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Performance Evaluation of the Magma 11.2MWe Binary Cycle Power Plant

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Performance Evaluation of
The Magma 11.2 MWe Binary Cycle Power Plant
(Paper given at EPRI's Third Annual Geothermal Conference)

EPRI Research Project 1195-3

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INTRODUCTION

The Magma 11.2MWe geothermal power plant has been constructed and is currently in the final stages of shakedown. It should be starting up at the end of August, 1979. This project has many exciting features which will be reviewed in this presentation. Generally, the adjective "exciting" is not used in a technical report but, in this case, there is no way to disguise the enthusiasm of the organizations which conceived, designed, constructed and will operate the plant. It is an example of private venture capital invested in new technology to stimulate production of a significant new energy resource.

This plant's characteristic features were described in an earlier report by Rozenman. The dual binary process, the heat rejection system, the heat exchangers and turbines are all of new design or being used for the first time in this service. The plant has been well instrumented so a reasonably complete picture of the plant's performance can be determined even if certain key items operate at off-design conditions. Therefore, the true potential of the plant can be determined early in the operational phase.

PFR's involvement in the project is sponsored by the Electric Power Research Institute (EPRI). This came about as a result of Magma's desire to make the plant's performance data generally available and mutual agreement that EPRI would conduct an independent analysis of plant performance for the purpose of reporting and disseminating this information to the utility industry in general. Both Magma and EPRI feel that such information will be valuable to the industry for geothermal development, as opportunities and need for the binary cycle evolve over the next few years.

The data provided by the instrumentation will be reduced by a data acquisition system (DAS) provided by EPRI. The data will be processed by a data processing system (DPS) consisting of a computer with a real time operating capability, computer programs, and technicians who will operate the DPS and data handling. The same computer will also be used for EPRI's PSEMT project RP1094. A different computer program will be used for this project, but with similar characteristics. The programs are interactive with the operator in that

they allow the operator to interact with the computer system on a real time basis. If a data item appears inconsistent, the operator is notified and is able to investigate. The DPS allows the operator to input data in the "foreground" while other data is being simultaneously processed in the "background". Initially, the data will be input by hand; however, automatic data acquisition may be added later if deemed desirable.

The large amount of data produced at the plant will be organized, tabulated and summarized in a manner so that both the plant operators and the EPRI project team can evaluate the performance of the plant and its subsystems. The main objectives of the project are to determine the following:

1. Operating conditions at design and off-design operating conditions
2. Plant and subsystem performance, net power produced and efficiency
3. Operating characteristics, including the controllability and the effect of scaling
4. Maintenance of equipment in regard to scaling and corrosion

These objectives will help to establish the potential of this type of process. This project will allow this potential to be determined and reported more quickly by EPRI to the utilities.

REVIEW OF MAIN SYSTEMS

This section reviews the main systems of the plant. These include the main process loops, the instrumentation, main equipment and other subsystems.

Process Systems. The conversion of the geothermal heat to electrical power will be performed using a dual binary Rankine system. Figure 1 provides an overall schematic flow diagram of the main process plant. The plant has four main process loops and a few ancillary subsystems. The figure does not attempt to describe the geothermal production well, injection well systems, heat rejection systems and turbine oil cooling systems which are beyond the scope of the EPRI project. From

Figure 1. System Schematic Diagram

close examination of the figure, it is apparent that the system is not difficult to comprehend on an overall basis. The main characteristics of each system follow in the next sections.

Brine System. The brine contains less salt than seawater and is expected to have a low scaling potential. The brine enters the iso-butane ($I-C_4$) superheater at about 360°F and is progressively cooled in 11 shell and tube exchangers to 180°F before entering the injection pumps. After the two superheaters, the brine travels through the two $I-C_4$ boilers, a propane (C_3) superheater and six $I-C_4$ heaters. There is a strong possibility of scaling in the last few $I-C_4$ heaters as the solubility of some minerals decreases as the temperature decreases. The system has been designed so that the six $I-C_4$ heaters can be maintained one pair (two) at a time.

