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ECONOMIC EVALUATION OF FOUR TYPES OF
DRY/WET COOLING APPLIED TO THE 5-MWe
RAFT RIVER GEOTHERMAL POWER PLANT

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July 1982

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FOREWORD

The Dry Cooling Enhancement project has been a Pacific Northwest Laboratory (PNL) activity for about six years at an approximate professional staff level of 12 man-years/year. 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. The Pacific Northwest Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy.

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.
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. Falletti, 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. Ard, 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.

The Pacific Northwest Laboratory 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.

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The following cooling tower manufacturers and their representatives deserve acknowledgment for the information they provided during this study: W.G. Sanderson and R.L. Cooke, Jr. of Tower Systems, Inc., R. Cates and J.J. Willmott of Baltimore Aircoil Company, Inc., and G.E. Kluppel and R. Martinez of Hudson Products Corp.

SUMMARY

This report describes a cost study which compared the economics of four dry/wet cooling systems currently available for geothermal plant cooling as possible systems to use at the existing Raft River Geothermal Plant. The results apply only at this site and should not be generalized without due consideration of the complete geothermal cycle. These systems are:

Tower Systems, Inc. - Binary Cooling Tower®

Baltimore Aircoil Company, Inc. - Evaporative Condenser

Hudson Products Corp. - Combin-aire®

Deluge Augmented/Dry Tower - metal fin-tube dry cooling tower with deluge augmentation.

The systems were evaluated using cooled, treated geothermal fluid instead of ground or surface water in the cooling loops. All comparisons were performed on the basis of a common plant site - the Raft River 5 MWe geothermal plant in Idaho. The Binary Cooling Tower® and the Combin-aire® cooling system were designed assuming the use of the isobutane/water surface condenser currently installed at the Raft River Plant. The other two systems had the isobutane ducted to the evaporative condensers. Capital credit was not given to the systems employing the direct condensing process.

The costs of the systems were estimated from designs provided by the vendors. The levelized energy cost range for each cooling system is listed below. The levelized energy cost reflects the incremental cost of the cooling system for the life of the plant. The estimates are presented in 1981 dollars.

<u>Concept</u>	<u>Cooling System Levelized Cost Range (mills/kWh)</u>
Tower Systems, Inc. Binary Cooling Tower®	4.53 - 4.83
Baltimore Aircoil Company, Inc. Evaporative Condenser	3.67 - 6.25
Hudson Products Corp. Combin-aire®	11.25 - 11.44
Deluge Augmented/Dry Tower	6.41 - 6.57

The levelized energy costs indicated that three of the four systems offer similar ranges of incremental cost for dry/wet cooling of geothermal power plants under the conditions imposed by the Raft River site. The levelized energy costs suggest that the Evaporative Condenser would have the lowest cost of the systems studied for replacement of the condensing system currently in use at Raft River.

CONTENTS

FOREWORD	iii
ACKNOWLEDGMENTS	ix
SUMMARY	xi
LIST OF FIGURES	xv
LIST OF TABLES	xvi
1.0 INTRODUCTION	1-1
1.1 BACKGROUND	1-1
2.0 BASES FOR COMPARISON	2-1
2.1 GENERAL CRITERIA FOR COMPARISONS	2-1
2.2 CONCEPTUAL DESIGN BASES	2-2
3.0 REFERENCE PLANT DESCRIPTION	3-1
3.1 LOCATION AND METEOROLOGY	3-1
3.2 DESCRIPTION OF REFERENCE UNIT	3-2
3.3 WATER AVAILABILITY AND QUALITY	3-2
4.0 DESCRIPTION OF THE DRY/WET COOLING TOWER CONCEPTS	4-1
4.1 TOWER SYSTEMS, INC. - BINARY COOLING TOWER [®] SYSTEM	4-1
4.1.1 GENERAL DESCRIPTION	4-1
4.2 BALTIMORE AIRCOIL COMPANY, INC. - EVAPORATIVE CONDENSER COOLING SYSTEM	4-5
4.2.1 GENERAL DESCRIPTION	4-5
4.3 HUDSON PRODUCTS CORP. - COMBIN-AIRE [®] COOLING TOWER SYSTEM	4-7
4.3.1 GENERAL DESCRIPTION	4-9
4.4 DELUGE AUGMENTED/DRY TOWER COOLING SYSTEM	4-13
4.4.1 GENERAL DESCRIPTION	4-13

5.0	COOLING WATER TREATMENT AND DISPOSAL	5-1
5.1	TOWER SYSTEMS, INC. - BINARY COOLING TOWER [®] SYSTEM	5-1
5.1.1	CLOSED RECIRCULATING SYSTEM	5-3
5.1.2	OPEN EVAPORATIVE RECIRCULATING SYSTEM	5-3
5.2	BALTIMORE AIRCOIL COMPANY, INC. - EVAPORATIVE CONDENSER	5-4
5.2.1	OPEN RECIRCULATING SYSTEM	5-6
5.3	HUDSON PRODUCTS CORP. - COMBIN-AIRE [®] COOLING TOWER SYSTEM	5-6
5.3.1	CLOSED RECIRCULATING SYSTEM	5-6
5.3.2	OPEN RECIRCULATING SYSTEM	5-6
5.4	DELUGE AUGMENTED/DRY TOWER COOLING SYSTEM	5-6
5.4.1	DELUGATE LOOP - OPEN RECIRCULATING SYSTEM	5-9
5.4.2	ZERO-HARDNESS RINSE WATER	5-9
5.5	EVAPORATIVE PONDS	5-9
6.0	BASES FOR COST ESTIMATES	6-1
6.1	CONSTRUCTION COSTS	6-1
6.2	ANNUAL OPERATING COSTS	6-2
7.0	RESULTS	7-1
7.1	CAPITAL COSTS OF THE COOLING SYSTEMS	7-1
7.2	OPERATING COSTS	7-1
7.3	COMPARATIVE CAPITAL COSTS AND LEVELIZED ENERGY COSTS	7-3
8.0	DISCUSSION	8-1
8.1	COMPARISON OF THE COOLING SYSTEM COSTS	8-1
8.2	CONCLUSIONS AND RECOMMENDATIONS	8-3

FIGURES

- 3-1. Raft River Geothermal Site and Location of Wells
- 4-1. Flow Diagram of Binary Cooling Tower[®]
- 4-2. Binary Cooling Tower[®] System Proposed for Raft River
- 4-3. Binary Cooling Tower[®] Module Detail
- 4-4. Flow Diagram of Evaporative Condenser Cooling System
- 4-5. Configuration of a B.A.C. Evaporative Condenser Unit
- 4-6. Flow Diagram of Combin-aire[®] Cooling System
- 4-7. Configuration of Combin-aire[®] Cooling System
- 4-8. Flow Diagram of the Deluge Augmented/Dry Tower Cooling System
- 4-9. Deluge Augmented/Dry Tower Cooling Tower Configuration
- 4-10. Trane Plate Fin Heat Exchanger Design
- 5-1. Binary Cooling Tower[®] Water Treatment Flow Diagram
- 5-2. Evaporative Condenser Water Treatment Flow Diagram
- 5-3. Combin-aire[®] Water Treatment Flow Diagram
- 5-4. Deluge Augmented/Dry Tower Water Treatment Flow Diagram

