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EXPERIENCE IN OPERATION AND MAINTENANCE OF BINARY GEOTHERMAL POWER PLANTS

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ABSTRACT

In this paper, Modular Geothermal Power Plants are described, together with the advantages they present in simplifying the Operation and Maintenance procedures. This has a direct impact upon the training of the Operation and Maintenance personnel which is also simplified. As part of each project, the customer personnel can receive factory training in Operation and Maintenance of the power plant, followed by on-site training after the commissioning stage. Examples of Operation and Maintenance training in some projects in the U.S., Thailand, New Zealand, and Iceland are discussed. In addition, a Remote Reporting and Diagnostics System is described. This system can connect the power plant operating console directly to the end user's control center or to the manufacturer's service center, allowing continuous follow up and diagnostics by the relevant engineers.

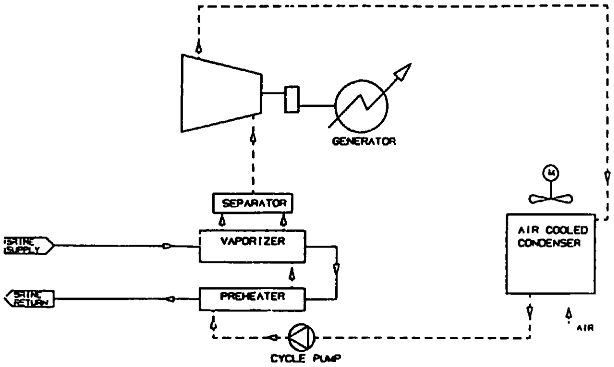

Figure 1 - Single Level Binary Power Plant

BINARY GEOTHERMAL MODULAR UNITS

Several types of modular units of various power generating capacities have been developed to optimize and match the power plant to existing geothermal resources.

A single level binary unit based on the Organic Rankine cycle is shown in Figure 1. In this unit the geothermal fluid heats an organic fluid which drives a turbine, in a closed cycle, without the geothermal fluid entering in direct contact with it. This environmentally clean unit presents numerous advantages such as fully automatic, grid compatible electrical power generation from low temperature and liquid dominated hydrothermal resources. The capacity of such modules ranges between 1 and 3.5 MW.

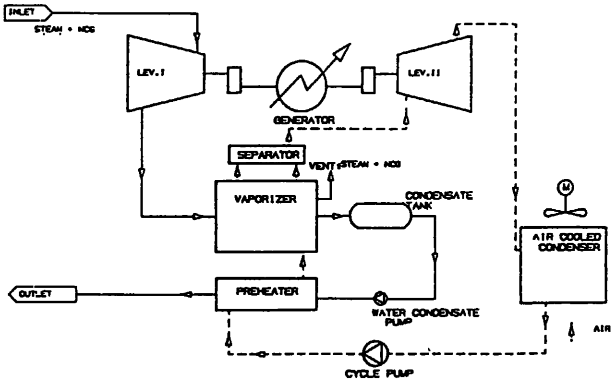

Figure 2 - Dual Steam/Binary Power Plant

A further development of these units is the Two Level Module shown in Figure 2, where two separate turbines are coupled to a common generator of up to 3.5 MW nominal power output. The first level turbine can either be driven by steam or by an organic fluid, while the second level turbine operates in the organic Rankine cycle, as above.

All the above modules can be either water cooled or air cooled, and can be installed either as single and stand alone modules or in clusters of up to several tens of units.

ORMAT MODULAR BINARY GEOTHERMAL POWER PLANTS

Modular Binary Power Plants consisting of various Ormat Energy Converter (OEC) modules are in operation in several geothermal fields worldwide, ranging from 1 MW or less, to several tens of MW, such as the East Mesa geothermal complex, totalling 72 MW. The complex was started with the construction of a 30 MW power plant, the Ormesa I, completed in December 1987, after a mere six months installation period. Following the commissioning of the Ormesa I plant, the Ormesa II, Ormesa IH and Ormesa IE plants were added at one year intervals. The Ormesa IH and IE are remotely operated through the Remote Monitoring and Control system. These plants run unattended, while their operation is monitored and controlled by a remote computer at the control center.

