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EVALUATION OF AMMONIA AS A WORKING FLUID FOR
A WET/DRY-COOLED BINARY GEOTHERMAL PLANT

M. K. Drost
H. D. Huber

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FOREWORD

The Dry Cooling Enhancement project has been conducted by Battelle at the Pacific Northwest Laboratory (PNL) for about six years, jointly supported by the U.S. Department of Energy and the Electric Power Research Institute, at an approximate professional staff level of 12 man-years/year. Battelle Memorial Institute operates the Pacific Northwest Laboratory for the U.S. Department of Energy. The objectives of the project are to develop, in conjunction with utilities in the cooling tower industry, dry cooling systems and dry/wet cooling systems that conserve scarce water resources and increase power plant siting flexibility with a minimum increase in the cost of generating electricity. The thrust of the project has included the following initial and ultimate objectives.

Initial Objectives

- Develop economic and performance models for cost optimization of total heat rejection systems using dry and dry/wet cooling.
- Analyze and disseminate operating experience on existing dry-cooled plant performance.
- Demonstrate certain features of existing technology equipment to provide confidence for specification by utilities.

Ultimate Objective

- Promote water conservation through industry use of dry cooling by developing and demonstrating the reliability of lower cost systems. The development of advanced dry/wet systems is also considered to be within this scope.

The depth and extent of this project can perhaps best be presented through a listing of the documents which have been issued by the staff involved in this project. Unless otherwise specified, these documents were prepared by the Pacific Northwest Laboratory, Richland, Washington.

Six documents have been written on the analysis of performance of existing dry-cooled plants and air-cooled heat exchanger equipment:

1. Dry Cooling Tower Project: Results of Industrial Contacts Through August 1972. BNWL-1878, November 1, 1974.
2. A Survey of Materials and Corrosion Performance in Dry Cooling Applications. A. B. Johnson, Jr., D. R. Pratt and G. E. Zima, BNWL-1948, March 1976.
3. European Dry Cooling Tower Operating Experience. J. G. DeSteele and K. Simhan, BNWL-1995, March 1976. *bul*
4. Mathematical and Experimental Investigations on Dispersion and Recirculation of Plumes from Dry Cooling Towers at WYODAK Power Plant in Wyoming. Y. Onishi and D. S. Trent, BNWL-1982, February 1976.
5. Aluminum Alloy Performance Under Dry Cooling Tower Conditions. A. B. Johnson, Jr., S. Begaj, M. W. Martini, and R. P. May, PNL-02392, December 1977.
6. Aluminum Alloy Performance in Industrial Air-Cooled Applications. K. R. Wheeler, A. B. Johnson, Jr., and R. P. May, PNL-SA-8103, April 1980.

Five documents have addressed advanced dry/wet-cooled systems.

1. Preliminary Evaluation of Wet/Dry Cooling Concepts for Power Plants. W. V. Loscutoff, BNWL-1969.
2. Compatibility of Ammonia with Candidate Dry Cooling System Materials. D. R. Pratt, BNWL-1992, April 1976.
3. Scale Formation in Deluged Dry Cooling Systems. D. R. Pratt, BNWL-2070, March 1976.
4. Ammonia as an Intermediate Heat Exchange Fluid for Dry-Cooled Towers. R. T. Allemann, B. M. Johnson and G. C. Smith, BNWL-SA-5997, September 1976.
5. Cost Analysis of an Ammonia Dry Cooling System with Chicago Bridge and Iron Peak Shaving System. M. K. Drost and B. M. Johnson, PNL-3272, November 1980.

Three reports have been issued which consider the future need for any cooling and the potential benefit/cost ratio for a large-scale demonstration.

1. An Overview of Economic, Legal and Water Availability Factors Affecting the Demand for Dry and Wet/Dry Cooling of Thermal Power Plants. P. L. Hendrickson, BNWL-2268, September 1978.

2. Estimation of Benefits from Demonstrating Advanced Dry Cooling Technology: A Framework and Partial Analysis. J. W. Currie and J. T. Foley, BNWL-2182, April 1977.
3. Potential Use of Dry Cooling in Support of Advanced Energy Generation Systems. D. W. Mayer, E. M. Arnold and R. T. Allemann, PNL-3149, September 1979.

Cost optimization of dry-cooled and dry-heat-cooled rejection systems has been extensively studied in three reports.

1. A Review and Assessment of Engineering Economic Studies of Dry-Cooled Electrical Generating Plants. B. C. Fryer, BNWL-1976, March 1976.
2. Heat Transfer and Pressure Drop Characteristics of Dry Tower Extended Surfaces. Part I: Heat Transfer and Pressure Drop Data. Prepared for the Pacific Northwest Laboratory by PFR Engineering Systems, Incorporated, PFR 7-100, March 1976.
3. Heat Transfer and Pressure Drop Characteristics of Dry Tower Extended Surfaces. Part II: Data Analysis and Correlations. Prepared for the Pacific Northwest Laboratory by PFR Engineering Systems, Incorporated, PFR 7-102, June 1976.