TABLES

- 2-1. Raft River Design Point
- 3-1. Meteorological Data for Raft River Geothermal Site, Taken from Wet and Dry Bulb Temperature Distributions for Pocatello, Idaho During 1959
- 3-2. Raft River Geothermal Fluid Composition
- 3-3. Raft River Geothermal Fluid Composition
- 3-4. Raft River Geothermal Fluid Suspended Particles
- 4-1. Binary Cooling Tower[®] Configuration at the Design Point for the Raft River Reference Plant
- 4-2. Evaporative Condenser Configuration at the Design Point for the Raft River Reference Plant
- 4-3. Combin-aire[®] Configuration at the Design Point for the Raft River Reference Plant
- 4-4. Combin-aire[®] Heat Exchanger Parameters
- 4-5. Combin-aire[®] Fan Specifications
- 4-6. Deluge Augmented/Dry Tower Cooling System Configuration at the Design Point for the Raft River Reference Plant
- 5-1. Bases for Closed Recirculating System Water Treatment
- 5-2. Bases for the BCT[®] Evaporative System Water Treatment
- 5-3. Cooling System Evaporative Pond Requirements
- 7-1. Results of the Capital Cost Estimates for the Cooling Systems for the Raft River Site (\$ thousands, 1981)
- 7-2. Breakdown of the Capital Costs of the Cooling Systems (\$ thousands, 1981)
- 7-3. Breakdown of the Annual Operating Costs of the Cooling Systems (\$ thousands/year, 1981)
- 7-4. Summary of Comparative Capital Costs of the Cooling Systems for the Raft River 5 MWe Plant (\$ thousands, 1981)
- 7-5. Summary of the Levelized Energy Costs of the Cooling Systems for the Raft River 5 MWe Plant (mills/kWh, 1981)
- 8-1. Comparison of the Cost of the Cooling Systems at the Design Point

ECONOMIC EVALUATION OF FOUR TYPES OF DRY/WET COOLING
APPLIED TO THE 5 MWe RAFT RIVER GEOTHERMAL POWER PLANT

1.0 INTRODUCTION

Geothermal power cycles produce three to four times more reject heat per unit of power output than do fossil- or nuclear-fired power plants. This is the result of the lower thermodynamic efficiency obtained from the low temperature geothermal heat source. The resulting water requirements for evaporative cooling of geothermal plants are three to four times greater than those of fossil or nuclear plants. Use of wet/dry cooling and dry cooling can appreciably reduce the geothermal plant cooling water requirements.

Most geothermal power sites are located in areas of light precipitation where the existing surface and ground water supplies are almost totally allocated (Robertson 1981). In some areas cooled geothermal fluid may be the only water source available for use in plant cooling systems; therefore, the economics of geothermal fluid for geothermal power plant heat rejection is of interest.

This report describes a cost study which compared the economics of four dry/wet cooling systems currently available for geothermal plant cooling. These systems are:

Tower Systems, Inc. - Binary Cooling Tower®

Baltimore Aircoil Company, Inc. - Evaporative Condenser

Hudson Products Corp. - Combin-aire®

Deluge Augmented/Dry Tower - metal fin-tube dry tower with deluge augmentation.

All of the systems are capable of using cooled geothermal fluid instead of water from other sources in the cooling system evaporative heat transfer loop. All comparisons were performed on the basis of a common plant site - the Raft River 5 MWe geothermal plant located in southern Idaho. Two of the cooling system designs were done assuming the use of the existing plant surface condenser.

2.0 BASES FOR COMPARISON

The criteria used to compare the four dry/wet cooling systems are described in detail in this section. Performance requirements on which the conceptual designs were based are also specified.

2.1 GENERAL CRITERIA FOR COMPARISONS

The economics of constructing and operating the four plant cooling systems were compared on the bases of comparable capital cost and levelized energy cost. The comparable capital cost is defined as the sum of the estimated capital cost of the cooling tower installation plus the capitalized operating cost. The method used to capitalize the annual operating costs is described in Section 7.3. The levelized energy cost indicates the incremental cost of operating the cooling system as applied to the power produced over the life of the plant.

Capital costs included the engineering, construction and material costs associated with the cooling tower, water treatment equipment and related pumps and piping. The contractor's profit and overhead were also included in the construction costs. Operating costs included the costs of auxiliary power for pumps and fans and for water treatment.

The estimates were prepared from cooling system design descriptions furnished by the vendors. All design descriptions utilized a common reference plant location, the Raft River 5 MWe geothermal plant in southern Idaho. This plant, described in Section 3.0 of this report, was selected as the reference plant for this study because the geothermal resources at the site are currently being developed. As a result, adequate data were available on which to base the designs of the four cooling systems. Also future replacement of the existing Raft River plant cooling system may be required due to the corrosiveness of the cooled geothermal evaporative coolant.

The costs of each of the dry/wet systems were estimated using the same procedures. One should recognize that this cost comparison study is of

scoping nature and is strictly applicable only to the reference plant design conditions. Other sites would have different conditions which could offset the resulting comparison.

Further details regarding the conceptual design bases are described in the following section.

2.2 CONCEPTUAL DESIGN BASES

The conceptual designs of the four cooling systems were based on performance requirements provided by Idaho National Engineering Laboratory, operators of the Raft River site. These requirements are listed in Table 2-1. The meteorological profile for the site is given in Section 3.1. The profile was used to determine water consumption. It was not used to optimize plant operating cycles or strategies, hence the existing plant cycle was assumed.

TABLE 2-1. Raft River Design Point

Condenser Heat Rate	34,388 Btu/sec
Hot Water Temperature	96°F
Cold Water Temperature	80°F
Dry Bulb Temperature	85°F
Wet Bulb Temperature	60°F
Circulating Water Flow Rate	2150 lbm/sec
Raft River Site Elevation	4870 ft

Cooled geothermal fluid is used for all plant recirculating water. The analysis of the geothermal fluid is given in Section 3.3. Water treatment for the closed loop recirculating system included demineralization, vacuum deaeration, corrosion inhibition and pH control. Water treatment for the open loop systems included side stream softening, scale inhibition and biofouling control. Treatment of the deluge water was similar to the open loop water treatment. A zero-hardness rinse of the heat exchanger following the deluge shutdown was specified.

3.0 REFERENCE PLANT DESCRIPTION

The Raft River geothermal power plant, used as the reference plant for this study, is described in this section. Site-specific parameters of meteorology and water composition which influence this study are included.

3.1 LOCATION AND METEOROLOGY

The Raft River geothermal site is located in the Raft River Valley of south-central Idaho. The test site is operated by the Idaho National Engineering Laboratory (INEL) for the U.S. Department of Energy.

The first plant under development at the site is a 5-MWe binary cycle plant with a dual-boiling isobutane cycle. Plans for additional site development include a second 5-MWe plant and a 50-MWe plant. A map of Idaho indicating the Raft River geothermal site and the location of the geothermal wells is shown in Figure 3.1 (Whitbeck 1978).

FIGURE 3-1. Raft River Geothermal Site and Location of Wells (Whitbeck 1978)

The Raft River meteorological profile described in Table 3-1 is modeled after that of nearby Pocatello, Idaho. The site elevation is 4870 ft, with an average barometric pressure of 0.841 atm. The annual water evaporation rate is 47.56 in/yr (Climatological Data).