Iso-Butane System ($I-C_4$). The $I-C_4$ is pumped from its receiver as a liquid at 86.5°F by two condensate pumps in series. At design, a turbine-powered feed pump increases the pressure to 605 psia at 93°F to the first of six $I-C_4$ heaters. The heaters increase the $I-C_4$ temperature to 275°F . Next, the flow is divided into two parallel streams which enter a boiler and superheater. The $I-C_4$ attains 345°F at 500 psia at the turbine entry. The thermodynamic process was designed to be subcritical because of temperature and pressure limitations of the turbine around which the plant was designed. New plants would probably use a supercritical process.

The $I-C_4$ is expanded across the two main power turbines and remains in the vapor state. About 10MWe of power is expected from the two turbines. A portion of the vapor is bled from each turbine and expands across the $I-C_4$ feed pump turbine. The three vapor streams converge and enter the recuperator shell side through two connections.

The $I-C_4$ is cooled further in the recuperator to 150°F by a liquid propane stream which is heated and partially boiled. The $I-C_4$ is then totally condensed in two condensers cooled by cooling water. The condensate stream then enters the $I-C_4$ receiver at 59 psia, where it is available to restart the process again.

Propane System (C_3). The propane circuit is designed to produce another 2.2MWe of power at full design conditions. After the $I-C_4$ system is operating close to steady-state conditions, the C_3 circuit is started up. It obtains heat from $I-C_4$ (in the regenerator) and from brine in the propane superheater exchanger.

The C_3 is pumped from its receiver at 72.5°F and is first heated and vaporized in the re-

generator to 177°F and then to 205°F in the superheater by brine. It is expanded across its turbine from 460 psia to 129 psia and then fully condensed by the coldest water available.

Cooling Water Circuit. The heat rejection system dominates the total acreage used by the plant. It consists of three interconnected ponds. The coldest water enters the plant from the deep storage pond at 62°F at the design wet bulb temperature. The water is heated in the single propane condenser to 65.5°F , divides into two streams entering each $I-C_4$ condenser and finally is heated to 79.5°F . One water stream goes to the west day-pond and the other goes to the east day-pond. Each pond is equipped with sprays which cool the water by evaporation at night close to the wet bulb temperature. The system has been designed to take advantage of night cooling caused by radiation to the "black" sky. As water is cooled, it drops to the bottom of the ponds by gravity, where it flows by gravity to the deep storage pond.

In a larger plant it is likely a conventional cooling tower would be more economic. It is important to note that even if the cooling pond system does not operate as planned, or better than expected, the results obtainable could still be used to determine the performance using a conventional cooling system.

Auxiliary Systems. There are other smaller systems which are not part of the PFR analysis, but which will have an effect on the plant's efficiency. Since there are four main circuits the pumps must perform with high reliability. The brine circuit contains a downhole pump for each of the five geothermal wells available. Only three wells will be in operation at any one time. In addition, the brine injection well pumps must function reliably.

The $I-C_4$ circuit contains a condensate pump and a booster pump which must force the fluid through the boiler feed pump powered by an $I-C_4$ turbine. An operator must visually check during start-up whether the turbine is rotating in the correct direction, so when the $I-C_4$ starts flowing through the turbine, it will not damage the blades.

The propane circuit contains a condensate and boiler feed pump. If these pumps do not perform correctly, it is not as serious since the propane circuit is an auxiliary power loop.

Equipment Description. In this section each of the main apparatus is described. The heat exchangers, turbines and $I-C_4$ feed pump are particularly critical to proper functioning of the process.

Heat Exchangers. All eleven brine heat exchangers use a new design developed by J. Hilbert Anderson, Inc. and reported by

Dambly (1). The heat exchangers are one of the most important cost elements in the plant and must operate reliably. The shell and tube design chosen uses a one-tube pass true countercurrent design. A countercurrent design has the advantage that the minimum surface area can be obtained. In the case of the I-C₄ heaters a temperature overlap of 25°F exists between the brine and I-C₄ exit temperatures. Since six heat exchangers in series were used, a true countercurrent design could also have been obtained with a multipass design.

