**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**

by
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September 1976

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Analysis of performance of existing dry-cooled plants:

DRY COOLING TOWER PROGRAM: RESULTS OF INDUSTRIAL CONTACTS THROUGH AUGUST 1974. BNWL-1878, November 1, 1974.

A SURVEY OF MATERIALS AND CORROSION PERFORMANCE IN DRY COOLING APPLICATIONS. A. B. Johnson, Jr., D. R. Pratt and G. E. Zima, BNWL-1958, March 1976.

EUROPEAN DRY COOLING TOWER OPERATING EXPERIENCE. J. G. DeSteeze and K. Simhan, BNWL-1995, March 1976.

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.

Advanced dry (dry/wet) cooled systems:

PRELIMINARY EVALUATION OF WET/DRY COOLING CONCEPTS FOR POWER PLANTS. W. V. Loscutoff, BNWL-1969.

COMPATIBILITY OF AMMONIA WITH CANDIDATE DRY COOLING SYSTEM MATERIALS. D. R. Pratt, BNWL-1992, April 1976.

SCALE FORMATION IN DELUGED DRY COOLING SYSTEMS. D. R. Pratt, BNWL-2060, March 1976.

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.

A group of reports (including this report) has recently been issued. This group serves the dual purpose of developing cost optimization models for dry cooling systems based on available technology and comparing the results of analyzing the costs of these systems with the projected cost of several advanced dry and dry/wet systems. Included in this group are:

AN ENGINEERING AND COST COMPARISON OF THREE DIFFERENT ALL-DRY COOLING SYSTEMS. B. C. Fryer, D. W. Faletti, Dan J. Braun, David J. Braun and L. E. Wiles, BNWL-2121, September 1976.

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.

FOREWORD

The Dry Cooling Tower Development Program at Battelle, Pacific Northwest Laboratory was initiated with a program scope that included the following near-term and ultimate emphases.

Near-Term Objectives:

- Develop economic and performance models for cost optimization of total heat rejection systems using dry cooling.
- Analyses of, and dissemination of 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.

Over the past two years the following documents have been issued, reporting the results of the work toward these objectives.

Cost optimization of dry-cooled heat rejection systems:

A REVIEW AND ASSESSMENT OF ENGINEERING ECONOMIC STUDIES OF DRY COOLED ELECTRICAL GENERATING PLANTS. B. C. Fryer, BNWL-1976, March 1976.

HEAT TRANSFER AND PRESSURE DROP CHARACTERISTICS OF DRY TOWER EXTENDED SURFACES. PART I: HEAT TRANSFER AND PRESSURE DROP DATA. PFR Engineering Systems, Inc., PFR 7-100, March 1976.

HEAT TRANSFER AND PRESSURE DROP CHARACTERISTICS OF DRY TOWER EXTENDED SURFACES. PART II: DATA ANALYSIS AND CORRELATION. PFR Engineering Systems, Inc., PFR 7-102, June 1976.

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.

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.

A USER'S MANUAL FOR THE BNW-I OPTIMIZATION CODE FOR DRY-COOLED
POWER PLANTS. David J. Braun, Dan J. Braun, Warren V. De Mier,
D. W. Faletti and L. E. Wiles, BNWL-2180, January 1977.

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In addition to the authors, the following personnel at PNL contributed to completion of the work: R. T. Allemann, P. A. Ard, C. H. Henager, H. L. Parry, G. C. Smith, R. D. Tokarz, R. A. Walter, F. R. Zaloudek and A. J. Currie (Technical Editor).

The information provided by Dott. Ing. Carlo Rocco and Vincenzo Leonelli of Italimpianti, Genoa, Italy, and by Professor Carlo Roma of the University of Rome on the natural draft system currently under development by Italimpianti was of invaluable assistance in our evaluation of the induced draft PLASTIC system.

Acknowledgments are also due to the following cooling tower manufacturers and their representatives for their interest during this study: M. Larinoff and E. C. Smith of Hudson Products, R. Landon and R. Cates of Marley Company, and G. Wistran of Ecodyne Cooling Products.