3.2 DESCRIPTION OF THE REFERENCE UNIT

The Raft River 5-MWe geothermal pilot plant is the reference unit for this study. The following information was obtained from EG&G Idaho, Inc., operators of INEL. The pilot unit is rated at 5-MWe gross at an ambient wet bulb temperature of 65°F. Up to 7.4 MWe gross can be generated at lower ambient temperatures. A flow diagram of the plant's dual-boiling binary cycle is shown in Figure 3-2. Isobutane is the working fluid. The present cooling system is a cross-flow, mechanical draft, wet cooling tower. Geothermal fluid is used for cooling instead of surface water (Demuth 1979).

3.3 WATER AVAILABILITY AND QUALITY

Insufficient clean surface and near-surface water for plant cooling at the Raft River site dictate that cooled effluent from the geothermal power plant must be used for condenser coolant and cooling tower fluid make-up (Suciu 1980). The geothermal fluid has extremely high silica and chloride concentrations. Analyses of geothermal fluid samples obtained from site wells 1, 2 and 5 are presented in Tables 3-2, 3-3 and 3-4.⁽²⁾ Twenty five hundred acre-ft (2500 acre-ft) of cooled geothermal fluid is available annually for plant cooling.

(2) Measurements made by Cecil Kindle, Battelle, Pacific Northwest Laboratory, Richland, WA, March 17-21, 1980.

State Point	Temp. (°F)	Flow Rate lbm/hr
1	105	9.34×10^5
2	180	6.13×10^5
3	240	6.13×10^5
4	240	6.13×10^5
5	130	6.13×10^5
6	128	9.34×10^5
7	101	9.34×10^5
8	180	3.21×10^5
9	180	3.21×10^5
10	123	3.21×10^5
11	290	1.04×10^6
12	250	1.04×10^6
13	222	1.04×10^6
14	190	1.04×10^6
15	144	1.04×10^6
16	96	7.74×10^6
17	80	7.74×10^6

Gross Power = 5 MWe

Brine Inlet Temp. = 290°F

Boiler #1 Pressure = 381.57 psia

Boiler #2 Pressure = 203.04 psia

FIGURE 3-2. Raft River Binary Cycle, Dual Boiling Geothermal Power Plant Nominal Design (Ingvarsson 1976)

TABLE 3-1. Meteorological Data for Raft River Geothermal Site, Taken from Wet and Dry Bulb Temperature Distributions for Pocatello, Idaho During 1959

Meteorological Interval	Corresponding		Dry Bulb Range °F	Fraction of Year
	Dry Bulb °F	Wet Bulb °F		
1	99	68	98-100	0.0009
2	96	66	95-97	0.0035
3	93	63	92-94	0.0086
4	90	62	89-92	0.0126
5	87	60	85-88	0.0223
6	82	58	80-84	0.0259
7	77	56	75-79	0.0401
8	72	54	70-74	0.0458
9	67	52	65-69	0.0548
10	62	49	60-64	0.0618
11	57	46	55-59	0.0736
12	52	43	50-54	0.0789
13	47	40	45-49	0.0868
14	42	37	40-44	0.1050
15	37	34	35-39	0.1154
16	33	32	low-34	0.2640

TABLE 3-2. Raft River Geothermal Fluid Composition

Units: mg/l (~ ppm) except where indicated

1. pH	6.9 - 7.5
2. Lab Analysis	
Conductivity (μ mho)	1840 - 2760
Total dissolved solids (IDS)	1071 - 1780
Suspended solids	3 - 5
Turbidity (FTU)	< 5
Hardness as CaCO_3	70 - 120
Alkalinity as HCO_3	50.6 - 61.4
CaCO_3 (Calc.-spec. results)	63 - 120
H_2S	0.45 - 0.65
$\text{SO}_4^{=}$	50 - 63
F^-	6.9 - 11
NO_3^-	< 1
$\text{PO}_4^{\equiv}$	< 1
Cl^-	490 - 776
SiO_2	140 - 155
3. Field Analysis	
O_2	0 - 0.10
NH_3	0 - 0.2
H_2S	0.1 - 0.2

TABLE 3-3. Raft River Geothermal Fluid Composition

Units: mg/l (~ ppm)

Methodology: Plasma Spectrometer

Element and Detection Limit

Al (.1)	<
As (.2)	<
B (.01)	0.12 - 0.18
Ba (.01)	0.03 - 0.21
Ca (.1)	25.1 - 48.3
Fe (.1)	< - 0.2
K (25)	50 - 75
Li (.05)	0.72 - 1.38
Mg (.05)	< - 0.09
Na (5)	305 - 463
P (.5)	<
Sr (.01)	0.68 - 1.16
Ag (.04)	<
Cd (.01)	<
Co (.01)	<
Cr (.01)	<
Cu (.01)	<
Mn (.01)	0.02 - 0.05
Mo (.1)	<
Ni (.08)	<
Pb (.1)	<
Sb (.05)	<
Se (.1)	<
Sn (.1)	<
Th (.1)	<
Ti (.05)	<
Tl (.1)	<
U (.05)	<
Zn (.05)	<
Zr (.05)	<
Hg* (2 x 10 ⁻⁶)	28 - 71 x 10 ⁻⁶

* Cold vapor atomic absorption

< Means below Specified Detection Limit

TABLE 3-4. Raft River Geothermal Fluid
Suspended Particles

Units: Concentration ratios (μg) except where indicated

<u>Suspended Solids</u>	
Al	13 - 15
Si	6 - 13
S	BDL
Ca	0.1 - 1
Cr	0.6 - 2
Mn	0.1 - 0.3
Fe	4 - 6
Ni	0.2 - 0.7
Cu	0.04 - 0.07
Zn	0.02 - 0.1
Pb	0.1 - 0.3
As	BDL
mg solids/l flow	0.04 - 0.08
Sample Mass (mg)	0.4

BDL: Undetectable

4.0 DESCRIPTION OF THE DRY/WET COOLING TOWER CONCEPTS

Details of the four dry/wet cooling tower systems are presented in this section. Design and site parameters are described and component specifications are noted.

4.1 TOWER SYSTEMS, INC. - BINARY COOLING TOWER[®] SYSTEM

Tower Systems, Inc. (TSI) has developed an advanced cooling tower system that can use low quality brackish water for plant cooling. The tower produces much less blowdown than a conventional wet cooling system. In the Binary Cooling Tower[®] (BCT)[®] the condenser (primary) cooling water flows through a plastic heat exchanger where it transfers heat to a secondary coolant. The secondary coolant, is simultaneously cooled by evaporation with air. Since there is no direct contact between the primary and secondary coolants, brackish or waste water can be used in the secondary loop. The BCT[®] is capable of handling secondary coolant total dissolved solids (TDS) concentrations up to 150,000 mg/l (Sanderson 1981). Since the Raft River geothermal fluid contains 1780 mg/l TDS 80 or more cycles of concentration can be achieved.