In New Zealand, the Tarawera Ormat Installation of Bay of Plenty at Kawerau, is a 2.6 MW geothermal power plant comprising two air cooled OEC modules. The modules utilize separated geothermal water which previously ran into the Tarawera River, thereby contributing to the conservation of the environment.

In Iceland the first step (3.9 MW) of Svartsengi Geothermal Power Plant is an example of two level dual (steam and organic) geothermal plants. It comprises three Ormat Energy Converters as bottoming cycle for a 6 MW back pressure steam turbine. This power plant is owned and operated by Sudurnes Regional Heating Corp., sole distributor of electricity and heat energy in the Reykjanes Peninsula.

An example of a single 800 kW module installed in a remote location is the geothermal installation at Travale in Italy.

TRAINING PROGRAM DESCRIPTION

Ormat's projects vary from the delivery of a single power plant to the construction of entire turnkey projects, including the Operation and Maintenance of such projects. The training courses, which form part of Ormat's supply contracts, are matched to the customer requirements and to the equipment supplied.

The training may be performed either at one of Ormat's training centers, at the site, or both. It ranges from the training of individuals, to that of entire O&M teams.

Complete Operation and Maintenance services for the interim period between the start up and the taking over of the O&M responsibility by the end user can also be provided. These services allow effective and smooth transfer of responsibility to the end user's O&M team.

The main purpose of the training course is to provide the O&M team with the knowledge it will require to effectively and smoothly operate and perform the maintenance of the power plant. It also provides the basic knowledge to perform trouble-shooting operations on the power plant.

Customers participating in training courses include O&M teams from the Fang Power Plant (Thailand), Bay of Plenty, Electrical Co. (New Zealand), and the Naqgu Power Co. (Tibet).

In the USA, on Ormat's various projects, Ormat engineers, as part of an O&M contract, trained the local staff on the job, until the O&M responsibility was transferred to them.

The typical 12 days training course includes the following:

General Introduction and Project Description

Theoretical and Basics Review:

- Thermodynamics: Work, thermodynamic cycle, cycle efficiency
- Fluid Dynamics: Turbine, nozzles, blades, turbine efficiency
- Heat Transfer: Heat balance, heat exchangers, cooling system
- Control: Feedback loop, Process & Instrumentation Diagrams, pneumatic control systems, electrical control systems, PLC - Programmable Logic Controller
- Power Generation: Generator, grid synchronization, power circuits
- Oil system: Bearings and lubrication
- Instrumentation

Description and operation of the Power Plant Subsystems:

The next step is the familiarization of the participants with all the subsystems and of the power plant. This is achieved through description, visual acquaintance, location identification and understanding of each sub system's function. Each subsystem is then divided into its component parts, each one of which is thoroughly studied.

The course includes thorough training on all the electrical and control circuits. Special attention is paid to the entirely automatic computerized control system. The control of the power plant is centralized by a Programmable Logic Controller (PLC). The training course familiarizes the participants with the logic of the PLC and thus helps them to better understand the computerized operation of the power plant.

Sequence of Operation:

All sequences of operation are studied, from start-up sequence to the sequence of synchronization to the grid, including the normal operation sequence, shutdown and heat removal mode of operation. In addition all the warning conditions and failure conditions are explained in detail.

Maintenance Training:

The philosophy of maintenance is explained. This philosophy is based on the large operating field experience accumulated and the very high level of power plant reliability and availability achieved with Ormat's power plants. This philosophy calls for simple preventive periodical inspections and procedures performed by a reduced team. Simple daily, weekly, monthly and semi annual inspections and procedures are explained, as well as special procedures including shaft assembly, alignment and other procedures.

Troubleshooting Training:

All the warning and failure conditions are discussed. The symptoms are described and the repair steps are given for every sequence of operation.

Spare Parts:

The spare parts philosophy, requiring a relatively small stock of spare parts at the plant is explained. This philosophy, based on past experience and proven equipment reliability includes also the concept of assembly replacement instead of component replacement. Once the fault has been identified in an assembly, this entire assembly is immediately exchanged in order to avoid wasting time in further investigation while the power plant is not operating.