Many manufacturers of components for cooling tower systems were contacted during the conduct of this study and provided essential cost information that was incorporated into the cost algorithms and estimates. This information is the basis of the comparisons made herein. We acknowledge this vital contribution to the study, although any mistakes in interpretation and formulization of this information are the responsibility of PNL.

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This report is an overall summary of the results of the most current ERDA supported studies of power plant cooling methods at PNL. The purpose of these studies has been the assessment of dry and dry/wet cooling technology with a view to identifying the need for improved technology and the investigation of the potential of several advanced cooling approaches that appear to offer major improvement either in reduced cost or reduced water use, or both, relative to other methods. This work showed that improved dry cooling using the advanced methods investigated would reduce the cost below existing dry cooling technology by 15 to 35 percent, i.e. an improvement of 2 to 4 percent in overall plant cost. The next step is to evaluate the benefits that can be anticipated for the market expected to develop for dry and dry/wet cooling, versus the cost of the required development to bring the advanced concepts into commercial use. This work is underway at the present time and will be reported early in 1977.

The discounted benefits of very limited application of the technology is expected to exceed the discounted cost by a substantial amount. However, timing is critical in this; scenarios based upon power and water use projections are currently being evolved and economic analysis will be performed in the next phase of this work. Power requirement projection is a particularly difficult task at the present time and the availability of water is similarly difficult, largely because of the societal choices that can be exercised. For this reason, this will be examined with low, medium, and high power requirement assumptions and with appropriate water availability assumptions. The option exists in some coastal areas to use salt water for cooling. Therefore, some consideration will have to be given to siting alternatives versus power transmission from wet to dry regions.

This document summarizes the results of two studies to identify the best prospect for reducing the cost of dry cooling among a set of advanced concepts which have been under consideration for a number of years. Two separate studies were made because the tools were not available to directly compare the cost of optimum designs of dry/wet cooling systems. Thus, in one study, a design-optimization code was used to compare the cost of a

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1.0 INTRODUCTION

Dry cooling of thermal power generating plants, i.e., the rejection of heat from the power generating cycle directly to the air without benefit of water evaporation, has been used in individual installations throughout the world for the past 15 years but is being given increased consideration for new large power stations. This interest stems from the projected increase in competition for existing water supplies among growing population, agriculture and industry. Although dry cooling is generally a more costly option than once-through cooling or evaporative cooling, there are some locations now, and far more places in the future, at which once-through and all-wet evaporative cooling tower approaches cannot be used. This is because of either a lack of water or a deliberate choice by society to use the limited water available for other purposes deemed by society to have higher priority, such as agriculture, municipal water supplies or environmental conservation.

The higher cost of dry cooling has been the main deterrent to its use. At present, power companies have concluded that, in most instances, if water can be obtained by any means (such as buying agricultural land, thereby obtaining the accompanying water rights which could then be diverted to power plant cooling), evaporative cooling should be used in preference to dry cooling. For example, although all cooling systems' cost and performance are site-specific, the general overall situation is that power from plants using off-stream wet towers and cooling ponds costs about 3 to 6 percent more than from plants using once-through cooling. Power from completely dry-cooled power plants using available technology costs 10 to 15 percent more than when wet towers of current design are used (15 to 20 percent more than once-through cooled units). However, completely dry-cooled plants would not, of course, use any water at all.

number of advanced all-dry systems. In the second study, five different dry/wet systems were carried through conceptual design and cost estimating (without the benefit of design optimization via a computer code). It was felt that the first study would identify the best concept and provide insight into the optimum configuration (albeit for an all-dry system) while the second would confirm that the selected concept was still the best when considered in the context of a dry/wet system by the more traditional method of cost estimation.