A group of reports has been issued that: 1) develop cost optimization models for dry cooling systems based on available technology; and 2) compare the cost analysis of three systems with the projected cost of several advanced dry and dry/wet systems. Included in this group of reports are:

1. Dry Cooling of Power Generating Stations: A Summary of the Economic Evaluation of Several Advanced Concepts via a Design Optimization Study and a Conceptual Design and Cost Estimate. B. M. Johnson, R. T. Allemann, D. W. Faletti, B. C. Fryer, and F. R. Zaloudek, BNWL-2120, September 1976.
2. An Engineering and Cost Comparison of Three Different All-Dry Cooling Systems. B. C. Fryer, D. W. Faletti, Daniel J. Braun, David J. Braun, and L. E. Wiles, BNWL-2121, September 1976.
3. A Study of the Comparative Costs of Five Wet/Dry Cooling Tower Concepts. F. R. Zaloudek, R. T. Allemann, D. W. Faletti, B. M. Johnson, H. L. Parry, G. C. Smith, R. D. Tokarz, and R. A. Walter, BNWL-2122, September 1976.
4. Costs and Cost Algorithms for Dry Cooling Tower Systems. P. A. Aro, C. H. Henager, D. R. Pratt, and L. E. Wiles, BNWL-2123, September 1976.

5. A User's Manual for the BNW-I Optimization Code for Dry-Cooled Power Plants. David J. Braun, Daniel J. Braun, W. V. DeMier, D. W. Faletti, and L. E. Wiles, BNWL-2180, January 1977.
6. Comparative Cost Study of Four Wet/Dry Cooling Concepts That Use Ammonia as the Intermediate Heat Exchange Fluid. Daniel J. Braun, R. D. Tokarz, B. M. Johnson, R. T. Allemann, David J. Braun, D. W. Faletti, L. J. MacGowan, H. L. Parry, G. C. Smith, and F. R. Zaloudek, PNL-2661, May 1978.
7. An Engineering and Cost Analysis of a Dry Cooling System Augmented with a Thermal Storage Pond. M. K. Drost and R. T. Allemann, PNL-2745, September 1978.
8. A User's Manual for the BNW-II Optimization Code for Dry/Wet Cooled Power Plants. Daniel J. Braun, J. A. Bamberger, David J. Braun, D. W. Faletti, and L. E. Wiles, PNL-2674, Vol. 1, May 1978.
9. A Description and Cost Analysis of a Deluge Dry/Wet Cooling System. L. E. Wiles et al., PNL-2498, June 1978.

The primary focus of the dry cooling project has been to carry out a large-scale test of the system in the Advanced Concepts Test (ACT) facility built at the Kern Plant of Pacific Gas and Electric of Bakersfield, California.

Battelle performed the conceptual design study and cost estimates of the proposed test facility with assistance from an architect-engineering firm, and has managed the subsequent design and construction by the C. F. Braun Company of Alhambra, California. Documents which have been issued on the ACT facility design and the testing project include:

1. Advanced Concepts Facility--Measurements and Suggested Test Plan. F. R. Zaloudek, L. J. Brown and R. T. Allemann. Prepared for the Electric Power Research Institute by Battelle, Pacific Northwest Laboratories, Richland, Washington. Research Project RP422-3. EPRI-CS-1530, September 1980.
2. Development of an Advanced Concept Dry/Wet Cooling of Power Generating Plants. B. M. Johnson, ed. Prepared for the Electric Power Research Institute by Battelle, Pacific Northwest Laboratories, Richland, Washington. Research Project RP422-3. EPRI-CS-1668, February 1981.

One of the methods of dry/wet cooling under test at the ACT facility is deluge cooling. In order to study the feasibility and performance characteristics of deluge cooling, PNL has constructed a small-scale air heat transfer facility. This facility is unique because its flexibility allows a combined heat and mass transfer phenomena to be studied in a variety of configurations. Studies of "limits" of water chemistry to avoid corrosion and deposition are being carried on in conjunction with these heat transfer studies in separate facilities. Reports of this work include:

1. Analysis and Experimental Results from the Pacific Northwest Laboratory Augmented Dry Cooling Surface Test Project. H. L. Parry, L. J. MacGowan, D. K. Kreid, and B. M. Johnson. PNL-2746, November 1978.
2. Dry/Wet Performance of a Plate-Fin Air-Cooled Heat Exchanger with Continuous Corrugated Fins. S. G. Hauser, D. K. Kreid and B. M. Johnson. PNL-3428, February 1981.
3. Experimental Evaluation of a Dry/Wet Air-Cooled Heat Exchanger with Helically Wound Tubes. S. G. Hauser, R. L. Gruel, J. C. Huenefeld, E. J. Eschbach, B. M. Johnson and D. K. Kreid. PNL-4043, July 1982.
4. Deposition and Corrosion Phenomena on Aluminum Surfaces Under Deluged Dry Cooling Tower Conditions. K. R. Wheeler, R. P. May, J. G. Douglas, and J. H. Tylczak. Prepared for the Electric Power Research Institute by Battelle, Pacific Northwest Laboratories, Richland, Washington. EPRI-CS-1926, July 1981.

Finally, the application of dry and dry/wet cooling to other energy-related situations has been treated in these documents:

1. Potential Use of Dry Cooling in Support of Advanced Energy Generation Systems. D. W. Mayer, E. M. Arnold and R. T. Allemann. PNL-3149, September 1979.
2. Cost Analysis of an Ammonia Dry Cooling System with a Chicago Bridge and Iron Peak Shaving System. M. K. Drost and B. M. Johnson. PNL-3272, December 1980.
3. Cost Benefits from Applying Advanced Heat Rejection Concepts to a Wet/Dry Cooled Binary Geothermal Plant. D. W. Faletti. PNL-3419, March 1981.