POWER PLANT COMPUTERIZED PROCESS CONTROL

The Ormat modular power plant and each OEC module start-up and operation are automatic and controlled by computer as shown in Figure 3. The main objectives of the plant control system are:

- To enable smooth plant operation at all acceptable input parameters and power output levels, allowing the operator to remotely change working parameters.
- To optimize operation and maintenance of the power plant.
- To minimize the number and qualifications of personnel required for operation and maintenance of the plant.
- To provide warnings and failure indications and automatically shut down the power plant or the problematic module in case operating parameters are out of limits.
- To provide automatic notifications of a problem to the operator and, by telephone, to a remote control center.
- To automatically restart the power plant when a condition of shut down is cleared.

The computerized process control system includes graphic screens allowing the display of all data in *real time* mode, to obtain on line indications of warnings and failures and to change parameters in the power plant subsystems in order to obtain the desired behavior of the subsystem. At the same time a quick analysis is provided indicating any maintenance action required.

The screen displays include the following:

- On line display of the power plant and each OEC module.
- On line status display of all the discrete inputs and outputs of the system.
- Last failure status display.
- Provision for the operator to automatically change the values of defined registers.
- Display of the values used by the program for setting operating points, term of failures/warnings, etc.
- Displays of minimum/maximum points of reference and time delays for failure/warning readings.
- Displays of last hour, last 10 hours, last day's readings.

All of the above can also be provided in hard copy by the system printer, or transmitted by modem/telephone to remote locations.

The control system simplifies the power plant operation and maintenance and also provides the feasibility for remote reporting. An operator with a limited technical background can learn to master the system within a week or two.

REMOTE MONITORING DIAGNOSTICS SYSTEM (Figure 3):

In order to further assist the Operation and Maintenance teams of the Ormat Geothermal Modular Power Plants, a Remote Monitoring and Diagnostics System can be supplied, to connect the power plant operation console to a Central Operating room or directly to Ormat' Service Center. This system consists of Personal Computers at each end, linked via modems and to printers, including adequate diagnostic software in the power plant controller. This system allows Ormat to receive weekly status reports from the power plant; the reports can then be analyzed and their conclusions sent to the end user. In case of any malfunction suspicion, immediate and direct manufacturer's engineering support to solve the problem is promptly available.

The Remote Monitoring and Diagnostics System is designed to collect data from any Ormat power plant, transfer it to the remote control center and analyze it. It can supply the following information:

- The momentarily on line information.
- Data accumulated and stored every four hours, six times a day.

The momentary data consist of all the on line available information, including temperatures, pressures, operating status, etc. according to the relevant screen.

The system is generally located and operated from a subdirectory of its own with the following minimum options available to the remote user:
- On line information.
- Accumulated information.
- End Program and exit to DOS.

The starting and ending dates to be tabulated are inserted after choosing the desired set of data. The previous 30 days' data is also available for retrieval. In addition, the accumulated information can be stored on a monthly basis onto a floppy disc at the power plant itself. This floppy disc is for backup purposes only.

The Remote Monitoring and Diagnostics System has been used on a few of Ormat's projects and undergone continual improvements, based on feedback from these projects.

An example of the application of the system is the TOI Power Plant in New Zealand, which is unmanned, remotely monitored, and its performance scanned on a weekly basis by the Ormat.

The weekly performance of the TOI Power Plant is automatically retransmitted, via telephone line, to the Ormat, where it is analyzed. As a result of this analysis, a weekly technical recommendation is issued to power plant operators so that a preventive adjustment or a maintenance operation of individual components can be made.

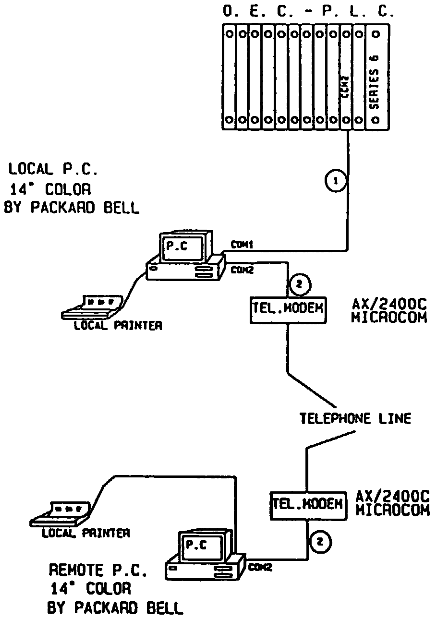

Figure 3 - Remote Monitoring and Diagnostics System

During March 1990, a detailed view of the daily performance of OEC 1 for two sequential time periods of 4 days each, enabled the plant to be fine-tuned for greater performance. A high pressure was identified in the condenser. Measurements and heat balance calculations indicated that there was possibly an accumulation of dirt on the surface of the air condenser.