2.0 CONCLUSIONS AND RECOMMENDATIONS

The results of the design optimization study of two advanced concepts, together with the optimization of several design approaches representing the "state-of-the-art" (SOA) of dry cooling systems, have shown that an advanced system using ammonia (NH_3) as an intermediate heat transfer fluid (between the turbine and the dry tower) has a projected incremental cost approximately 35 percent less than systems presently offered by U.S. vendors. Assuming a nominal 22 mills/kWh power production cost, the potential savings in total power production cost using ammonia in comparison to the SOA tube system is about 4 percent. This is a significant amount because it can represent a tremendous saving when the quantity of energy which will eventually have to be generated in dry-cooled plants is considered.

Similar conclusions resulted from the second method of analysis, the conceptual design and cost estimate of five alternative dry/wet concepts. The five concepts were:

- an integrated dry/wet tower similar in design to that currently offered by a U.S. manufacturer,
- separate dry and wet towers,
- a conventional design of metal fin-tube tower equipped with provisions to deluge (completely cover) a portion of the surface with water to provide augmented cooling by evaporation,
- a plastic heat exchanger tower with deluge water augmentation,^(a) and
- an ammonia system equipped with deluge water augmentation.

(a) Natural draft plastic systems are under active investigation by Italimpianti in Italy. The plastic system studied here is a mechanical draft system using fabrication techniques applicable to U.S. construction practices. The differences between the plastic mechanical draft system and the Italimpianti natural draft system are sufficiently great that it is not possible to predict the competitiveness of the Italimpianti system by using the results shown here.

The cost estimates of the five concepts indicated that the comparable capital cost, i.e., the capital cost of the cooling system plus the capitalized operating cost (based on a fixed charge rate of 18 percent) of the ammonia dry/wet system was about 20 percent less than the integrated dry/wet approach. The absolute cost values are time- and site-dependent, but should generally show the cost ranking of the systems.

One significant advantage of the ammonia system not apparent in the economic evaluations is the absence of any potential trouble from freezing during very low temperature operation. This may have a large impact on the acceptance of dry cooling by the utility industry.

It is recommended that additional attention be given to the development of the ammonia concept by industry and particularly by the ERDA Dry Cooling Tower Program to further quantify the potential benefits within the context of other sites and to work toward providing the experimental data and operating experience required to demonstrate the performance and reliability of the ammonia system.

3.0 SELECTION OF THE ADVANCED COOLING TOWER CONCEPTS

Several advanced concepts, both dry and dry/wet cooling of power generating plants, have been extensively investigated by different organizations in both this country and Europe. Those selected for detailed evaluation had either been investigated in depth with respect to technical feasibility or were felt to represent sufficiently feasible extrapolations of existing technology to consider proceeding on into demonstration.

3.1 SELECTION OF ALL-DRY SYSTEMS

For the study of optimized all-dry systems, three concepts were initially selected to be compared with several variations of state-of-the-art designs. The three advanced concepts were:

- a fluidized bed heat exchanger,
- a plastic tube heat exchanger, and
- the use of ammonia as an intermediate heat exchange fluid between the condenser and the dry tower.

The fluidized bed heat exchanger was dropped from consideration before extensive optimization studies were carried out because it became apparent that the performance results of the concept in laboratory-size equipment were outside the envelope of key design parameter values that would result in costs competitive with state-of-the-art designs.

The plastic tube heat exchanger concept has been extensively evaluated in Italy in conjunction with a low-profile natural draft configuration developed in response to criticism that huge high natural draft towers were not esthetically pleasing. The low-profile natural draft arrangement results in low air flow and consequently low heat transfer coefficients which, in turn, require very large, inexpensive surfaces. From these considerations emerged a design using a bundle of small-diameter smooth polyethylene tubes. The plastic heat exchanger bundle considered in this study was designed for a mechanical draft tower rather than natural draft, but was otherwise similar to the bundle configuration tested by Roma in Italy.⁽²⁾ The tower configuration is, of course, quite different, and no conclusions as to the competitiveness of the Italian system can be drawn from this study.