SUMMARY

Under the sponsorship of the U.S. Department of Energy, Geothermal Division, and Advanced Nuclear Systems and Projects Division, the Pacific Northwest Laboratory (PNL) performed a comparative analysis of binary cycle geothermal plants using isobutane and ammonia as the Rankine cycle working fluid. Four cases were considered:

<u>Working Fluid</u>	<u>Heat Rejection System</u>
Isobutane	Wet Cooling--evaporative cooling tower
Ammonia	Wet Cooling--evaporative cooling tower
Isobutane	Wet/Dry Cooling--ammonia indirect dry cooling tower with deluging
Ammonia	Wet/Dry Cooling--ammonia direct condensing with deluging

Using the BNWGEO computer code developed at PNL, the wet/dry heat rejection systems were optimized and designed for geothermal application. With those results as input, the geothermal plants were analyzed using the GEOCOST computer code, also developed at PNL. The results of the GEOCOST simulation included performance and cost information allowing a comparison of the four concepts. The study results led to the following conclusions:

- The wet-cooled isobutane cycle arrangement gives the lowest levelized energy cost of all cycles considered. If water is available for evaporative cooling at a price less than approximately \$1.50 per thousand gallons, then the isobutane cycle arrangement produces the least expensive power.
- If water for cooling is limited so the plant uses wet/dry cooling, where 9% of the cooling load is provided by evaporative deluge cooling, the wet/dry ammonia cycle gives levelized energy costs substantially less than those for the wet/dry isobutane cycle arrangement. In fact, the levelized energy cost of the wet/dry ammonia cycle is less than the wet-cooled ammonia case.
- For dry or wet/dry applications, the heat rejection subsystem is the dominant plant cost, approximately twice as expensive as the next largest component. This implies that substantial effort must go into selecting and optimizing the dry or wet/dry heat rejection system.

ACKNOWLEDGMENTS

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INTRODUCTION

The widespread use of geothermal resources for power generation depends on the availability of either sufficient quantities of cooling water or advanced dry cooling technology. Because geothermal power plants consume about four times more water for evaporative cooling than do fossil or nuclear plants of the same net power, the availability of water for this purpose in the semi-arid Western United States, where most known geothermal resources are located, is particularly questionable. While wet/dry or dry cooling could eliminate this constraint, the use of currently available dry cooling technology results in a substantial increase in the cost of electricity from geothermal plants.

The U.S. Department of Energy (DOE), Division of Geothermal Energy, has supported several studies utilizing Pacific Northwest Laboratory (PNL) experience in advanced dry and dry/wet cooling analysis to determine whether advanced concepts can significantly reduce the costs of dry and dry/wet systems. Falatti (1981) reviewed the application of advanced dry cooling technology to existing geothermal plant designs and reported that wet/dry ammonia systems offer substantial economic advantages when compared to conventional dry and wet/dry cooling technologies. One of his recommendations was to evaluate alternate geothermal power plant working fluids because costs might be reduced if a working fluid were chosen specifically for dry cooling applications. Based on the Faletti's results a follow-on study to evaluate ammonia as a Rankine cycle working fluid in a binary cycle geothermal power plant was initiated. This report evaluates ammonia as a working fluid.

The binary cycle geothermal power plant is one of several methods for using geothermal resources. This type plant uses an intermediate fluid, rather than steam from the geothermal resource, as the Rankine cycle working fluid. The geothermal brine is extracted from the field and passed through a heat exchanger to vaporize the working fluid driving the turbine. The working fluid is then condensed and returned to the heat exchanger. The geothermal brine is then returned to the field and reinjected. The binary systems are most economical at lower geothermal temperatures. Unlike plants directly using geothermal

steam, condensate is not available for use in evaporative cooling of binary-cycle plants. If a binary-cycle plant is to be evaporatively cooled, a source of make-up water must be available.

Current binary-cycle geothermal designs use a working fluid such as isobutane or a mixture of isobutane and isopentane for intermediate temperature geothermal resources (360°F). The working fluid is condensed in a surface condenser by cooling water that is heated in the process. The water is then cooled in a cooling tower and returned to the condenser. This study considers an alternate arrangement using ammonia as the working fluid. Rather than condensing the ammonia vapor in a surface condenser (as with isobutane), the ammonia vapor is piped to an air-cooled heat exchanger, where the ammonia is condensed and the waste heat is rejected to the atmosphere. The liquid ammonia then is returned to the surface condenser in the plant. This study is an economic comparison of the conventional design using isobutane as a working fluid and ammonia as an alternate working fluid, with ammonia also being directly condensed in the cooling tower. The study also considered both wet and wet/dry cooling.

2.0 DESCRIPTIONS OF CONCEPTS

The concepts considered in this study involve various arrangements of the binary geothermal power cycle with advanced dry cooling schemes. Brief descriptions of the binary cycle and advanced cooling schemes are included in this section. Also included are descriptions of the base case concept and the ammonia working fluid concept.

2.1 BINARY GEOTHERMAL POWER CYCLE

The binary geothermal power cycle uses geothermal brine as a heat source in a heat exchanger to vaporize a working fluid which is then expanded in a turbine and condensed. Then the liquid working fluid is pressurized in a feed pump and returned to the heat exchanger. Figure 1 shows a schematic of a binary fluid cycle geothermal power plant. The geothermal brine is produced in a field of wells and, after providing heat for the power plant, the brine is transported to a second set of wells for reinjection into the field.