The OEC output was measured at a level of under 1,100 kW. A recommendation to clean the condenser surface was issued to the operating team.

Steam cleaning of the condenser surface was carried out at the beginning of April, with the immediate result that a new OEC output of 1,250 kW was achieved, an improvement of over 13%, equivalent to 150 kW.

OPTIMIZATION ON POWER PLANT AVAILABILITY & CAPACITY

The modular concept calls for self contained power modules, each factory tested, requiring minimum installation effort and time. Each module includes components necessary for its automatic operation. Major subassemblies are mounted on skids and standardized. Each skid is entirely factory integrated and tested. The standardized modules power plant concept allows for the optimization of the power plant availability. It greatly simplifies the Operation and Maintenance operation as well as the end user's staff training.

Each module is designed for operation at overload conditions. This design allows for periodic the shut-off of one or two modules for either scheduled or un-scheduled maintenance purposes, while the remaining modules, receiving the excess geothermal flow, deliver additional power, offsetting the equipment shortfall and thus maximizing the power plant capacity. In this configuration the modules are interrelated and high capacity levels may be obtained.

The following example demonstrates how high capacity levels may be obtained with the modular concept. Given a power plant consisting of "n" modules with equal probability of failure, statistical theory may be used to determine the probability of "x" modules operating in any given time period. In other words this probability represents the percent of any given time that "x" modules will be operating (on-line) for a power plant consisting of "n" modules. The binomial probability distribution results in the following probability law:

$$P(x)=P\left(\frac{x}{n}\right)=\binom{n}{x}p^{x}(1-p)^{(n-x)},$$

$$x=1,2,3,\ldots n$$

$$\text{where} \quad \binom{n}{x}=\frac{n!}{x!(n-x)!}$$

In this particular case, "p" represents the module availability, based on field experience which is known to be between 90% and 95%. Assuming a power plant consisting of 10 modules, the above equation may be solved for various availability assumed rates and is summarized in Table 1. For example, if the equipment availability is 90%, 10 modules are expected to operate for 34.87% of the time, 9 modules operate for 38.74% of the time and 8 modules operate for 19.37 % of the time based on the above probability law.

In conventional power plants, each unit operates independently from the other. Therefore, when one of the units is shut down, the other units cannot accept the additional available geothermal fluid flow. As a result, the plant capacity drops and is proportional to the number of operating units. For such plants, the power output capacity is equal to the units availability.

By contrast, in the modular power plant concept presented herein, where each module is designed to operate at overload conditions and where the modules are interrelated the entire power plant capacity is drastically improved as can be seen in Table 2.

For example, the stoppage of one unit out of ten will reduce the entire plant capacity by only 1% (capacity factor of 99%). Multiplying the on-line time percentages of Table 1, for each assumed module availability, leads to the total power plant capacity.

To conclude, assuming 90% equipment availability, the modular concept results in a power capacity of 97.39% vs. only 90% in a conventional power plant.

As a result a new active approach to Operation and Maintenance of the power plant in general, and of the training of end user's staff is possible. Preventive maintenance, including scheduled stoppages of each unit at a time, is performed throughout the year by a small O&M team without significantly affecting the power plant capacity output. For example in the Ormesa Geothermal Complex, two operators per shift, in three shifts, and a total of twelve Maintenance staff operate 46 MW power plants. Furthermore, the required workshop facility is small.