4.1.1 GENERAL DESCRIPTION

A flow diagram of the Binary Cooling Tower[®] Cooling System is shown in Figure 4-1. In the BCT[®] the primary cooling water takes heat from the isobutane working fluid in the surface condenser. The warm water flows through alternate channels in the BCT[®]. Heat is transferred through thin channel walls to the secondary cooling water which flows parallel to the primary coolant. The secondary coolant is evaporated by cross flow air through the secondary coolant channels. The BCT[®] is designed to operate as a completely dry system during the cooler periods of the year. When the ambient temperatures are sufficiently high, secondary coolant flows through alternate channels in the BCT[®] to increase cooling capacity.

FIGURE 4-1. Flow Diagram of Binary Cooling Tower[®] System

4.1.1.1 BCT[®] Design Parameters

A sketch of the BCT[®] cooling tower proposed for Raft River is shown in Figure 4-2. The cooling tower consists of two 20-module cells. Details of the modules and the isolation between the primary and secondary coolant are shown in Figure 4-3. High quality recirculated water and cooled geothermal fluid are the respective primary and secondary coolants. There are 69 heat transfer panels per module.

Each cell can be operated all-dry, all-wet, or fractions thereof. With wet/dry operation the secondary coolant pumps are shut down in stages to allow the appropriate number of modules to operate dry. In the wet/dry mode the hot water temperature remains nearly constant at the design value, which allows the turbine to operate at the design efficiency. With totally wet operation the hot water temperature rises when the ambient weather conditions are above the design dry bulb and wet bulb temperatures.

The air flow through each cell is mechanically induced by a 30-ft diameter fan mounted at the top of the tower structure. Table 4-1 provides a summary of the tower design parameters.

TABLE 4-1. Binary Cooling Tower[®] Configuration at the Design Point for the Raft River Reference Plant

Model	40
Number of Cells	2
Number of Modules/Cell	20
Number of Heat Transfer Panels/Module (2 surfaces each)	69
Number of Fans	2
Fan Diameter (ft)	30
Air Flow/Cell (cfs)	23,740
Brine Recirculation Rate (gpm)	22,900
Tower Size (Plan)(ft x ft)	57 x 120
Performance (Btu/sec)	34,388

PRELIMINARY PLAN & ELEVATION

CASE I
MODEL 40

TSI NO. 9833
DATE 8/6/81
CLIENT Battelle, N.W.
INSTALLATION Raft River

FIGURE 4-2. Binary Cooling Tower® Configuration Proposed for Raft River

FIGURE 4-3. Binary Cooling Tower[®] Module Detail

4.2 BALTIMORE AIRCOIL COMPANY, INC.

Baltimore Aircoil Company, Inc. (B.A.C.) is developing a proprietary corrosion-resistant coating system to enable metal structures to be resistant to geothermal brine allowing specification of off-the-shelf equipment for operation in low quality, waste or brackish water environments. The effectiveness of this coating has not yet been demonstrated. For the Raft River plant B.A.C. specified an Evaporative Condenser system to condense the iso-butane working fluid without the use of an intermediate heat exchange fluid. Successful demonstration of the protective coating of the Evaporative Condenser surfaces to be exposed to geothermal fluid was assumed for this study.

4.2.1 GENERAL DESCRIPTION

A flow diagram of the B.A.C. Evaporative Condenser system is shown in Figure 4-4.

The B.A.C. Evaporative Condenser system omits one step of heat transfer by eliminating the primary coolant loop of high quality

FIGURE 4-4. Flow Diagram of Evaporative Condenser Cooling System

recirculating water used in the BCT[®] system. The turbine working fluid, isobutane vapor, is circulated directly through an air-cooled condensing coil. A recirculating spray of cooled geothermal fluid is used to continually wet the outside of the coil. Air flow across the coil causes the spray to evaporate. This evaporation removes heat from the coil, condensing the isobutane.

4.2.1.1 Evaporative Condenser Design Parameters

Six Evaporative Condenser units are required to condense the isobutane working fluid of the Raft River geothermal plant. One of these units is shown in Figure 4-5. Table 4-2 provides a summary of the Evaporative Condenser system design.

TABLE 4-2. Evaporative Condenser Configuration at the Design Point for the Raft River Reference Plant

Model Number	VXC-1360
Number of Units	6
Air Flow/Unit (cfm)	220,400
Fans/Unit	4
Fan Motor (hp)	30
Pumps/Unit	2
Pump Motor (hp)	5
Spray Water	Geothermal Fluid
Geothermal Fluid Flow Rate/Unit (gpm)	1480
Approximate Operating Weight/Unit (lbm)	65,000
Unit Size (Plan)(ft x ft)	10 x 36
Performance (Btu/sec)	34,388

4.3 HUDSON PRODUCTS CORPORATION - COMBIN-AIRE[®] COOLING TOWER SYSTEM

The Combin-aire[®] cooling tower developed by Hudson Products Corp. combines an air-cooled heat exchanger with a separate water-spray air-precooler. Because there is no direct contact between the water spray and the heat exchanger, brackish or salt water may be used to humidify

FIGURE 4-5. Configuration of a B.A.C. Evaporative Condenser Unit

the inlet air. The salts and minerals present in the water spray remain in solution as the water evaporates and concentrate in the cooling tower basin.

4.3.1 GENERAL DESCRIPTION

A flow diagram of the Combin-aire[®] cooling system is shown in Figure 4-6. Below the design wet bulb temperature the Combin-aire[®] is operated as a dry cooling system. The primary cooling water, high quality recirculated water, takes heat from the isobutane working fluid in the surface condenser. Then the warm water flows through the tower heat exchangers. Air flow through the heat exchangers transfers heat to the atmosphere.

Above the design wet bulb temperature secondary coolant, cooled geothermal fluid, is sprayed through the air as it enters the tower. Some water evaporates, cooling and humidifying the air stream. Salts and minerals that remain concentrate in the secondary coolant. Mist eliminators upstream from the heat exchangers remove water droplets and particles entrained in the air. The cooled, humidified air flows through the heat exchanger and removes heat from the finned tubes.

4.3.1.1 Combin-aire[®] Design Parameters

A sketch of the proposed cooling tower is shown in Figure 4-7. The air flow through both the humidification and heat exchange portions of the tower is controlled by 38 fans positioned in two rows along the top of the tower. The secondary coolant flow is controlled to provide only the amount of air humidification required for heat transfer. A summary of the tower design parameters is provided in Table 4-3.

The cooling tower consists of 38 heat transfer sections, two heat exchangers in series followed by 19 units in parallel, positioned horizontally beneath the fans. Heat exchanger specifications are provided in Table 4-4.

Specifications for the induced draft fans are provided in Table 4-5.