The use of an intermediate fluid which undergoes a change of phase evolved from consideration of a binary cycle. In this concept, work is extracted from the lower temperature portion of the Rankine cycle using a second fluid, vaporized by condensing steam at a relatively high temperature (hence relatively high pressure), and allowed to expand through a turbine to a low temperature and pressure into a condenser. The incentive for using the second fluid was that, by choosing one having a low specific volume and other favorable properties over the operating range, one could greatly reduce the equipment size of the low pressure turbine and thus save money. A study by the Franklin Institute⁽³⁾ showed the binary cycle would reduce plant cost under certain assumed conditions; however, for dry-cooled plants under the most likely set of conditions, one was further ahead to simply let the ammonia serve as a heat exchange fluid rather than a second "working fluid". That is, the ammonia is vaporized by the condensing steam at nearly the heat rejection temperature and is condensed in the dry tower without further work being extracted from it by expanding it through a turbine. The liquid ammonia is then returned to the steam condenser and again vaporized to complete the loop.

As a baseline for comparison, conventional or state-of-the-art (SOA) configurations of dry cooling systems were optimized and cost-estimated using several different extended surfaces. These were chosen to represent surfaces offered by some of the leading vendors of dry cooling equipment as well as a variety of lower cost surfaces judged to be more cost effective. The two classes of conventional surfaces are designated as "expensive" and "inexpensive" SOA metal finned tubes.

3.2 SELECTION OF DRY/WET SYSTEM CONCEPTS

The five dry/wet concepts carried through conceptual design were selected as the result of preliminary studies of their potential thermodynamic and economic benefits. Important specific reasons for their inclusion are as follows:

- Integrated dry/wet tower - The evaluated configuration was essentially the same as that planned for the San Juan Unit 3 and

consequently provided a base case reference to SOA technology in dry/wet cooling systems. All the other conceptual designs involved fitting the other four systems to the general design requirements for this installation.

- Separate dry and wet towers - This concept was included to provide a comparison to the cost advantages of this rather straightforward application of existing technology, because a recent study of the use of separate dry and wet towers for power plant cooling⁽⁴⁾ has suggested several important operational and cost advantages.
- Metal fin-tube with deluge augmentation - The augmentation of the dry cooling capability of an extended-surface heat exchanger by completely covering a portion of the surface with water from which evaporation takes place has been termed deluge cooling. The concept has been under study in eastern Europe and is believed to have some important advantages over the two previously mentioned approaches. It appears simpler to operate, can be operated with less cost for water treatment and cleanup, and can use cheaper materials in the liner of the finned tubes.
- Plastic heat exchanger with deluge augmentation - The design approach adapted in the study of plastic heat exchangers in the all-dry system optimization and comparison was intended to include deluge augmentation. The plastic system is well-suited for this concept because the tubes are not subject to corrosion and the smooth tubes make the trade-offs of design conditions between dry and deluge operation less difficult to reconcile. Other advantages include less likelihood of freezing damage and low susceptibility to fouling.
- The ammonia heat transport system with metal fin-tube heat exchanger and deluge augmentation - The advantages of using ammonia in an all-dry system (smaller pipe lines for the fluid, lower pumping requirements, and no freezing problems, as well as a potentially higher heat transfer temperature difference in the cooling tower) would also apply to augmenting an all-dry ammonia system with a deluged system. Augmentation by any other approach appears to be more complicated and costly because of the need for two steam condensers, one cooled by ammonia, the other by water.

4.0 DESIGN BASES FOR COMPARISON

The two studies used different site locations for setting the design bases. The all-dry concepts were designed to provide cooling for a 1000 MWe fossil-fueled plant located in the vicinity of Wyodak, Wyoming while the dry/wet conceptual designs were for a 500 MWe fossil-fueled plant at Farmington, New Mexico.

4.1 ALL-DRY SYSTEM BASES FOR COMPARISON

The general design bases for the all-dry concepts are listed in Table 1. In this study most of the parameters were held constant to the extent of comparisons between systems. However, additional sensitivity analyses were made to determine how sensitive the final results were to the design bases and whether selection of the bases unduly jeopardized the competitive position of any one concept.