The performance of a binary cycle geothermal power plant can be influenced by many factors. Four are particularly important in this study:

- Geothermal Source Temperature--This temperature directly affects the theoretical (Carnot) cycle efficiency of the binary plant cycle. A low source temperature results in a low cycle efficiency. As discussed below, the geothermal source temperature will influence the selection of the cycle working fluid.
- Geothermal Brine Return Temperature--The efficient use of geothermal brine as an energy source requires that the maximum amount of heat be extracted from the brine in the power cycle, making the lowest possible brine return temperature desirable. In this study a limit of 160°F is placed on the minimum brine return temperature to prevent precipitation of dissolved solids contained in the brine.
- Minimum Working Fluid Temperature--This temperature is the temperature of the fluid as it exists the condenser and represents the heat sink (rejection) temperature for calculating the theoretical cycle

FIGURE 1. Binary Fluid Cycle Power Plant

efficiency. A low minimum working fluid temperature will allow the working fluid vapor to be expanded to a lower pressure, producing a more efficient cycle. Conversely, a high minimum working fluid temperature results in a lower cycle efficiency.

- Working Fluid Selection--Working fluid selection can influence cycle efficiency in many ways. The details of the working fluid selection on cycle efficiency are fully discussed by Milora and Tester (1976) and will not be discussed here. In general, working fluids with a low critical temperature are desired because this produces a supercritical cycle that efficiently utilizes the available geothermal energy, but which has the penalty of high pumping power requirements. Ammonia has a high critical temperature, and Milora and Tester indicated that ammonia may be the working fluid of choice at higher geothermal resource temperatures (482°F). Ammonia also was considered the most attractive working fluid, based on turbine design requirements. At lower temperatures ammonia, while producing a more efficient plant design, did not effectively utilize the geothermal brine and was, therefore, considered less attractive than other fluids such as isobutane.

The design of a binary cycle power plant is a complicated optimization process beyond the scope of this study. Therefore, where possible, previously published results were used to select design conditions. Particular attention was given to the design developed by Fluor Engineers and Constructors (1979) for the Heber Geothermal Demonstration Power Plant Project.

2.2 WET/DRY HEAT REJECTION SYSTEMS

A wet/dry heat rejection system combines evaporative cooling (as with a conventional wet cooling tower) with air cooling without evaporation (i.e., with an air-cooled heat exchanger). This avoids the need for a very large air-cooled heat rejection system to reject the design heat load during the hottest hour of the year or, conversely, to avoid the significant loss of power during the hottest hour.

The dry-cooled portion of the system (i.e., the air-cooled heat exchanger) can have one of two general arrangements. First, the turbine exhaust vapor can be transported directly to the air-cooled heat exchanger where it is condensed, transferring heat to the air. This arrangement is called direct cooling, and the air-cooled heat exchanger is called the air-cooled condenser (ACC). A direct-cooled system is shown in Figure 2.

The second arrangement uses a circulating fluid such as water to condense the turbine exhaust vapor in a condenser. The heated circulating fluid is transported to the cooling tower, where the fluid is cooled in the air-cooled heat exchanger and returned to the condenser. This arrangement is called an indirect cooling system and is shown in Figure 3. An alternative to using water as the circulating fluid is to use a fluid that evaporates as the turbine exhaust vapor is condensed and is then condensed in the air-cooled heat exchanger. This circulating fluid remains isolated from the turbine. The ammonia dry cooling system is of this type; exhaust steam from the turbine is first condensed by circulating ammonia on the tubes of a heat exchanger, not unlike a conventional condenser. The ammonia is partially vaporized and the two-phase mixture flows to a phase separator. The liquid ammonia is pumped back to the condenser/reboiler to be further vaporized, while the vapor is

FIGURE 2. Direct Wet/Dry Cooling System

FIGURE 3. Indirect Wet/Dry Cooling System

transported to the air heat exchanger in the cooling tower. The rejection of heat to the air causes the ammonia to condense; the liquid falls into the hot well and is pumped back to the condenser/reboiler.

For conventional power plants, an ammonia phase-change dry cooling system should be economically more attractive than conventional indirect dry cooling design. The study conducted by Faletti (1981) demonstrated that the ammonia phase-change cooling system substantially reduced the cost of dry cooling for a binary cycle geothermal power plant when compared to dry cooling technologies. The binary cycle plant considered by Faletti used isobutane operating in a supercritical cycle with a geothermal source temperature of 360°F.

2.3 BASE CASE CYCLE ARRANGEMENT

In this study a binary cycle plant using ammonia as a working fluid is compared to a base-case, conventional design. A plant with characteristics

similar to the Holt/Procon Binary Plant Design, with an assumed location on the Heber site, was chosen to represent the former. To represent the conventional design, a supercritical cycle using isobutane as the working fluid was chosen.

Cost estimates were prepared for the following options to cool the base-case design: 1) wet cooling, and 2) wet/dry cooling, where 9% of the annual cooling capacity is provided by deluge cooling. The wet/dry cooling system is an ammonia phase-change system with deluging. This system is described in Wiles et al. (1978). Flow diagrams for the Two isobutane cycle arrangements are shown in Figures 4 and 5.

Another option considered for the base-case design is a cooling system that directly condenses isobutane in an air-cooled condenser. Faletti (1981) has shown that a direct cooling system is more expensive than the ammonia cooling system because of the much lower energy density of isobutane compared to ammonia. This requires very expensive supply piping which outweighs the other capital cost savings. Accordingly, this option was not selected for analysis with the base-case design.