FIGURE 4-6. Flow Diagram of Combin-aire® Cooling System

FIGURE 4-7. Configuration of Combin-aire® Cooling System

TABLE 4-3. Combin-aire® Configuration at the Design Point for the Raft River Reference Plant

Model	19.0-326
Number of Units in parallel	19
Number of Sections in series per unit	2
Total Air Flow (scfm)	5,567,760
Cooling Water Flow Rate (lbm/hr)	7,740,000
Heat Exchanger Surface Area (ft ²)	1,781,733
Overall Heat Transfer Coefficient (Btu/hr·ft ² ·°F)	5.39
Number of Passes	3
Tower Size (Plan)(ft x ft)	55 x 366
Performance (Btu/sec)	34,388

TABLE 4-4. Combin-aire® Heat Exchanger Parameters

Fin Design	Extruded
Fin Material	Aluminum
Tube Material	Carbon Steel
Tube OD (in.)	1.00
Tube ID (in.)	0.83
Fins/in.	10
Fin OD (in.)	2.25
Width of One Section (ft)	9.5
Length of One Section (ft)	32
Number of Rows/Section	6
Number of Passes/Section	3
Face Velocity (sfm)	495
Bare Tube Surface Area (ft ²)	84,044
Bare Tube Heat Transfer Coefficient - Service (Btu/hr·ft ² ·°F)	114.3

TABLE 4-5. Combin-aire[®] Fan Specifications

Fan Diameter (ft)	13
Blade Material	Tuf-Lite [®] Plastic
Number of Blades	5
Blade Angle (degrees)	11.5
Fan Speed (rpm)	1160
Flow Rate/Fan (acfm)	180,121
hp/Fan	40
Total Number of Fans	38
Blades	Manually Adjusted
Drive	Gear

4.4 DELUGE AUGMENTED/DRY TOWER COOLING SYSTEM

In the Deluge Augmented/Dry Tower cooling system the isobutane working fluid is condensed in the cooling tower. Deluge augmentation of the cooling tower air-cooled heat exchanger will provide additional evaporative heat transfer at ambient temperatures above the air-cooled heat exchanger design temperature.

4.4.1 GENERAL DESCRIPTION

A flow diagram of the Deluge Augmented/Dry Tower cooling system is shown in Figure 4-8.

The cooling tower is designed to operate as a completely air-cooled system during cooler portions of the year. Above the dry heat exchanger design temperature a portion of the heat exchanger finned tube surface is deluged with water to increase heat rejection capability. Sensible heating of the air passing through the heat exchanger is augmented by heat transfer to the air by evaporation of the deluge water.

FIGURE 4-8. Flow Diagram of the Deluge Augmented/Dry Tower Cooling System

4.4.1.1 Deluge Augmented/Dry Tower Cooling System Design Parameters

The design for the Deluge Augmented/Dry Tower cooling system at the Raft River site is modeled after the Advanced Concept Test Facility in Bakersfield, CA funded by the Electric Power Research Institute (EPRI) (Johnson 1981). A sketch of the proposed cooling tower configuration is shown in Figure 4-9. A summary of the tower design parameters is presented in Table 4-6.

When ambient temperatures exceed 55°F, the tower capacity will be water augmented by deluging. During deluge augmentation the fins of the heat exchanger sections will be covered with a continuous film of treated geothermal fluid. During conversion from wet to dry operation the heat transfer surfaces will be rinsed with zero-hardness water to inhibit mineral deposition on the heat exchanger surfaces.

The heat exchangers are all-aluminum plate fin units manufactured by The Trane Company. To allow deluging the plates are oriented vertically with tubes running horizontally. The plate fins are stamped in a sinusoidal contour to produce a turbulent boundary layer and to increase the heat transfer rate. The plate fin design is shown in Figure 4-10.

Two heat exchanger bundles will be joined at an angle of 50° to form an A-frame or "delta" configuration. The deluge water distribution assembly is at the apex of the delta. The deluge water is collected in a trough at the base of each bundle.

The tower contains two rows of seven delta assemblies positioned side by side at right angles to the tower sides. Air flow through the tower is controlled by eight 16-ft diameter fans positioned in two rows along the top of the tower.

FIGURE 4-9. Deluge Augmented/Dry Tower Cooling Tower Configuration

TABLE 4-6. Deluge Augmented/Dry Tower Cooling System Configuration
at the Design Point for the Raft River Reference Plant

Cooling Tower

Type	Mechanical Draft
Performance (Btu/sec)	34,388
Design Inlet Air Temperature/Dry (°F)	55
Design Deluge Inlet Air Conditions	
Dry Bulb (°F)	85
Wet Bulb (°F)	60

Heat Exchangers

Manufacturer	Trane
Type	Wet/Dry
Number of Bundles	28
Bundle Height (in.)	8.08
Bundle Length (in.)	33
Bundle Depth (in.)	0.916
Tube Orientation	Horizontal
Tube Length (ft)	31
Airside Fins Thickness/Pitch (in.)	0.0085/0.1
Tube Material	7072 Al
Airside Fin Area/Bundle (ft ²)	19,147
Total Airside Area/Bundle (ft ²)	20,024
h Airside (Btu/hr·ft ² ·°F)	10.3
U Based on Airside Area, Dry, Clean (Btu/hr·ft ² ·°F)	7.47
U Service, Dry (Btu/hr·ft ² ·°F)	6.10
Deluge Flow Rate, Total (gpm)	1,350
Deluge Temperature (°F)	85
Deluge Consumption (lb/hr)	76,000
U Service, Wet (Btu/hr·ft ² ·°F)	1.68

Fans

Number	8
Diameter (ft)	16
Blades/Fan	6
hp/Fan	50

FIGURE 4-10. Trane Plate Fin Heat Exchanger Design

5.0 COOLING WATER TREATMENT AND DISPOSAL

In this section the types of water treatment required for the four dry/wet cooling systems are discussed. The cooling systems use treated, cooled, geothermal fluid to supply all cooling water needs. System blowdown is contained in an evaporative pond.

In each system the water must be treated to prevent corrosion, scaling and/or fouling. The Binary Cooling Tower[®] and the Combin-aire[®] each use a closed recirculating loop to carry the cooling water from the condenser to the dry cooling tower. The water in this loop must be treated to lower the dissolved solids content, then deaerated and inhibited to prevent corrosion of the condenser, tower heat exchanger and piping.

Open recirculating evaporative loops are used in the Binary Cooling Tower[®], Evaporative Condenser and Combin-aire[®] systems. The water treatment is similar to that of a conventional cooling tower: side-stream treatment plus inhibition and chlorination for scaling and biofouling control. The high chloride concentration of the geothermal fluid will inhibit biofouling.

The delugeate loop in the Deluge Augmented/Dry Tower Cooling system requires an additional rinse of especially clean water to eliminate solids build up resulting because the delugeate is periodically turned off and allowed to evaporate on the heat exchanger fin surfaces.

5.1 TOWER SYSTEMS, INC. - BINARY COOLING TOWER[®] SYSTEM

The T.S.I. Binary Cooling Tower[®] uses a closed recirculating loop to carry the cooling water from the condenser to the cooling tower. This is followed by an open evaporative recirculating loop. Concentrations of 120,000 ppm total dissolved solids (TDS) are permitted in the open recirculating loop. A process flow diagram is presented in Figure 5-1.

FIGURE 5-1. Binary Cooling Tower[®] Water Treatment Flow Diagram

5.1.1 CLOSED RECIRCULATING SYSTEM

The water circulating from the condenser to the cooling tower must be treated, deaerated and inhibited to prevent corrosion of the condenser and piping. Assumptions for the bases of the water treatment are listed in Table 5-1 (Pratt 1976).

The water will be treated in a demineralization unit sized at 3000 gallons/day. The initial system fill time is 1 month. Treated makeup water will be supplied at 3 gpm.

Vacuum deaeration can be used to reduce the oxygen content of the makeup water (Ard 1976).