Because of the multiplicity of design parameters that could be varied during the design optimization process, the selected design parameters sometimes differed markedly among the alternatives. The optimization code provides the capability of holding constant some of these design parameters. Through this mechanism, it was possible to force the design into certain configurations that could be made similar for all the concepts. When this was done, the cost of the system was seen to be affected only very slightly. Therefore, the cost comparisons of all the systems used the design bases in Table 2.

In addition, three dry cooling systems were evaluated under nuclear plant conditions, different meteorological sites, rectilinear tower arrangements with horizontal heat exchanger orientation, different turbines, different fan/roof area packing factors, and without velocity recovery stacks.

TABLE 1. Design Bases for All-Dry Cooling
Concepts Design Optimization Study

Plant Type	Fossil
Plant Size	1000 MWe
Nominal Heat Rejection	5.1×10^9 Btu/hr
Reference Base Plant Cost	440 \$/kWe
Base Plant Fuel Cost	81¢/10 ⁶ Btu
Base Plant Incremental Steam Supply Cost	146 \$/kWe
Capacity Charge	121 \$/kWe
Energy Charge	2.4¢/kWh
Capacity Factor	65%
Fixed Charge Rate	17.4%
Cooling System Annual O&M	1% of cooling system capital
Meteorological Site	Wyodak, Wyoming
Turbine Type	Modified Conventional (Maximum back pressure 8 in. Hga)
Condenser Type	Surface - Single Pressure
Tower Arrangement	Circular
Heat Exchanger Orientation	Vertical
Cooling System Type	Indirect Mechanical Draft
Fan Draft	Induced
Fan Discharge	Recovery Stacks
Ratio: Tower Roof Area/ Fan Swept Area	Packing Factor 2.0
Plant Operating Condition	Full Load

TABLE 2. Near-Optimum Design Values for
All-Dry Cooling Concepts

Tower Diameter	195 ± 10 ft
Heat Exchanger Tube Length	80 ft
Fan Diameter	28 ft
Heat Exchanger Depth (NH ₃ Only)	≥4 rows

4.2 DRY/WET SYSTEM BASES FOR COMPARISON

All the dry/wet systems conceptual design comparisons were made for the reference plant location—the San Juan Unit 3 of the Public Service of New Mexico at Farmington, near the northwest corner of New Mexico. It was selected because the San Juan Unit 3 with integrated dry/wet cooling towers is currently under construction at this location. Hence, important design variables were available on which to base the comparison. These include:

- site characteristics
- meteorology
- water availability and cost
- onsite construction cost
- transportation cost
- fuel cost
- power cost.

Additional requirements set by site conditions and operating philosophy, or arbitrarily set to avoid the actual operating mode at the existing plant, include:

- heat rejection - 2.5×10^9 Btu/hr
- normal plant size - 500 MWe
- turbine back pressure - ≤ 4.5 in. Hg for temperature $\leq 95^\circ\text{F}$
5.0 in. Hg maximum
- water available for cooling - 1900 acre ft/yr
- 4000 gpm maximum rate
- quality as shown in Table 3.
- temperature range of condenser coolant - 24°F
- meteorology - equivalent to that of Farmington, New Mexico, shown in Table 4.

TABLE 3. Water Quality Assumed for Conceptual Design

Total Hardness	20 - 40 mg/l as CaCO_3
Calcium Hardness	15 - 30 mg/l as CaCO_3
Total Alkalinity	10 - 25 mg/l as CaCO_3
Sulfate	10 - 15 mg/l as CaCO_3
Total Dissolved Solids	50 - 100 mg/l

TABLE 4. Meteorological Profile at
Farmington, New Mexico

<u>Dry Bulb Air Temperature (°F)</u>	<u>Wet Bulb Air Temperature (°F)</u>	<u>Hours per Year</u>
7	7	55
12	11	98
17	16	198
22	20	336
27	25	553
32	29	698
37	33	688
42	36	708
47	39	678
52	41	648
55	44	388
57	45	259
62	47	704
65	49	411
67	50	274
70	52	351
72	53	234
75	54	295
77	54	197
80	55	245
82	56	164
87	58	331
92	61	179
97	62	34
102	63	1