The "one pass" tube design has the following other characteristics:

1. The high pressure fluid (the hydrocarbon) is on the tube side, thereby making a theoretically less expensive exchanger.
2. The brine is on the shell side.
3. The shell side does not contain baffles which promote crossflow, but uses a specially patented flow-through type of tube support which promotes longitudinal flow.
4. The tubes are rolled into the tube sheet.
5. To allow the tubes to expand, the rear header uses a piston-packing device to separate shell and tube side fluids. The packing is continuously lubricated with an oil.
6. The exchanger tubes are about 80 feet long and have comparatively small diameter shells. Therefore, the cost of manufacture may be lower than conventional shell and tube-type exchangers.
7. Optimum surface area to pressure drop ratio.

It is important to note that, even if problems arise with these new exchangers, the data which will be obtained can be extrapolated using conventional multipass U-tube or pull-through floating head designs. The process is what is important and the individual performance or maintenance of each exchanger is secondary.

The condensers are of more conventional design, with the cooling water in the tubes and the hydrocarbons in the shell. The regenerator sits prominently above the entire plant. The characteristics of this exchanger are currently being obtained.

Turbines and Feed Pumps. The main turbine is a York 3338 tandem design with dual three-stage units. The turbine drives an Allis-Chalmers 10MW, 1200 RPM synchronous generator through a General Electric reduction gear. The turbine speed is 6391 RPM. The turbine is a redesigned York compressor.

Vapor is extracted from the main turbines through a flow orifice and through to the boiler feed pump turbine (BFPT). The BFPT is a York 226 two-stage turbine driving a

United Centrifugal Pump three-stage horizontal centrifugal pump through a Western reduction gear.

Piping and Insulation. The piping for the most part has been insulated from the concept of manpower protection and not heat loss. There are significant portions of large diameter piping from the knockout drum to the turbines and, hence, to the regenerator which is uninsulated. Therefore, the performance of the unit may be improved over what is actually measured.

Instrumentation. Extensive instrumentation has been provided for all the main circuits. Certain key parameters which are not measured may be deduced by calculation. The main measurements such as flow rates have no redundancy, so if the main instrument malfunctions, not much useful data will be available. Measurements of power produced at the bus-bar contain redundancies, as might be expected.

The time it takes to read all the data may be as much as 15 minutes. Most of the data is in the control room, while other key values will be read locally at the instrument stations. The method used for data reduction requires that the plant must be in a steady state. Strip chart recorders are available for many key parameters, which will help in the determining steady state.

DATA ACQUISITION SYSTEM

The data acquisition system (DAS) consists of the following elements:

1. The "technician-operators" who manually read the data and fill out the data-logging sheets.
2. The data-logging sheets which contain all the data required by the data processing system (DPS).
3. A technician who reviews the data sheets and inputs the data to the DPS.
4. The DPS is shown in Figure 2 and consists of the computer, computer programs, and procedures.

The data will be stored in three formats: the original data sheets, the computer output sheets and the computer storage medium (a removable disc cartridge). Therefore, in case any one of these is destroyed, the data will still be recoverable by two methods.

Technician-Operators. The technician-operators read the data and fill out data-logging input forms. Most of the data is in the control room. Certain required items must be read locally at individual instrument stations. It is expected that data will be required about every three hours after design steady-state operation has been attained. More

Figure 2. DATA PROCESSING SYSTEM

frequent data will be required during start-up when important partial-load data will be available.

Data-Logging Sheets. The data-logging sheets will contain all important flow rates, temperatures and pressures, bus-bar power delivered by the turbine-generators and other parameters. Each set of sheets will comprise one data point. The data is organized so the operator can quickly record the data in the same order it is displayed. The data which is required from local instruments will be recorded on a second sheet. Each will be dated, show the operator name, and have incidental information concerning the conditions of the unit.