To prevent corrosion an inhibitor containing 85% sodium nitrite (NaNO_2) and 15% sodium metasilicate (NaSiO_3) is recommended. The circulating water pH should be controlled between 7.5 and 9.0 (Betz 1980).

TABLE 5-1. Bases for Closed Recirculating System Water Treatment

Condenser Material	Admiralty	
Piping	Carbon Steel	
System Volume (gal)	1.0×10^5	
Flow Rate (gpm)	1.5×10^4	
Water Quality	<u>Makeup</u>	<u>Recirculating</u>
pH	6.9-7.5	6.5-7.5
Total Hardness (mg/l)	70-120	20-40
Alkalinity (mg/l)	51-62	10-25
Total Dissolved Solids (mg/l)	1071-1780	50-100
Iron (mg/l)	0.2	< 0.1
Silica	140-155	2

5.1.2 OPEN EVAPORATIVE RECIRCULATING SYSTEM

The evaporative loop of the Binary Cooling Tower[®] can handle concentrations of 120,000 mg/l of total dissolved solids because the loop heat transfer and evaporative surfaces are made of plastic. Assumptions for the bases of the water treatment are listed in Table 5-2.

TSI recommends addition of sodium hydroxide (NaOH) and magnesium chloride (MgCl_2) to precipitate the silicon dioxide (SiO_2) and to convert the bicarbonate (HCO_3) to carbonate (CO_3). Magnesium chloride addition is acceptable because chloride ion accumulation does not cause corrosion in nonmetallic systems. The high chloride concentration inhibits biofouling.

The recirculating water pH is controlled by sulfuric acid (H_2SO_4) addition.

TABLE 5-2. Bases for the BCT[®] Evaporative System Water Treatment

<u>Water Quality</u>	<u>Makeup</u>	<u>Blowdown</u>
Ca^{++} (mg/l)	48	450
Mg^{++} (mg/l)	0.09	2,000
Na^+ (mg/l)	463	40,000
K^+ (mg/l)	75	4,000
HCO_3^- (mg/l)	61	100
SO_4^{--} (mg/l)	63	11,000
Cl^- (mg/l)	776	60,000
SiO_2 (mg/l)	155	200
TDS (mg/l)	1780	120,000

5.2 BALTIMORE AIRCOIL COMPANY, INC. EVAPORATIVE CONDENSER

In the B.A.C. Evaporative Condenser system the isobutane working fluid flows directly to the cooling system in a closed recirculation loop. This is followed by an open evaporative recirculation loop. B.A.C. advised that 3 to 20 cycles of concentration are permitted in the evaporative loop depending on the degree of water treatment. A process flow diagram is presented in Figure 5-2.

FIGURE 5-2. Evaporative Condenser Water Treatment Flow Diagram

5.2.1 OPEN RECIRCULATING SYSTEM

Water in the open recirculating system must be treated to inhibit scale and control biofouling. Addition of alum, soda ash and lime to a side stream followed by addition of sulfuric acid to control the pH can effectively inhibit scale formation at low cycles of concentration. Addition of phosphonate to inhibit the crystallization of calcium carbonate from saturated solutions and polyacrylate to limit crystal growth and scale formation will allow operation at higher cycles of concentration (Betz 1980). The B.A.C. corrosion protection system used to coat metal surfaces is expected to inhibit corrosion at up to ten cycles of concentration.

Quaternary ammonium salts are added to control biofouling (Betz 1980 and Ard 1976).

5.3 HUDSON PRODUCTS CORP. COMBIN-AIRE[®] COOLING TOWER SYSTEM

The Hudson Products Corp. Combin-aire[®] uses a closed recirculating loop to transport the cooling water from the condenser to the cooling tower. This is followed by an open evaporative recirculating loop. Five to 10 cycles of concentration are permitted in the evaporative loop depending on the degree of water treatment. A process flow diagram is presented in Figure 5-3.

5.3.1 CLOSED RECIRCULATING SYSTEM

This system is identical to the system discussed in Section 5.1.1.

5.3.2 OPEN RECIRCULATING SYSTEM

This system is identical to the system discussed in Section 5.2.1. The air is humidified in the evaporative, recirculating loop of the Combin-aire[®]. Treated redwood and concrete construction is used in the humidification section to minimize corrosion.

5.4 DELUGE AUGMENTED/DRY TOWER COOLING SYSTEM

The delugeate loop in the Deluge Augmented/Dry Tower cooling system is similar to an open evaporative system. The delugeate loop supplies

FIGURE 5-3. Combin-aire® Water Treatment Flow Diagram

FIGURE 5-4. Deluge Augmented/Dry Tower Water Treatment Flow Diagram

water for deluging the finned heat exchanger surfaces during warm periods of the year. In addition a supply of zero-hardness water is required to flush the fin surfaces each time the delugeate flow is turned off (approximately once per day)(Ard 1976). The zero-hardness water is allowed to evaporate on the heat exchanger fin surfaces. A process flow diagram of the water treatment is shown in Figure 5-4.

5.4.1 DELUGEATE LOOP-OPEN RECIRCULATING SYSTEM

Water treatment for the delugeate loop is similar to the treatment for the open recirculating system discussed in Section 5.2.1. Alum, soda ash and lime are added to a side stream followed by addition of sulfuric acid to control pH to inhibit scale formation. Polyphosphate inhibitor may be added for additional scale control. The alternate wetting and drying cycles should control biofouling.

5.4.2 ZERO-HARDNESS RINSE WATER

A sodium-zeolite water treatment system will produce the zero-hardness rinse water used to flush the heat exchanger fin surfaces prior to deluge shutoff. The sodium-zeolite unit is capable of producing water of less than 5 ppm calcium (as CaCO_3) at the rate of 36 gpm.

5.5 EVAPORATIVE POND

The blowdown from the cooling and water treatment systems will be stored at the Raft River site in an evaporative pond. The pond acreage necessary to contain the annual system blowdown is listed in Table 5-3.

TABLE 5-3. Cooling System Evaporative Pond Requirements

Cooling System	Cycles-of-Concentration	Blowdown (gal/yr)	Pond Size (acres)	Wet Operation (fraction of year)
Binary Cooling Tower®	10 67*	6.50×10^6 1.03×10^6	5.0 0.8	0.49
Evaporative Condenser	3 6 10* 20	56.4×10^6 22.6×10^6 12.5×10^6 5.9×10^6	44 18 9.7 4.6	1.0
Combin-aire®	5* 10	5.39×10^6 2.40×10^6	4.2 1.9	0.22
Deluge Augmented/Ammonia	5* 10	5.61×10^6 2.49×10^6	4.3 1.9	0.35

* Design Point

6.0 BASES FOR COST ESTIMATES

The cost estimates for the cooling system construction and annual operation were based on information from a variety of sources that are documented in this section.

6.1 CONSTRUCTION COSTS

Construction costs for the cooling systems described in Sections 4.0 and 5.0 were estimated from conceptual designs prepared from system descriptions. Tower Systems, Inc.; Baltimore Aircoil Company, Inc.; and Hudson Products Corp. provided design, performance and cost information for their cooling systems. The design for the Deluge Augmented/Dry Tower system was modeled after the Advanced Concept Test Facility (Johnson 1981).

