 3600 rpm.
3. **Gear box:** Uses two double-helical gears.
Gear mesh and bearings are lubricated by an independent lubrication system which consists of oil

pump, relief valve, oil filter, and oil cooler.

Protected from high temperature and pressure failure by the lubrication system.

Specification:

Reduction ratio : 2.4088:1

Input: 3612 rpm.

Output: 1500 rpm.

Power rating: 2012 hp.

Cooling water flow: 72 l/me.

Cooling water temp.: max 25°C.

Oil temp : 40+(-) 10°C.

4. **Valves:** There are many valves that control both the steam and the motive fluid at different stages. The following valves are the main components of the plant:
 - main valve - open during normal operation and closed under stop and failure conditions;
 - governor valve - function as a turbine acceleration valve;
 - bypass valve - shut during normal operation, open during abnormal and shutdown condition;
 - injection valve: supplies vapour to the turbine three high-pressure chambers.
5. **Feed pump:** multistage, centrifugal and motor driven.
Strainer is installed at the top.
Sucks iso-pentane from the condenser and feeds it to the vaporizer inlet.
6. **Condenser:** Two types of condenser are in the plant,
 - a) Water cooler - horizontal tube and shell type heat exchanger;
 - b) Air cooler - condenses the working fluid of four units of the power plant.
7. **Generator:** Three-phase, brush-less revolving field synchronous (water-cooled units) and asynchronous (air-cooled units).
Driven by the turbine via gear box.
Brush-less rotating DC exciter.
Cooled by cooling fins and fan mounted on the generator.
Air-water cooling system is also applied for extra cooling.
Solid state voltage regulation.
Six thermostats in the windings.
8. **Power and control cabinets:** Consist of sheet metal boxes with doors containing Perspex windows.
Contain all the devices and circuits required for automatic control

The Ormat units are equipped with other auxiliary systems for overall plant output. The main auxiliary systems at Svartsengi plant are the following:

1. **Pneumatic system:** Provides compressed air at approximately 100 psi.
 - Regulated, filtered and distributed by pneumatic control panel;
 - Reducers are applied for equipment that needs less pressure;
 - Solenoid control valves control the air delivered to equipments.

Pneumatic consumers are described in Table 2.

2. **Lubrication system:** Supplies oil to the mechanical seal of the turbine for pressure sealing.
Supplies oil to the turbine and generator bearings for lubrication and cooling.
In both cases the system contains: tank, pump, cooler, filters and accumulators.
One solenoid shut-off valve used to control seal oil system.
One high-pressure relief valve to control lubrication system.
3. **Instrumentation and control system:** This system controls all the start-up, normal and shutdown procedures. The control system consists of the following elements:
 - Measuring instruments and input devices;
 - Programmable controller;
 - Auxiliary controllers and relays;
 - Indication lamp panel;

- Synoptic panel;
 - Pressure sensors;
 - Level sensors;
 - Temperature sensors (thermostats);
 - Input devices of different equipment.
4. **Heat source valve system:** Governs the operation of heat source control valve (HSV), consists of:
- Heat source valve;
 - Heat source controller;
 - Vaporizer pressure transmitter; and
 - Current transformer CT4 1200/5 and transmitter.

TABLE 2: Pneumatic consumers

Equipment description	Actuator type	Mode of operation
Heat source valve	Spring-return pneumatic Cylinder actuator with I/P positioner	NC (air to open)
Main valve cv1	Diaphragm actuator type	NC
Governor valve	Double-acting and positioner piston type	NC
Bypass valve cv4	Diaphragm actuator type	NO (air to close)
5-inch injection valve cv3	Spring-return pneumatic cylinder	NC
10-inch injection valves cv6 and cv8	Spring-return pneumatic cylinder	NC
Feed pump discharge valve	Diaphragm actuator	Proportional (3 to 15 psi)
Vaporizer liquid level controller		Proportional and integral control modes

3.2 Operation procedures in Svartsengi Ormat units

In Svartsengi, the operation system is fully automatic and remotely monitored. The power station is monitored by a SCADA system. The software is PCIM, which is made by Afcon company. The Ormat units are operated via integration with the other power plants of Svartsengi. Figure 7 shows a diagram of the Svartsengi power plant SCADA system Ethernet connection (by courtesy of Hitaveita Sudurnesja). There are two servers in the connection. The server in Svartsengi is for the connection of the SCADA system; and the server in Keflavik is only for office use.