FIGURE 4. Isobutane Cycle with Wet Cooling

FIGURE 5. Isobutane Cycle with Wet/Dry Cooling

2.4 AMMONIA WORKING FLUID CYCLE ARRANGEMENT

The alternative cycle arrangement consisted of a subcritical cycle using ammonia as the working fluid. Cost estimates were prepared for a wet-cooled case and a wet/dry case where 9% of the annual cooling capacity was provided by deluge cooling. The wet/dry cooling system was assumed to be an ammonia direct condensing system where ammonia vapor from the power cycle is transported to an air-cooled condenser and directly condensed. Flow diagrams for the two ammonia cycle arrangements are shown in Figures 6 and 7.

The original hypothesis was that the wet-cooled ammonia working fluid cycle would not be cost-competitive with the wet-cooled isobutane base case cycle arrangement. When wet/dry cooling was considered, it appeared possible that the advantages of coupling the ammonia power cycle with direct condensing might offset the other advantages of the isobutane cycle. The main advantages of the alternate (ammonia) cycle arrangement consist of eliminating the capital cost of the condenser and eliminating the required terminal temperature

FIGURE 6. Ammonia Cycle with Wet Cooling

FIGURE 7. Ammonia Cycle with Direct Condensing

difference (TTD) between the working fluid vapor and the cooling water in the condenser. Eliminating the condenser TTD would improve thermal performance, particularly at high ambient temperatures.

3.0 METHOD OF ANALYSIS

Performance and cost estimates were developed for a wet-cooled isobutane cycle plant, wet/dry cooled isobutane cycle plant, wet-cooled ammonia cycle plant, and a wet/dry cooled ammonia cycle plant. The performance and cost estimates were calculated using the GEOCOST computer code developed at PNL. Inputs for GEOCOST were calculated based on the Heber site. The characteristics of the wet/dry cooling system were determined using the BNWGEO computer code developed at PNL.

3.1 PLANT PERFORMANCE AND COST ANALYSIS

The performance and cost of the various designs were estimated using the GEOCOST computer code. GEOCOST simulates the production of electricity from geothermal resources and calculates the potential costs of geothermal power. GEOCOST combines resource characteristics, power recovery technology, tax rates and financial factors into one systematic model and provides the flexibility to individually or collectively evaluate their impacts on the cost of geothermal power. Both the geothermal reservoir and the power plant are simulated to model the complete energy-production system.

In GEOCOST, geothermal fluid is supplied from wells distributed throughout a hydrothermal reservoir through insulated pipelines to a binary power plant. The power plant is simulated using a binary fluid cycle in which the geothermal fluid is passed through a series of heat exchangers. Thermal energy is transferred from the hot geothermal fluid to a working fluid. The working fluid is brought to a superheated state and then expanded through a turbine coupled to a generator. After passing through the heat exchangers, the geothermal fluid is reinjected.

the thermodynamic state points in basic subcritical and supercritical Rankine cycles are calculated for a variety of working fluids. Working fluids which are now in the model include isobutane, n-butane, R-11, R-12, R-22, R-113, and R-114, and ammonia. Thermodynamic properties of the working fluids at the state points are calculated using empirical equations of state. The Starling equation of state is used for fluorocarbons and ammonia. Physical properties

of working fluids at the state points are calculated using polynomial functions of phase and temperature correlated to data in the literature by least-squares curve fits.

GEOCOST has been used for many applications and the thermodynamic analysis results have agreed with other published data, so the performance results can be used with some confidence. The cost results depend on economic assumptions and cost methodology, particularly for the field, therefore the relative costs are more meaningful than the absolute costs. The GEOCOST program is discussed in detail by Huber et al. (1976).

While GEOCOST is not a thermodynamic cycle optimization code, other published results and previous applications of GEOCOST have given us confidence in our ability to pick a nearly optimum isobutane cycle arrangement. We conducted several sensitivity studies on the impact of variations in cycle operating temperature and brine return temperature on energy cost. The least-cost case was picked as the design point.

3.2 WET/DRY COOLING SYSTEM PERFORMANCE AND COST

The performance and cost of the wet/dry cooling systems were determined using the BNWGEO computer code. The results were used as input to GEOCOST. The wet/dry cooling systems were analyzed in detail because they were a substantial fraction of plant cost and severely impacted plant performance. BNWGEO is an optimization code that determines the optimum wet/dry cooling tower design for a specific application. The code computes the incremental cost of electricity from the plant for a series of designs and selects the design giving the lowest cost.

The BNWGEO code uses the same utility model as in the BNW-II codes (Braun et al. 1978). In this model, the utility must meet a fixed demand for a fraction of the year equal to the capacity factor. The downtime of the utility is distributed uniformly throughout the year. Combustion turbines provide the makeup power whenever high ambient temperatures cause power production of the geothermal plant to fall below fixed demand.

The most economical way to operate within the constraints of the utility model is for the plant to maintain a constant backpressure whenever wet augmentation is used. (This constant backpressure minimizes the size of the gas turbine power supplement required.) As the ambient temperature falls below the minimum where wet augmentation is used, the turbine backpressure falls as the turbine exhaust temperature "tracks" the ambient temperature. Under certain conditions, the plant, when operated all-dry at low temperature, may deliver more than the fixed utility load. Under these circumstances, no credit is given for the surplus power, assuming that no market exists. However, credit is given for reduced fuel consumption--in this case, lower geothermal energy usage. If it was assumed that credit could be given for surplus power, then the levelized cost of wet/dry cooling would be reduced.