Design criteria for each of the five dry/wet towers were developed by Battelle, Pacific Northwest Laboratory (PNL) from which sufficient conceptual designs were made to provide the basis for conceptual cost estimates. The

conceptual designs and construction cost estimates were performed by Vitro Engineering, a division of Automation Industries, Inc. Table 5 summarizes the most significant design parameters established for each of the concepts. Figures 1 through 5 show plan and sectional sketches of each of the five concepts.

Operating costs for the heat rejection system concepts considered in this report include those for the recirculating system pumping, fan power, deluge water pumping, cover gas, water treatment, and ammonia makeup (where applicable). Normal maintenance costs were assumed to be approximately the same for all concepts and were not included in the operating cost estimate.

The annual operating cost was credited for fuel savings resulting from lower turbine back pressure made possible by each particular concept. These cost savings were estimated from plant heat rate data for San Juan Unit 3 and were defined as savings over those costs associated with the existing design. In all cases, all water available for consumptive use (6.15×10^8 gal annually) was assumed to be used for cooling purposes, subject only to a maximum instantaneous flow limitation of 4000 gpm. Other data used in defining operating costs are:

- plant size - 450,000 kWe
- capacity factors - 0.758
- cost of power consumed by auxiliary equipment - 24.7 mill/kWh
- turbine back pressure - 4.5 in. Hg rated; 1.0 in. Hg min.
- standard heat rate - 8,168 Btu/kWh
- fuel costs - 81¢/MMBtu.

The San Juan River was assumed to be the only source of water for the cooling tower and a separate water treatment plant for the cooling towers was assumed. The assumed analysis of river water was given in Table 3.

To facilitate comparison of the concepts under study, operating costs were capitalized on the basis of the fixed charge rate of 18 percent; i.e., the annual operating costs as defined above were divided by 0.18 to give an equivalent capital cost.

TABLE 5. Dry/Wet Towers Design Parameters

	Integrated Dry/Wet		Separate Dry/Wet		Conventional	Plastic	Ammonia
	Dry	Wet	Dry	Wet	w/Deluge	w/Deluge	w/Deluge
Design ITD	90	30	90	30	70	70	70
Air Design Temp., °F	35	95	35	95	55	55	55
Cooling Water Flow Rate lb/hr	1.1×10^8	1.1×10^8	1.1×10^8	5×10^7	1.0×10^8	1.1×10^8	$5.5 \times 10^6(\text{NH}_3)$
Air Flow Rate, lb/hr	2.2×10^8	2.8×10^7	2.2×10^8	3.2×10^7	3.3×10^8	0.93×10^8	2.9×10^8
Mass Flow Rate of Air, lb/hr, ft ²	2.38×10^3	0.5×10^3	5.43×10^3	1.58×10^3	5.4×10^3	0.66×10^3	2.71×10^3
Frontal Area of Exchanger, ft ²	9.2×10^4	5.7×10^4	9.9×10^4	2×10^4	1.45×10^5	1.42×10^5	1.1×10^5
Total Surface Area, ft ²	7.2×10^6	-	8.1×10^6	-	1.07×10^7	6.5×10^6	8.1×10^6
Air-Side Pressure Drop, in. H ₂ O	0.35	0.35	0.45	0.74	0.35	0.34	0.34
Number of Towers - Shape	2 Rectangular		2 Rectangular		4 Circular	2 Circular	2 Circular
Tube Geometry	Equilateral		Equilateral		Equilateral	Equilateral	Equilateral
Transverse Tube Pitch, in.	2.35		2.375		2.625	0.5	2.625
Fin Design	Single-leg wrapped		Extruded		Extruded	Bare Tube	Extruded
Fin Material	Aluminum		Aluminum		Aluminum	-	Aluminum
Tube Material	Admiralty		Carbon Steel		Carbon Steel	High Density Black Polyethylene	Aluminum
Tube OD, in.	1.07		1.07		1.07	0.30	1.0
Fin OD, in.	2.25		2.25		2.25	-	2.25
Fins/in.	10		10		10	-	10
Bundle Length & Width, ft	48 x 12		49-1/2 x 10-3/4		49-1/2 x 11-7/8	70 x 12	49-1/2 x 10-3/4
Bundle Depth, Rows of Tubes	3		3		3	28	4
Bundles/Tower	160		64		64	90	104
Overall Heat Transfer Cof- ficient Btu/hr, °F, ft ²	6.1		6.2		6.3	15.1	6.6
Fan Diameter, ft	32	24	32	26	28	28	28
Number of Blades	12	6	12	8	6	6	6
Blade Angle, Degrees	16°	16°	-	-	16°	11°	18°
Fan Speed, rpm	120	156	-	-	136	-	-
hp/Fan	210	90	217	115	110	74	125
Fans/Tower	20	5	14	10	17	31	31