TABLE 1 - Percent of Time that "x" Modules have to be On-Line to achieve given availability

Number of Modules on line - x (n = 10)	Assumed Module Availability(1) 90%	95%
10	34.87%	59.87%
9	38.74%	31.51%
8	19.37%	7.46%
7	5.74%	1.05%
6	1.16%	0.01%

(1) Module availability range between 90 - 95%, based on field experience

TABLE 2 - Calculation of Total Power Plant Capacity

Units On-Line	Plant Capacity Factor(2)	% Time on-line (3) For 90%	For 95% Availability	Availability
10	100%	34.87%	59.87%	
9	99%	38.35%	31.13%	
8	96%	18.60%	7.16%	
7	84%	4.82%	0.88%	
6	65%	0.75%	0.01%	
Total Power Plant Capacity			97.39%	99.05%

(2) Calculated plant capacity given "x" modules on-line, for an existing power plant with 10 modules.

(3) Percent of time on line from Table 1.

In order to emphasize the benefits of the modular concept in substantially enhancing the actual power plant availability, Figure 4 shows the monitored availability of operating power plants in Southern California and Nevada, since 1985.

Modularity allows to maintain a reasonably low level of spare parts, even for major components such as turbines and generators. The operation and maintenance of the plant is simplified, improved and its cost is reduced thanks to small, compact and easily interchangeable key components. Quick replacement of these components, (e.g. a generator or turbine can be replaced within several hours), yields a very high availability of the modules even in the event of a major component failure. As a result of the use of standard components, the training of the end user's staff is also greatly simplified.

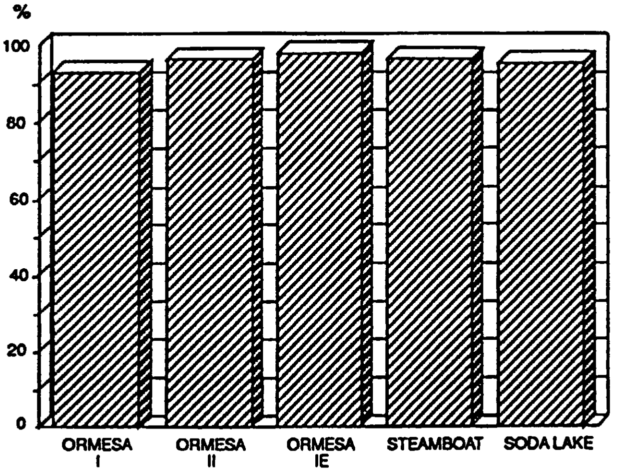

Figure 4 - Typical Monitored Availability of ORMAT Geothermal Power Plants in Operation since 1985

OPTIMIZATION OF PLANT OPERATION

Another example of plant optimization is that of the plant operation, through the optimization of major components' useful life.

The profitability of a geothermal power plant is directly related to the sale of electricity and the cost of providing geothermal fluid to the plant. Therefore the power plant should be maintained and operated accordingly. An example of the various types of optimization is that of the geothermal fluid pump. Since the sale of power and the cost of providing geothermal fluid are interrelated, it is necessary to optimize the geothermal pump's maintenance overhaul schedule.

The modular units in the Southern California Ormesa Complex have gained years of operating experience: 68 modules generating a total of 72 MW, out of which 26 are operating for the last five years and 20 additional ones are operating for 4 years. Since the beginning,more than five years ago, geothermal pump operating and monitoring procedures were developed in order to minimize the pump's down-time, the pump's mechanical wear and prevent a sudden breakdown. With the geothermal pump at maximum operating capability, experience and knowledge of the pump's handling during installation and during regular operation was acquired. The result is a significant improvement in the geothermal pump life cycle, and some pumps have been operating for more than 30 months. Was it a correct design to operate the pump continuously for 30 months? Should the pump have pulled earlier? What is the correct strategy for the geothermal pump replacement? The answer to these questions were obtained by a mathematical optimization model simulating the actual site conditions. The previous operation strategy of "letting the pump die" before replacement was consequently reviewed.

There are a number of pump-performance parameters associated with the maintenance costs that relate among other parameters to the power plant electrical output:

The pump performance parameters are:
- Electrical consumption of the geothermal pump;
- Damage to the geothermal pump beyong repairability;
- Reduction in the capacity of the geothermal pump;

The maintenance cost parameters are:
- Cost of equipment;
- Labor required to pull/push the pump;
- Loss of electricity during the geothermal pump down-time;

Given these parameters quantified on the basis of experience gained in the Operation and Maintenance of thirteen power plants (air cooled and water cooled) and of more than 100 wells, a method of determining the impact of each parameter on the plant total profitability was developed. This method can be used to determine the optimum time for geothermal pump replacement in order to achieve maximum plant profitability. The data which is required to implement this optimization method were examined, together with calculating and quantifying the alternative cost of damages that occur by not implementing this model (Ref. 5).