Power for the heat rejection system's fans and pumps is provided by the geothermal plant. The size of the plant plus its heat rejection system is "scaled up" to meet this need. Braun et al. (1978) gives a detailed description of the utility model and the computation of the incremental cost, as well as the computational procedure followed by the BNW-II code.

The capital cost of the wet/dry cooling system includes the capital cost of the condenser (if required), the piping, the cooling tower, the gas turbine for replacement power and the plant scaling for fans, pumps, and efficiency variations. The annual cost of the wet/dry cooling system includes; the variable cost of the gas turbine replacement power, variations in the base plant fuel use and operation, and maintenance cost for the wet/dry cooling system.

3.3 WET COOLING SYSTEM PERFORMANCE AND COST

The performance and cost of the wet cooling systems were determined using an algorithm in GEOCOST. The algorithm was checked for consistency with the wet/dry design methodology and with vendor design procedures.

3.4 GROUND RULES AND ASSUMPTIONS

To provide a consistent basis for comparing the concepts, ground rules and design assumptions were established at the start of the project. These included plant location, meteorology, geothermal reservoir characteristics, and economic assumptions.

The Heber site is the assumed plant location. The pertinent site and geothermal reservoir characteristics are listed in Table 1. The assumed meteorological conditions are shown in Table 2. It should be noted that the Heber site experiences an extremely high peak ambient temperature. It was beyond the scope of this study to consider a variety of meteorological conditions but, based on the results of other dry cooling studies, site meteorology probably will have a substantial impact on the study results.

The BNWGEO and GEOCOST codes both required economic input data. Where possible, these were calculated on a consistent basis, but in some cases, it was not possible to determine comparable values for the economic parameters. Listed in Table 3 are significant economic inputs to BNWGEO. The replacement power cost presented on Table 3.3 appears lower than projected geothermal power costs. This is due to replacement power cost being given in 1976 dollars. Also, it represents first year costs rather than levelized costs (required by BNWGEO). This parameter was used in the cooling tower optimization and only indirectly effects the geothermal plant design. Significant economic inputs to GEOCOST are listed in Table 4. Costs calculated in BNWGEO are in January 1, 1976, dollars but were escalated to January 1, 1980, dollars for use in GEOCOST. All results from GEOCOST are in January 1, 1980, dollars.

TABLE 1. Site Characteristics

Location	Heber, California
Plant Type	Binary
Net Power Rating	50 MWe
Brine Temperature	360°F
Minimum Brine Return Temperature	160°F

TABLE 2. Site Meteorology

<u>Period</u>	<u>Dry Bulb Temperature (F)</u>	<u>Dry Bulb Temperature (F)</u>	<u>Fraction of Year at These Conditions (%)</u>
1	114.0	80.0	1.9
2	106.0	78.0	2.5
3	102.0	76.0	3.3
4	99.0	74.0	3.1
5	97.0	72.0	3.1
6	93.0	70.0	7.6
7	91.0	65.0	7.5
8	81.0	65.0	7.2
9	78.0	60.0	13.7
10	77.0	55.0	8.3
11	65.0	55.0	11.7
12	61.0	50.0	11.2
13	53.0	45.0	1.5
14	46.0	40.0	4.3
15	41.0	35.0	2.5
16	32.0	30.0	0.6

TABLE 3. Economic Parameters for BNWGE0
(January 1976 Dollars)

Plant Capacity Factor	0.75
Geothermal Energy Cost	58.2¢/mm btu
Replacement Power Cost	29.47 mills/kWh
Replacement Power Levelizing Factor	2.471
Capacity Charge (cost of replacement gas turbine)	\$156/kW
General Inflation Rate	6%
Fuel Inflation Rate	8%

TABLE 4. Economic Parameters for GEOCOST
(January 1980 Dollars)

First Year of Operation	1984
Project Life (yrs)	33
Fraction of Initial Investment in Bonds (%)	48
Bond Interest Rate (%)	10
Equity Earning Rate (% After Taxes)	15
Federal Income Tax Rate (%)	46
Depreciable Life of Plant (yrs)	30
Plant construction and Licensing (yrs)	3
State Income Tax Rate (%)	9
Property Tax Rate (%)	1.0
Interim Capital Replacements (Rate/Yr)	0.35
Plant Operating Life (yrs)	30
Investment Tax Credit (%)	5

4.0 RESULTS AND CONCLUSIONS

Results of the cooling system analysis are presented first, followed by results of the geothermal plant analysis. Conclusions and comments also are included.

4.1 RESULTS OF WET/DRY COOLING TOWER ANALYSIS

The results of the wet/dry cooling tower design for the isobutane cycle plant are fully discussed in Faletti (1981) and will only be summarized here. The results are representative of a wet/dry system using deluge cooling. The characteristics of the cooling tower are listed in Table 5.

The wet/dry cooling tower design for the ammonia case was assumed to be identical to the tower used for isobutane except that the condenser/reboiler was eliminated, reducing capital cost and, more importantly, eliminating the 14°F TTD in the condenser. The performance of the two systems is shown in Table 6. The assumption that the cooling towers are identical for both cases is conservative because the ammonia cycle is more efficient than the isobutane cycle, producing less waste heat for equal-sized plants. The cooling tower described on Table 4 has a nominal output of 30 MWe. These cooling tower costs were used to develop cost scaling relations for GEOCOST so that cooling tower costs were scaled with plant size. The components of capital cost and operating cost are shown in Table 7.