The following operation procedure is taken directly from the operation manual of the Ormat converter units of the Svartsengi power plant prepared by the Ormat Company (Ormat, 1992b):

1) Preconditions for start up of the units: check

- Cooling water in the condenser;
- Control air at the desired pressure;
- No working fluid leakage;
- Electrical and pipe connection according to the design condition;
- Enough oil in the tanks: it should be 5 cm above the middle of the gauge;
- No oil leakage;
- Feed pump should be operated by hand;
- Feed pump manual valve is open;
- Enough working fluid in the system;
- Settings of oil pressure should be according to the design points.

2) Start up procedure

- Put selector switch in CO-GEN or stand-alone position;
- Close all auxiliary circuit breakers;

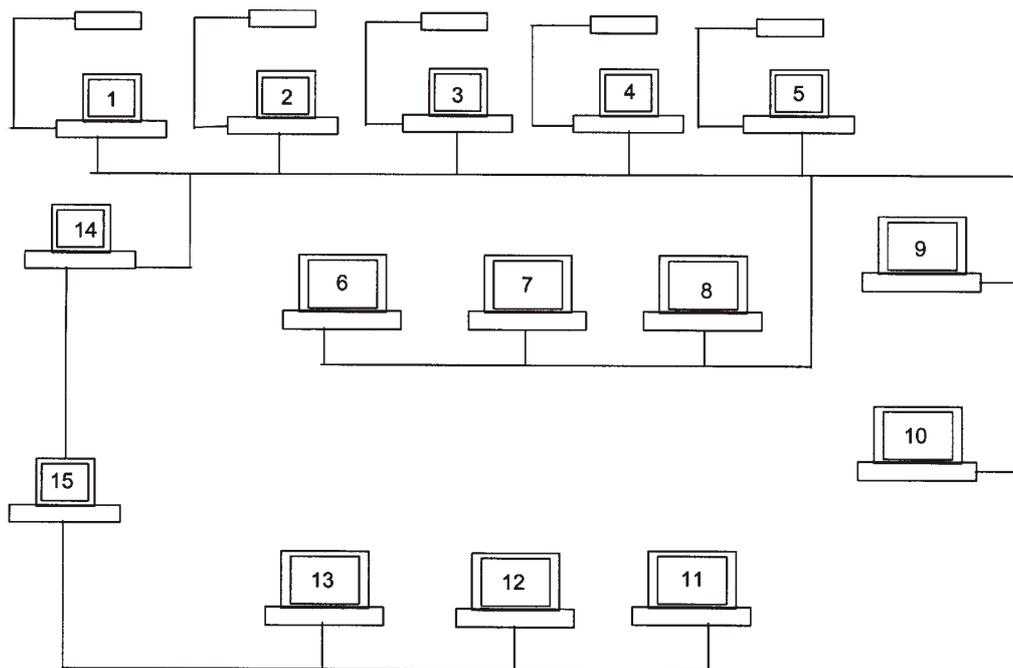


FIGURE 7: Hitaveita Sudurnesja SCADA System; description of stations

- 1) Controls Fitjar pumping station, cold water system Reykjanes power plant, PCIM;
- 2) Controls Steam supply system, cold water system, hot water distribution, PCIM;
- 3) Controls the Ormat units, PCIM;
- 4) Controls electric distribution power line protection, PCIM;
- 5) Controls new power plant 30 MW turbine, PCIM;
- 6) Operator work station Svartsengi, PCIM;
- 7) Operator work station Svartsengi, PCIM;
- 8) Operator work station Svartsengi, PCIM;
- 9) Site licensed master computer Svartsengi, PCIM;
- 10) Maintenance management system computer, Svartsengi, PCIM DMM;
- 11) Remote control Engineer, Keflavik, PCIM;
- 12) Remote control Engineer, Keflavik, PCIM;
- 13) Remote control Engineer, Keflavik, PCIM;
- 14) Server, solely for PCIM, Svartsengi;
- 15) Common server for office use, Svartsengi