FIGURE 1. Integrated Dry/Wet Cooling Tower Plan, Section and Elevation

Elevation View

Plan View

FIGURE 4. Plastic Heat Exchanger Cooling Tower Arrangement

5.0 BASES FOR COST COMPARISONS

The bases of comparison among the several concepts evaluated for all-dry operation via a computer optimization of the total system design and for dry/wet operation via a conceptual design and cost estimate are not precisely the same. Consequently, the results should be compared as to ranking and cost differences among the alternatives but cost comparisons between all-dry and dry/wet systems are not warranted here.

5.1 COST ESTIMATING THE ALL-DRY SYSTEM ALTERNATIVES

The costing of the all-dry cooling alternatives is based on a system optimized in such a way as to minimize the power production cost of a utility system using a dry-cooled plant. The method of minimizing the actual production cost and handling the "lost performance" of the plant was significantly different than that used in many studies to date. Each concept was compared to a plant having a "zero-cost" cooling system and a conventional turbine operating at 3.5 in. Hga. The following stepwise procedure was then used to size the plant and cooling system and to define the incremental cost difference between the dry-cooled plant and reference plant.

- 1) The turbine type and capacity was selected and its cost defined.
- 2) The design and cost of the rest of the plant, including the scaling up of the steam supply system required by the dry-cooled turbine to match the capacity of the conventional plant, was fixed.
- 3) A physically consistent set of cooling system design operating parameters was selected and the cost of the cooling system was determined.
- 4) The net capability of the dry-cooled plant over the annual meteorological cycle was determined.
- 5) The most cost effective way to interface this base loaded plant into the utility system for minimum power productive cost was determined.

- 6) Steps 3 through 5 were repeated until the definition of the most cost effective cooling system and most cost effective way to interface the dry-cooled plant into the utility (the optimum design) was accomplished.

Step 5 involved combining the capital and operating cost of the dry-cooled plant and the peaking gas turbine plant capital and operating costs required to match the performance of the reference plant to yield a minimum overall cost.

The absolute values of the incremental power production costs and percentage increases in total power production cost obtained from this approach are significantly less than would result from the approaches generally used in previous studies. It is believed that the present approach does not affect the ranking of competitive dry cooling systems, but it can definitely have a significant impact on the comparison between dry cooling and wet cooling.

The incremental costs due to dry cooling consist of:

- cooling system capital cost
- energy fuel for fans and pumps in the form of increased plant size and fuel costs
- plant capital and operating cost due to scale-up of the steam supply system and the additional fuel required because of the higher heat rate at high turbine back pressure
- capacity and energy penalties associated with the capital and operating cost of the gas turbine peaking plant.

Items not included in the costing analyses are:

- cover gas system
- land costs
- cooling system instrumentation costs
- cooling loop water treatment costs.

Costs are in January 1976 dollars; neither interest during construction nor inflation prior to or during construction is combined.