4.2 RESULTS OF GEOTHERMAL PLANT ANALYSIS

The performance and cost analysis state variables of the alternatives considered in this study are presented in Table 8. The capital cost components of the binary cycle plant are shown in Table 9 and the components of levelized energy cost in Table 10.

While there are several methods of calculating life-cycle costs, this study calculates the levelized cost of energy. This approach calculates the present value of all cost associated with the plant, and converts the present value to an annualized cost which over the lifetime of the plant has exactly

TABLE 5. Characteristics of Isobutane Cycle Wet/Dry Cooling Tower

<u>% Heat Rejected by Deluging</u>	9
<u>Condenser-Reboiler</u>	
TTD (°F)	14.0
Heat Transfer Area (10^5 ft^2)	2.1
Tube Length (ft)	30
Total Number of Tubes	26,700
Number of Shells	9
Diameter of Shells (in.)	96
NH ₃ Flow Rate ^(a) (10^6 lb/hr)	1.9
<u>Dry Cooling Tower</u>	
Length (ft)	675
Width (ft)	121
Height to Base of Bundles (ft)	36
Number of 28 ft Diameter Fans	52
Frontal Area (10^3 ft^2)	75.9
Heat Transfer Area (10^6 ft^2)	5.8
Tube Length (ft)	50
Heat Exchanger Depth (in.)	4.5
Air Flowrate (10^6 lb/hr)	199
Face Velocity (ft/sec)	8
Auxiliary Power (MWe)	
Fans	1.56
Pump	0.06

(a) At 32°F Ambient Temperature and all dry operation.

the same present value. Dividing the annualized cost by the annual energy output of the plant produces an energy cost which is constant, or leveled, over the plant's operating lifetime.

TABLE 6. Performance of Wet/Dry Towers

<u>Meteorological Interval</u>	<u>Ambient Dry Bulb Temperature (°F)</u>	<u>Net Power Generated by Isobutane Cycle Plant (MWe)</u>	<u>Net Power Generated by Ammonia Cycle Plant (MWe)</u>
1	114	36.9 ^(a)	42.4 ^(a)
2	106	36.9 ^(a)	42.4 ^(a)
3	102	36.9 ^(a)	42.4 ^(a)
4	99	36.9 ^(a)	42.4 ^(a)
5	97	36.9 ^(a)	42.4 ^(a)
6	93	36.9 ^(a)	42.4 ^(a)
7	91	36.9 ^(a)	42.4 ^(a)
8	81	36.9 ^(a)	42.4 ^(a)
9	78	38.0	43.6
10	77	38.4	44.0
11	65	43.1	45.4
12	61	44.4	48.7
13	53	46.9	50.0
14	46	48.8	50.0
15	41	50.0	50.0
16	32	50.0	50.0

(a) Deluging is occurring during this meteorological interval.

4.3 CONCLUSIONS AND COMMENTS

The results of this study support the following conclusions:

- The wet-cooled isobutane cycle arrangement gives the lowest levelized energy cost of all cycles considered. If water is available for evaporative cooling, the isobutane cases produces less expensive power than either the wet-cooled ammonia cycle or the wet/dry cycles. This confirms similar conclusions drawn by other investigators (Milora and Tester, 1976) and (Flour, 1979).

TABLE 7. Components of Capital and Operating Cost

Components of Capital Cost (in 1976 dollars x 10 ³)		
	Isobutane Cycle Design	Ammonia Cycle Design
Tower	8,266	8,266
Piping	1,972	1,972
Condenser	4,913	--
Replacement Gas Turbine	2,039	1,179
Plant Scaling ^(a)	<u>-1,823</u>	<u>-1,823</u>
	15,367	9,594

Components of Levelized Annual Cost (in 1979 dollars x 10 ³ /yr)		
Gas Turbine Fuel	5,693	2,973
Base Plant Energy ^(a)	-694	-676
Operation and Maintenance	<u>407</u>	<u>212</u>
	5,406	2,509

(a) The nature of these cost components was not described in this report. For a full explanation refer to Braun et al., 1978.

- For wet/dry cooling, the wet/dry ammonia cycle gives levelized energy costs substantially less than those for the wet/dry isobutane cycle arrangement. In fact, the levelized energy cost of the wet/dry ammonia cycle is less than the wet-cooled ammonia case. This surprising result is discussed below.
- For dry or wet/dry applications, the heat rejection subsystem is the dominant plant cost, approximately twice as large as the next largest component. This implies that substantial effort must go into optimizing and selecting the dry or wet/dry heat rejection system.