- Check out the following systems are energized after pressing the START push button: (Over speed relay, Pressure controllers, Heat source controller and Turbine speed accelerator);
- Turbine lubricating oil pump started;
- Lubricating oil system solenoid-valve opened;
- Cooling water flow rate through the condenser tubes should be above 200 gal/min;
- Vaporizer level is correct;
- Heat source valve relay is energized;
- Heat source control should be connected to the heat source valve transducer;
- Heat source control output is 12 MA;
- Heat source valve is partially open;
- Vaporizer pressure increases;
- Vaporizer pressure, $P_1 = 3$ bar;
- Turbine main solenoid valve is energized and open;
- Turbine speed accelerator is connected to governor valve transducer;
- Turbine speed reaches $SR1 = 400$ rpm;
- Feed pump activated;
- Over speed protection ready;
- Turbine working hours meter starts

- Turbine speed continues to increase;
- When turbine speed reaches 2800 rpm, electrical oil pumps stop;
- Turbine speed reaches SR3=3200 rpm;
- Synchronizer ready for operation;
- Vaporizer pressure continues to increase; but P3 should be less than 6 bar before synchronization;
- Synchronizing condition reached;
- Main circuit-breaker closes;
- All injection valves open;
- Governor valve works with droop control system;
- Bypass valve works as vaporizer pressure controller.

If the above conditions are not fulfilled at each step, the start-up procedures stop. The cause for the failure should be identified and corrected. RESET push button should be depressed to continue the start-up sequence.

For **normal operation** the following optimum values are set in the OEC unit devices:

- Condenser fluid level at mid-level gauge;
- Vaporizer fluid level at mid-level gauge;
- Condenser pressure at 1 bar (failure = 3 bar);
- Vaporizer pressure at 6.5 bar (warning = 8 bar, failure = 10 bar);
- Turbine lubrication oil system pressure at 4 bar (failure, low limit = 1 bar & high limit = 7.8-8 bar);
- Turbine lubrication oil system tank level at 50 mm above level;
- Turbine/Generator bearing temperature at 40°C (failure, turbine = 120°C and generator = 100°C);
- Generator overheating at 50°C (winding failure = 120°C);
- Turbine speed at 3600 rpm (failure = 3780 rpm);
- Control air pressure at 6 bar (warning = 4 bar);
- Cooling water flow 500 m³/hr (failure = 200 m³/hr);
- Battery voltage at 25.5 V (warning = 24.0 V and failure, low limit = 23.5 V and high limit = 27.8 V);
- Reverse power failure at 100 kW;
- Main voltage at 660 V (failure, low limit = 580 V and high limit = 700 V);
- Main asymmetry, failure at 5%;
- Seal oil system pressure at 4 bar (failure, low limit = 2.2 bar and high limit = 8 bar).

3) Normal shutdown procedures:

- Press STOP pushbutton heat source valve closes;
- Control system waiting for power and vaporizer pressure to reduce;
- By pass valve opens, main breaker disconnects;
- Turbine speed decreases to 2600 rpm, electrical oil pumps start;
- Turbines speed decreases to 100 rpm, timer starts;
- Control, feed pump and pumps stop after 6 minutes;
- Seal oil pump maintains pressure at seal.

4) Automatic shutdown procedure for system failure:

- At least one of the unit failures present;
- OEC failure condition present
- Heat source valve, turbine main valve, all injection valves and governor valve close
- Main circuit breaker opens;
- By-pass valve opens;
- Turbine speed decreases;
- Turbine working hours meter stops;
- Feed pump stops;
- Lubricating oil system solenoid valve closes, oil pumps stop;
- Seal oil pump continues to operate intermittently as a function of the oil pressure in the turbine sealing oil return line.

3.3 Maintenance system for Svartsengi Ormat units

In the Svartsengi power plant the maintenance system is scheduled and planned by the maintenance manager. There is no specific group under the maintenance manager responsible only for maintenance. All the technicians, who operate the plant, work under the maintenance manager in daily shifts. There is no specified team for each plant. The same people maintain all five plants at Svartsengi. The shift operators are responsible for troubleshooting and emergency corrective maintenance. Condition monitoring and major corrective maintenance are done during the daily maintenance shift. Work that might involve considerable scheduling effort in terms of job methods and major spare part resources, like overhauling the plants and working over the wells, is done by contractors and the operators. Figure 8 shows the administrative structure in Svartsengi.

Corrosion and scaling are the most common problems of geothermal plants, and require special care. These problems can be corrected by condition monitoring and preventive maintenance as in the Svartsengi power plant. The big problems for the Ormat units are the failure of fans which are mounted on the air-cooled condensers. In Svartsengi, these problems were solved by design change maintenance. The driving mechanisms of all fans were changed from belt-driven to a gear mechanism. Other advanced maintenance equipment like laser aligning and vibration monitoring are frequently used in the plant.