Computer Operator. The computer operator for the first three months will be provided by PFR. This person is trained in the operations of the DPS, understands the underlying heat transfer and power aspects of the plant, understands the computer programs, and is able to make corrections in the field, if necessary, and will train the Magma personnel in use of the DPS.

Data Processing System (DPS). The DPS hardware consists of the PDP 11/34, an input/output device and a disc file storage system housed in the air-conditioned atmosphere of the control room. The computer is controlled by a real time operating system (RT-11) which allows more than one program to be processed simultaneously. Two computer programs have been developed for Magma. One program allows the inputting of data, checks its validity, and stores it into the computer disc file as

a permanent data point. The second program reads the data, reduces the information to the required parameters and then outputs both the data output and the results.

PERFORMANCE EVALUATION

Large amounts of data may be obtained from the plant. The main parameters which will be determined at first are the heat rates. The heat rate of a power plant is typically used to measure its efficiency and will be determined by the following:

- Gross Heat Rate - Ratio of heat delivered to gross bus-bar power generated (BTU/kWhr)
- Net Heat Rate - Ratio of heat delivered to net bus-bar power generated (BTU/kWhr)

The efficiencies of the main I-C₄ turbines (EFBMT), I-C₄ boiler feed pump turbine (EBBFP) and the C₃ turbine (EFPT) are of prime importance. The values will be determined in the following manner:

- EFBMT - Energy delivered by I-C₄ turbine/
Energy lost by I-C₄ expansion across turbine
- EBBFP - Energy increase in I-C₄ fluid/
Energy lost by I-C₄ extraction stream across BFPT⁴
- EFPT - Energy delivered by C₃ turbine/
Energy lost by C₃ fluid expansion

The parameters needed to calculate the heat rates and efficiencies is a consistent set of mass and energy balances around the plant. Energy balances will be calculated around exchangers whenever possible to assure the validity of the data. The basic set of over-all parameters required for calculating the above are the following:

1. Total heat delivered by brine
2. Heat delivered by brine to I-C₄ in boilers and superheaters
3. Heat delivered by brine to C₃ in C₃ superheaters
4. Heat delivered by brine to I-C₄ in heaters
5. Heat received by I-C₄ in boilers and superheaters
6. Heat received by I-C₄ in heaters
7. Total heat received by I-C₄
8. Enthalpy lost by I-C₄ in expanding over main turbines
9. Enthalpy lost by I-C₄ extraction stream by expansion across BFPT
10. Heat lost by I-C₄ in regenerator
11. Heat lost by I-C₄ in condensers
12. Enthalpy lost by C₃ in expanding across C₃ turbines
13. Heat lost by C₃ in condenser
14. Calculated heat gained by C₃ in regenerator and superheater
15. Heat received by water in C₃ condenser and I-C₄ condensers

The power produced by the I-C₄ and C₃ turbines are directly read from meters in kWh and also totalized in kW in the control room. In addition, the net power produced by the plant is also measured.

To determine these enthalpies and energies, the basic temperatures, pressures and flow rates are measured. The increments are processed by the DPS and the required enthalpies, qualities and state points are reduced. Consistent sets of thermodynamic data for propane, isobutane and water are stored in the computer system. The physical property data were derived from corrected BWR equations of state. The above mentioned values are calculated on a regular basis. The results are statistically analyzed to produce a complete overall picture of the plant at different loadings and as a function of time. If fouling starts building up in the brine exchangers, its affect will lower the heat absorbed by the I-C₄ and, hence, produce less power.

A more detailed analysis will provide the performance for each heat exchanger. A history of heat transfer coefficients and pressure drops for each exchanger would indicate, for example, when maintenance is required and/or scale-up design factors for the next plant. The regenerator process

conditions are complex, and a detailed analysis on this unit would be fruitful.

CONCLUSIONS

The plant is currently in the final stages of start-up. The turbines are expected to roll at the end of August, 1979. The computer system is in the final stages of preparation. The computer program is being verified by testing against the design data. The computer operator is being trained in all phases of the DAS. In summary, all systems and organizations anxiously await the first data from the first U.S. geothermal power plant operating on the binary Rankine cycle.

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