TABLE 8. Performance and Cycle State Variables

	<u>Wet Cooled Isobutane Cycle</u>	<u>Wet Cooled Ammonia Cycle</u>	<u>Wet/Dry Cooled Isobutane Cycle</u>	<u>Wet/Dry Cooled Ammonia Cycle</u>
Cycle State Variables				
Turbine Inlet Temperature (°F)	305	340	305	340
Turbine Inlet Pressure (psia)	575	1,044	575	900
Turbine Outlet Temperature (°F)	170	108	163	110
Turbine Outlet Pressure (psia)	73	212	63	181
Condenser Outlet Temperature (°F)	105	100	90	90
Geothermal Fluid Variable				
Superheater Inlet Temperature (°F)	360	360	360	360
Return Temperature (°F)	160	191	160	179
Parasitic Losses (kW)				
Fans	880	929	1616	1616
Condensate Pumps	1,430	1,511	--	--
Cooling Water Pump	2,855	3,011	5	6
Feed Pumps	6,839	3,953	6,396	3,239
Others	802	757	752	707
Gross Plant Output (kW)	62,500	65,000	62,500	65,000
Geothermal Fluid Flow Rate (lb/hr)	7,285,000	9,137,000	6,950,000	8,535,000
Working Fluid Flow Rate (lb/hr)	7,456,000	2,754,000	6,906,000	2,650,000
Cooling Water Flow Rate (lb/hr)	62,749,000	66,174,000	116,000	120,000
Net Heating Rate (Btu/kWh)	43,469	49,396	38,234	42,432
Net Output (MWe)	49.7	54.8	53.7	59.4

TABLE 9. Components of Plant Capital Cost (January 1980 \$K)

	Wet Cooled Isobutane Cycle	Wet Cooled Cycle	Wet/Dry Cooled Isobutane Cycle	Wet/Dry Cooled Ammonia Cycle
Power Plant Components				
Piping, Insulation and Tanks	3,039	5,526	2,800	6,386
Crane	319	321	319	321
Turbo Generator	4,673	2,263	4,390	2,210
Vapor Generator	2,760	3,236	2,446	2,864
Misc. Process Support Equipment	253	261	253	261
Instrumentation and Controllers	1,396	1,700	795	776
Electrical Support Equipment	719	715	430	347
Condenser	2,558	4,255	--	--
Buildings, Foundations, and Support Equipment	1,892	1,944	1,892	1,944
Cooling Water Pump	512	532	46	46
Reinjection Pump (Plant-located)	173	199	168	191
Condensate Pump	338	354	--	--
Working Fluid Feed Pump	3,193	2,030	3,028	1,696
Working Fluid Booster Pump	757	247	694	237
Heat Rejection System	2,750	2,900	21,011	13,542
Switch Yard System	1,328	1,355	1,328	1,355
Indirect Field Cost(a)	2,666	2,784	1,859	1,863
Engineering and Design(a)	3,519	3,675	2,454	2,460
Contractor's Fee(a)	1,466	1,531	1,022	1,025
Contingency Cost(a)	4,399	4,593	3,067	3,075
Environmental Impact Statement	315	315	315	315
Total Power Plant Cost	39,025	40,736	48,317	40,914
Specific Cost (\$/kW)	785	743	899	689

(a) These overheads for the heat rejection system are included in the cost of the heat rejection system rather than in the overhead accounts.

TABLE 10. Components of Levelized Energy Cost
(Mills/kWhr, January 1980 Dollars)

	<u>Wet Cooled Isobutane Cycle</u>	<u>Wet Cooled Ammonia Cycle</u>	<u>Wet/Dry Isobutane Cycle</u>	<u>Wet/Dry Ammonia Cycle</u>
Initial Plant Capital Cost	13.81	13.06	15.81	12.1
Interim Capital Replacement	0.42	0.39	0.48	0.36
Energy Supply	36.42	42.21	32.34	35.65
Operating Expenses(a)	1.29	1.22	1.48	1.13
State Income Tax	0.92	0.87	1.05	0.81
Federal Income Tax	3.67	3.47	4.2	3.22
Bond Interest	2.78	2.63	3.19	2.44
Total	59.97	64.48	75.54	62.99

(a) Includes penalties associated with dry cooling, such as replacement power.

The following comments relate to the conclusions:

- The wet/dry cooled ammonia system produces lower cost power than the wet-cooled ammonia system apparently because of the impact of the wet/dry system on auxiliary loads. The wet/dry system has auxiliary loads of ~5600 kW, while the wet system has auxiliary loads of ~10,200 kW. This effectively increases plant output by 10% for the wet/dry system. The reduction in auxiliary loads was caused by eliminating the cooling water pumps and condensate pumps. The impact of dry cooling on cycle efficiency is accounted for in the plant operating cost, which included the fuel cost of the gas turbine used to replace lost generation due to high ambient temperature.

- The major advantages of the direct condensing system are the reduction in capital cost and in gas turbine replacement power when compared to the indirect system used with isobutane. Of the two, the reduction in gas turbine replacement power is the most significant.
- The cost difference between the wet-cooled isobutane system and the wet/dry ammonia system is 3.02 mill/kWh, representing an annual cost of \$990,000. In this study, cooling water was assumed to be free, but if cooling water were to have a levelized cost of ~\$1.50 per thousand gallons, the two systems would have approximately equal levelized energy costs.

Based on the study results, the following actions are recommended:

- A more detailed optimization study on an ammonia wet/dry system with direct condensing should be conducted. This would allow the investigation of energy cost sensitivity to variations in design parameters, geothermal resource characteristics, load meteorology, and economic assumptions.
- A working fluid screening study to examine other working fluids for direct condensing wet/dry applications should be considered. Other working fluids besides ammonia should be considered for wet/dry condensing applications. In particular, isobutane should be considered. Faletti (1981) rejected isobutane based on capital cost estimates. However, the results of this study, which were not available to Faletti, indicate that the most significant impact is on annual costs and replacement energy penalty. An evaluation which includes both may produce a different conclusion.

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