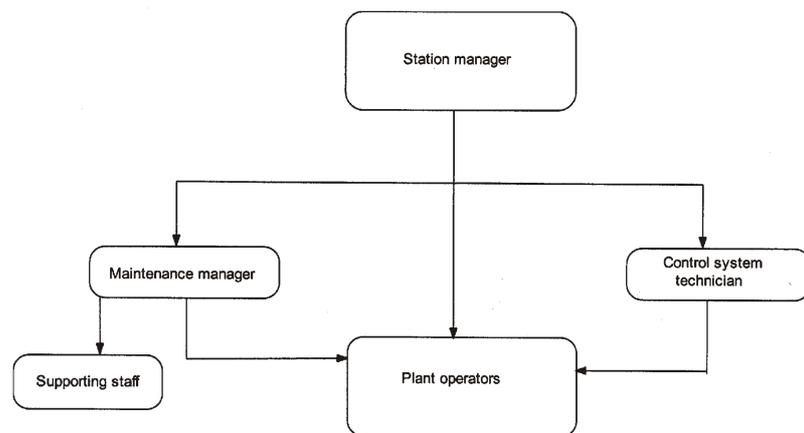


FIGURE 8: Administrative structure of the Svartsengi plant

Periodic maintenance procedures in the Ormat units, which are recommended by the manufacturing company (Ormat, 1992b) include the following:

Periodic maintenance procedures in the Ormat units, which are recommended by the manufacturing company (Ormat, 1992b) include the following:

- 1) **Daily inspection** (performed by the operators):
 - Check generator, turbines, gearbox, feed pump and oil pumps for vibrations, noise or oil leaks.
 - Check turbine and feed pump for motive fluid leaks.
 - Noise and leaks should be checked by a technician and repaired as necessary.
 - Check the unit out put power.
 - Fill out and print the data report sheet:
 - Compare the present report to the previous day's report;
 - Compare to the design point.
 - Adjust the voltage setting in order to reduce VAR to minimum.
 - Check for the presence of warnings, correct and/or clear as necessary.
- 2) **Weekly inspection** (during operation period):
 - Fill out the ORC test sheet and compare the results to the design point values.
 - Check and compare condenser pressure with the pressure obtained from the P/T diagram at the existing condensing temperature, if higher, release air from condenser.
 - Check oil level in the oil tanks, add oil if necessary.
 - Check oil level in the gearbox.
 - Verify proper operation of feed pump control valve.
 - Inspect vibrations of turbine, generator gearbox and feed pump.
 - Check valve shafts and feed pump mechanical seal for leaks.
 - After first 200 hrs replace gearbox oil.

- 3) **Monthly inspection** (during operation):
 - Check valve shafts and pump seals for leaks.
 - Check the oil ring in the generator bearing housing visually.
 - Check battery.
 - Check for hot spots in the power and control cabinets (connections, switches and contractors).

- 4) **First month inspection:**
 - Clean motive fluid strainer.
 - Replace line oil filter elements.
 - Check the oil ring in the generator bearing housing visually.
 - Grease all motors according to manufacturer's instructions.
 - Grease couplings.

- 5) **Six months inspection:**
 - Shut down the OEC.
 - Replace line filters in all systems (lubrication oil, seal oil, and gearbox).
 - Tighten all construction bolts.
 - Check flanges for leaks (use a leak detector).
 - Tighten flange bolts.
 - Verify tightness of all power terminals and cables at the generator output and at the power board.
 - Grease all electrical motors and couplings.
 - Change gearbox oil check oil .
 - Check oil quantity and purity.
 - Check and approve daily and weekly reports and log box.

- 6) **Yearly inspection:**
 - Check feed pumps shut-off pressure by operating the pump against closed valve and reading the delivery pressure.
 - Perform 6-month inspection.
 - Perform feed pump, generator and gearbox maintenance as required by manufacturer.
 - Check turbine/gearbox coupling as required by manufacturer.
 - Check turbine/gearbox alignment, correct if required.
 - Check gearbox/generator couplings, check alignment and correct if required.
 - Replace oil in the lubrication and oil tanks.
 - Check for leaks from the motive fluid system.
 - Check calibration of the gages and transducers in accordance with OEC specification sheet.
 - Fill out calibration reports.
 - Check mechanical adjustments in accordance with OEC design point.
 - Remove rust and touch up paintwork on the system as necessary.
 - Fasten piping connections, unions, flanges etc.
 - Tighten all electric connections at power and control panels, inside the junction boxes on skid, in the generator junction boxes, exciter, etc.
 - Check contractors condition.
 - Replace filters in the hydraulic block.
 - Perform turbine oil system adjustment.