Estimates of the cost of the cooling system components were made using the design information and specifications obtained from the cooling system suppliers. The line item listings were extended to include system components that were not listed by some suppliers so that each system contained the same essential elements. The costs were compared with estimates received from the suppliers and discrepancies were rectified.

The suppliers provided the following information. TSI estimated the cost of the Binary Cooling Tower[®], basin, construction, water treatment system, and evaporative pond as well as the annual power requirements and water treatment chemical requirements and costs. B.A.C. estimated the cost of the Evaporative Condenser with corrosion protection and specified annual power requirements. Hudson Products Corp. estimated the cost of the Combin-aire[®] and specified annual power requirements.

The report, Cost and Cost Algorithms for Dry Cooling Tower Systems (Ard 1976), was used extensively to estimate the cost of the system components. Betz Laboratories provided water treatment information. Evaporative pond construction costs ranged from \$60,000 to \$100,000 per acre (EPRI 1981, Faletti 1981).

General contractors overhead was assumed to be 10% of labor costs. Profit was assumed to be 10% of labor and equipment costs. Shipping and installation costs ranged from 12 to 15% of the component costs, depending on the component (Ard 1976).

Marshall and Stevens Engineering Cost Index was used to convert all costs to 1981 dollars.

6.2 ANNUAL OPERATING COSTS

Operating costs for the cooling systems analyzed in this report include costs for recirculating system pumping, fan power, deluge water pumping and water treatment. Normal maintenance costs were assumed to be approximately the same for all concepts and were not included in the operating cost estimate.

Data used to define the operating costs are listed below:

- Year of pricing: 1981
- Plant size: 5 MWe
- Capacity factor: 0.80
- Cost of power consumed by auxiliary equipment: 36.0 mill/kWh
(Zaloudek 1976)
- Expected plant operation: 30 years
- Interest rate: 8%
- Inflation rate: 8%

Cooled geothermal fluid was assumed to be the only source of plant cooling water. The water treatment for the cooling system was assumed to be totally separate from any other plant water requirements. Analysis of the geothermal fluid was presented in Section 3.3.

The annual operating costs were capitalized to facilitate comparison of the costs of the four cooling systems. The operating costs were assumed to increase annually by a fixed rate over the life of the plant. The

present worth (P) of the plant operating costs was determined by using the sum of the uniform series present worth factor (P') and the gradient present worth factor (P'').

$$P = P' + P''$$

$$P = A(P/A, i\%, n) + G(P/G, i\%, n)$$

where $G = (A)(i\%)$

A = amount

i = interest rate

n = number of years.

7.0 RESULTS

The capital and operating costs for the four cooling systems are presented in this section. Comparative capital costs and levelized energy costs are also determined.

7.1 CAPITAL COSTS OF THE COOLING SYSTEMS

A summary of the estimated capital costs of constructing the four cooling systems for the Raft River 5 MWe plant is provided in Table 7-1. The price range in the total capital cost of each cooling system reflects the variation in system costs with evaporative pond requirements. Sizing of the evaporative ponds is discussed in Section 5.5.

All estimates summarized in Table 7-1 are subject to the validity of the assumptions defined in Sections 2.0 and 6.0. A breakdown of the costs summarized in Table 7-1 is provided in Table 7-2.

TABLE 7-1. Results of the Capital Cost Estimates for the Cooling Systems for the Raft River Site (\$ thousands, 1981)⁽¹⁾

TSI Binary Cooling Tower®	2514 - 2768 ⁽²⁾
B.A.C. Evaporative Condenser	2003 - 4351
Hudson Products Corp. Combin-aire®	6791 - 6930 ⁽²⁾
Deluge Augmented/Dry Tower	3773 - 3917

- (1) Cost variances are due to the assumed ranges of cycles-of-concentration (see Tables 5-3 and 7-2).
(2) Cost analysis assumed use of surface condenser (isobutane/water) currently installed in the Raft River Plant.

7.2 OPERATING COSTS

The annual operating costs for the four cooling systems were estimated using the assumptions and data provided in Section 6.2. The results of these estimates are summarized in Table 7-3.

The costs presented in Table 7-3 include only costs associated with the dry/wet cooling tower operation and water treatment.

TABLE 7-2. Breakdown of the Capital Costs of the Cooling Systems (\$ thousands, 1981)

Item	TSI Binary Cooling Tower®	B.A.C. Evaporative Condenser	Hudson Products Corp. Combin-aire®	Deluge Augmented/Dry Tower
Cooling System Interface with Geothermal Power Plant				
Condenser				
Isobutane/Water	(1)		(1)	
Isobutane/Air		(2)		(2)
Cooling Tower				
Structures	607	218	1548	749
Circulation System				
Closed Loop				
Water	262		489	
Isobutane		441		441
Open Loop				
Water	265	199	225	431
Heat Exchanger Unit				
Water/Air-Water	607		3210	
Isobutane/Air-Water		233		1264
Fans				
Axial	161		524	164
Centrifugal		217		
Louvers	83	20	173	-0-
Electrical System and Instrumentation	182	344	434	62
Water Treatment				
Closed Recirculation Loop	19		19	
Open Recirculation Loop	280	57	57	311
Zero-Hardness Rinse				235
Evaporative Ponds	48 - 302	274 - 2622	112 - 251	116 - 260
TOTAL	2514 - 2768	2003 - 4351	6791 - 6930	3773 - 3917

(1) Cost analysis assumed use of surface condenser (isobutane/water) currently installed at the Raft River Plant.

(2) Isobutane/air-water evaporative condenser cost is included under heading Cooling Tower/Heat Exchanger Unit.

TABLE 7-3. Breakdown of the Annual Operating Costs of the Cooling Systems (\$ thousands/year, 1981)

Item	TSI Binary Cooling Tower®	B.A.C. Evaporative Condenser	Hudson Products Corp. Combin-aire®	Deluge Augmented/ Dry Tower
Fan Power Cost	46.8	135.5	199.5	75.3
Circulation Pump Power Cost				
Closed Loop	150.6	23.5	169.4	23.5
Open Loop	23.6	11.3	16.2	118.5
Water Treatment Cost				
Closed Loop	4.4		4.4	
Open Loop	68.1	68.3	68.6	85.9
Rinse				6.3
TOTAL	293.5	238.6	458.1	309.5

7.3 COMPARATIVE CAPITAL COSTS AND LEVELIZED ENERGY COSTS

To facilitate comparison of the total costs of the dry/wet cooling tower concepts under study, a "comparable capital cost" and "levelized energy cost" were identified for each concept. The comparable capital cost was defined as the sum of the estimated capital cost and the capitalized operating cost. The capitalized annual operating cost was determined by assuming that the estimated annual operating costs increased with inflation during the life of the plant. The levelized energy cost of each cooling system is the system incremental cost per net unit of energy produced during the life of the plant. The capital costs and capitalized operating costs are prorated to an annual cost for the life of the plant.

The comparable capital costs and levelized energy costs of the four cooling systems considered in this report are summarized in Tables 7-4 and 7-5. The range in the cost estimates reflects the variation in system cost with evaporative pond requirements.