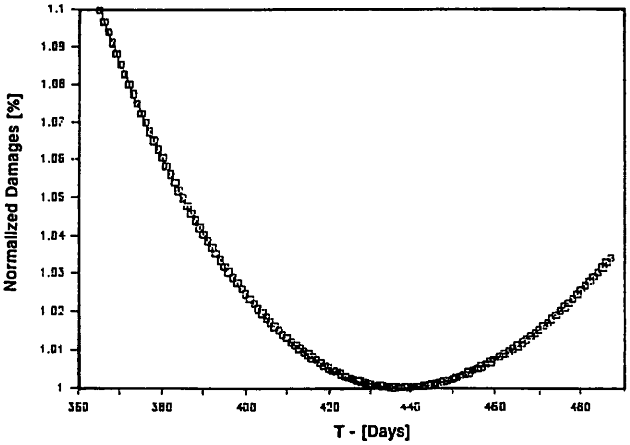

Figure 5 - Normalized Damage Caused by Deviation from Optimum Pump Replacement Time (Ref. 5)

This study led to an optimum number of days of operation and replacement strategy required to minimize the operation expenses and potential revenue losses due to pump malfunction and stoppages as shown in Fig. 5. Based on the cost assumptions (given in Ref. 5), related to the

Ormesa I power plant, the model shows that the optimum time to change the pump is 438 days after start-up.

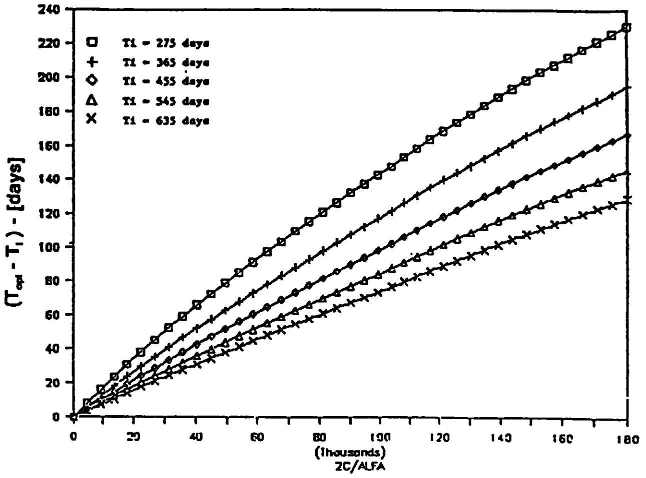

Figure 6 - The Optimum Required Additional Time for Pump Replacement (T_{opt} - T_i) as Function of (2C/ALFA), for Different Values of T_i (Ref. 5)

In the combined Southern California Ormesa 72 MW Geothermal Power Plant complex, a yearly saving in the range of one million U.S. Dollars of net income is achieved with the strategy implemented with this model. Furthermore, the pump being 1,400 ft underground, it is difficult to precisely measure pump parameters required to determine operational optimum time for the pump replacement. The graph in Fig. 6 derived in the model (Ref. 5), presents a useful managerial tool to determine precisely enough the optimum replacement time as a function of the initial time elapsed between pump replacement assumed, (T_i) on one hand, and the ratio of the fixed cost over the daily variable costs (2A/ALFA) on the other hand, as described in Reference 5.

CONCLUSIONS

The numerous advantages of Modular Binary Geothermal Power Plants pioneered by Ormat have a direct and positive impact on simplifying the Operation and Maintenance procedures. Modularization and standardization of the power units, in addition to allowing a more efficient and smoother power plant operation, higher degree of availability and capacity, also allows for simple and user friendly training of the O&M staff, who then becomes more efficient. The thorough training courses and further continual close contact between the manufacturer and the customer's O&M team after commissioning provides further confidence to the team, and thus smoother power plant operation.

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