- 7) **Two years maintenance procedure:**
 - Disassemble the turbine wheel and nozzles ring.
 - Check condition of turbine wheel and nozzles ring.
 - Check turbine mechanical seal, o-rings and bearings.
 - Change feed pumps mechanical seals.
 - Perform feed pump performance test.
 - Perform generator and gearbox preventive maintenance, according to manufacturer's instructions.

The power station uses the DMM software to manage the maintenance system (DMM, 2002). The maintenance manager uses the software in sending work orders to the operators and receiving reports from them. The software is designed to tailor-make interfaces with SCADA or other systems to suit all requirements. DMM has been especially designed to handle every aspect of asset registry and work management. It is technically sophisticated and can be shaped to suit the needs of virtually any operation. The interface is carefully designed for ease of use. Assets are located through a code structure or by direct use of interactive CAD drawings. It is easily configured to suit individual needs and preferences. Adjustment is as easy as drag and drop. It gathers and organizes valuable information that can be used in establishing best practices. Knowledge of processes and procedures is stored within the company regardless of staff changes. The history of every asset is known. Maintenance is triggered by equipment condition, run time or a fixed schedule. Maintenance work will result in lower cost, minimum down time and extended equipment lifetime. The end result is an improved return on investment within the company. It is the key asset to management performance measures, giving managers direct access to the data needed for evaluation in an organized and simple way.

DMM takes full advantage of the features of MS Project and MS Excel. Work orders can be selected and exported to MS Project. After adjustment, the updated data is sent to DMM. Data can be read directly from DMM, for example in Ms-Excel, for future processing. DMM has all the necessary features for asset modelling and exploring. Efficient filtering capabilities are used to view only relevant assets for each department or even for each employee. An efficient asset registry is the key to the functionality of an asset management system. DMM is designed around this fact. The asset registry is simple, yet effective. Assets are accessed by CAD viewer or by an MS Explorer-like tree view. The workbook keeps track of all work orders. Supervisors have a complete overview whilst the employee can focus on his tasks. Data can be exported easily to MS Project to organize work. Revised data is then imported back to DMM, fully updated. Each work order can contain job descriptions, maintenance procedures, safety precautions, and material requirements. Electronic documents containing further information can be attached to work orders. Extensive filtering capabilities allow work orders to be sorted and filtered in many ways. Asset costs, especially installation and maintenance costs, need to be monitored by the people that do the work, people who have first-hand knowledge of asset history and asset attributes. DMM provides this facility, enabling all resource planning to be undertaken within DMM, with complete equipment information and history availability. Comparison between actual cost and planned costs is just as important, giving managers the necessary feedback to improve models. One of the features of DMM is condition monitoring. Data is gathered through a number of channels to the asset history. This data can originate from inspections, work orders, SCADA systems or directly from the asset registry (DMM, 2002).

DMM technical data (DMM, 2002)

1) Application:

Native Windows 32 Bit.

Programmed in C++.

OLE DB database connection.

Terminal server ready.

Microsoft Office Export/import.

Dynamic

- | | |
|-------------|-----------------------------------|
| - Reports; | - List Columns; |
| - Menus; | - User defined data; |
| - Toolbars; | - Connection to external systems. |

2) Database server:

Oracle.

Microsoft SQL server.

Others by agreement.

4. CONCLUSIONS

- It is wise to install binary plants for electricity production in low-temperature fields, if there is demand for it.
- Utilizing the waste heat in high-temperature fields using binary plants can increase the total efficiency of the plant.
- Choosing the working fluid is the first consideration in constructing of binary plants.
- The simplicity of the working fluid cycle of organic binary plants aids the operator in running the plant safely.
- Operator training, technological, operational and maintenance manuals are the most significant factors affecting smooth operation of the plant.
- Utilizing modern computerized systems is important for plant maintenance. They are, however, not the ultimate remedy to one's maintenance troubles.
- DMM seems a good choice for the Svartsengi power plant maintenance system, as the software is designed primarily for power plants.
- Changing the drive mechanism of the air-cooled condensers to a gear-driven system is a good idea.

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