TABLE 7-4. Summary of Comparative Capital Costs
of the Cooling Systems for the Raft
River 5 MWe Plant (\$ thousands, 1981)

	<u>Basic Capital Cost Range</u>	<u>Capitalized Operating Cost</u>	<u>Comparable Capital Cost Range</u>
TSI Binary Cooling Tower®	2514 - 2768	5741	8255 - 8509
B.A.C. Evaporative Condenser	2003 - 4351	4667	6670 - 9018
Hudson Products Corp. Combin-aire®	6791 - 6930	8961	15752 - 15891
Deluge Augmented/ Dry Tower	3773 - 3917	6054	9827 - 9971

TABLE 7-5. Summary of the Levelized Energy Costs
of the Cooling Systems for the Raft
River 5 MWe Plant (mills/kWh)

	<u>Levelized Energy Cost Range</u>
TSI Binary Cooling Tower®	4.53 - 4.83
B.A.C. Evaporative Condenser	3.67 - 6.25
Hudson Products Corp. Combin-aire®	11.25 - 11.44
Deluge Augmented/Dry Tower	6.41 - 6.57

8.0 DISCUSSION

Results of the analysis are discussed in this section followed by conclusions and recommendations.

8.1 COMPARISON OF THE COOLING SYSTEM COSTS

The levelized energy costs (Table 7-5) of the Binary Cooling Tower[®], Evaporative Condenser and Deluge Augmented/Dry Tower cooling systems range from 3.67 mills/kWh to 6.57 mills/kWh. The levelized energy cost of the Combin-aire[®] cooling system ranges from 11.25 mills/kWh to 11.44 mills/kWh, twice the energy cost of the other three systems. The large physical size, and number of heat exchangers and fans increase the cost of the Combin-aire[®] relative to the cost of the other systems.

Table 8-1 compares the capital costs and levelized energy costs of each system at the evaporative loop design point.

TABLE 8-1. Comparison of the Cost of the Cooling Systems at the Design Point

	<u>Evaporative Loop Cycles-of- Concentration</u>	<u>Capital Cost (\$, thousands)</u>	<u>Levelized Energy Cost (mills/kWh)</u>
TSI Binary Cooling Tower [®]	67	2514	4.53
B.A.C. Evaporative Condenser	10	2310	4.01
Hudson Products Corp. Combin-aire [®]	5	6930	11.44
Deluge Augmented/ Dry Tower	5	3917	6.57

The Binary Cooling Tower[®] has a low capital cost at acceptable cycles-of-concentration because a relatively small (0.8 acre) evaporative pond is adequate to contain cooling tower blowdown. The Binary Cooling Tower[®] can operate at high total dissolved solids (TDS) concentrations. The Raft

River system was designed to operate at 120,000 ppm TDS; hence, 67 cycles-of-concentration are acceptable. The resulting system cost is roughly \$2500K. If, for comparison purposes, only 10 cycles-of-concentration are permitted, the system cost rises to \$2800K. The capital cost range due to the change in cycles-of-concentration is small because the Binary Cooling Tower[®] Cooling System adjusts the cooling system wet/dry operating ratio to follow the annual temperature profile, and the change in the evaporative pond size is small. At 67 cycles-of-concentration the levelized energy cost of the Binary Cooling Tower[®] system is 4.53 mills/kWh.

The Evaporative Condenser cooling system requires one less piece of equipment than the BCT[®] system since the isobutane is condensed in the cooling tower without the use of an intermediate water loop. Operation of the system at 10 to 20 cycles-of-concentration depends on the corrosion protection of the condenser surfaces in contact with the geothermal fluid. The capital cost of the Evaporative Condenser system ranges from about \$2000K at 20 cycles-of-concentration to \$4400K at 3 cycles-of-concentration. The capital cost range due to the change in cycles-of-concentration is relatively high because 100% wet operation of the evaporative condenser is required and a large variation in evaporative pond size results. At 10 cycles-of-concentration the levelized energy cost of the Evaporative Condenser system is 4.01 mills/kWh.

The Combin-aire[®] cooling system is basically a dry cooling system. Water is used to pre-cool air at temperatures above the design dry bulb temperature. This is not as efficient a method for heat transfer as direct evaporation. Hence the Combin-aire[®] requires a larger cooling tower structure and more heat exchangers and fans are necessary. The system capital cost ranges from \$6800K at 10 cycles-of-concentration to \$6900K at 5 cycles-of-concentration. The capital cost range due to the change in cycles-of-concentration is small because wet operation is required for only a fraction of the year and the variation in evaporative pond size is small. At 5 cycles-of-concentration the levelized energy cost of the Combin-aire[®] is 11.44 mills/kWh.

The Deluge Augmented/Dry Tower cooling system also requires one less piece of equipment since the isobutane is condensed in the cooling tower

without the use of an intermediate water loop. The capital cost of the Deluge Augmented/Dry Tower ranges from \$3500K at 10 cycles-of-concentration to \$3600K at 5 cycles-of-concentration. The capital cost range due to the change in cycles-of-concentration is small because wet operation is required for only a fraction of the year and the variation in evaporative pond size is small. At 5 cycles-of-concentration the levelized energy cost of the Deluge Augmented/Dry Tower is 6.57 mills/kWh.

The annual operating costs of the cooling systems are shown in Table 7-3. The Evaporative Condenser and the Combin-aire® have higher fan power requirements than the other systems because their systems have a large number of small fans. Pumping costs are relatively high for the closed loop of the Binary Cooling Tower® and the Combin-aire® because water is circulated as the heat transport medium. The open loop of the Deluge Augmented/Dry Tower also has a relatively high pumping cost because of the large volume of flow.

The costs of the cooling systems in this report are approximate. For this scoping study it was not possible to quantify all site-related factors which could influence construction costs. Also, the design bases described in Sections 2.0 and 3.0 may not be optimum for a total system design which would include the power plant itself. However the designs and estimates were done with the same bases and similar procedures. It is not anticipated that exhaustive optimization would change the cost ranking of the cooling systems. Therefore it is believed that the results of this study are valid for comparing the cooling systems as used herein.

The four concepts studied in this work were conceptually designed and cost estimates performed on the basis of assumptions identified in Sections 3.0 and 6.0. They are applicable only to conditions existing at the Raft River 5 MWe plant and the results may change if the systems are evaluated for another site.

8.2 CONCLUSIONS AND RECOMMENDATIONS

- The four cooling systems studied were designed to mitigate the corrosion problems of using geothermal brine for power plant cooling at the Raft River site.

- Of these the Evaporative Condenser shows the lowest levelized energy cost as a modification to the Raft River plant.
- Of the two systems which use the existing condenser, the Binary Cooling Tower® system shows the lowest levelized energy cost.
- The levelized energy costs at the design point are:

TSI Binary Cooling Tower®	4.53 mills/kWh
B.A.C. Evaporative Condenser	4.01 mills/kWh
Hudson Products Corp. Combin-aire®	11.44 mills/kWh
Deluge Augmented/Dry Tower	6.57 mills/kWh
- The systems were studied as modifications to the existing Raft River facility and are not representative of optimizations of the cycle or of annual operating strategies.
- Further evaluation of the cooling systems should include physical testing of the resistance of the systems' components to exposure to geothermal fluid at various cycles of concentration.
- In addition a more detailed design and budget/authorization cost estimate for each system is recommended.
- Site specific factors may modify results and should be considered in other applications.

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