5.2 COST ESTIMATING THE DRY/WET CONCEPTUAL DESIGNS

The comparative cost estimates of the five dry/wet systems which were carried through conceptual design are based somewhat differently from the computer-optimized studies of all-dry systems. The estimates are not compared with a "zero-cost" cooling system to establish the incremental cost of electricity from the various dry/wet-cooled plants. Rather, all of the systems were designed to have essentially the same performance, with the exception that the deluge-cooled systems required somewhat larger dry cooling towers (because adding evaporative cooling involves taking some dry cooling out of service, i.e., replacing dry cooling with evaporative cooling) and thus are able to maintain lower back pressures under all-dry operating conditions. A small credit for the lower heat (hence lower fuel costs) resulted to the deluge systems under all-dry operation.

The cost summary, presented as the "comparable capital cost" for each system, includes the capital costs plus the "capitalized annual cost." This latter contribution is the projected operating cost divided by 18 percent, the factor for the annualized cost of capital. The estimated capital cost includes the general contractors' overhead (assumed to be 14 percent of labor costs) and profit (assumed to be 10 percent of labor and equipment and 5 percent of subcontractors' price). It also includes engineering services and construction management (each 10 percent of construction costs). No escalation or contingency is included in the comparable capital cost.

Operating costs include energy costs for fans and pumps plus water treatment costs. A credit is also given for fuel savings achieved during times at which the cooling system was able to maintain the turbine back pressure lower than 4.5 in. Hga. The calculation of this credit does not infer that the design back pressure is 4.5 in Hga but is intended only as a measure of the difference in performance of the five alternatives at temperatures below the point of all-dry cooling.

6.0 RESULTS

The principal results of both the computer-optimized and the conceptual design study are the comparative cost estimates for the various alternatives. In addition, the design optimization provides insights into the impact of various design parameters upon the incremental cost of electricity.

6.1 DESIGN OPTIMIZATION OF ALL-DRY SYSTEMS

The general configuration to be optimized was determined by preliminary cost evaluation which indicated that large round towers with vertically-oriented bundles located around the periphery yielded the lowest cost arrangement of those investigated. Draft is induced by large fans on the roof of the tower. The height and diameter of the tower is selected for minimum overall cost of electricity. Although the computer program could vary the tower diameter and height along with many other variables, the sensitivity of cost to the tower height and diameter was low because other design parameters could be adjusted to compensate for the changes in height and diameter. Consequently, the final cost comparisons were made on systems in which certain key variables were arbitrarily set so as to more easily identify the unique features of each concept.

The PLASTIC and NH_3 cooling systems consisted of six circular towers, and the SOA system eight towers, about 190 ft in diameter and 80 ft high. Figure 6 is a schematic of the arrangement for the NH_3 , PLASTIC and one of the SOA systems. The similarities (mainly resulting from the constrained parameters) and some of the distinct differences in the cooling towers, condenser and piping systems are noted.

The condensers for the SOA and PLASTIC systems are essentially the same in design and cost. The condenser/reboiler design utilized the enhanced aluminum heat transfer surface developed by LINDE.^(a) With this surface, the condenser/reboiler has only slightly less total heat transfer area, despite the significantly lower temperature differences, but the cost of the unit is somewhat higher than a conventional condenser. If smooth tubes

^(a) LINDE Division of Union Carbide Co.

EXPENSIVE STATE-OF-THE-ART

FIGURE 6. Optimized Designs of State-of-the-Art and Advanced Dry Cooling Systems and Concepts

or enhanced stainless steel tubes were required for some as yet undetermined reason, the size and cost would be significantly higher.

A major difference in the NH_3 system is the smaller diameter piping between the condenser/reboiler and the tower for the recirculating NH_3 . Although this is high pressure piping, it is estimated to cost considerably less than the piping for the other systems. The pumping requirements for the NH_3 system are also very much less and contribute significantly to the lower cost projection for the ammonia concept.

Figure 7 summarizes the comparison of incremental power production costs for a 1000 MWe fossil plant with the all-dry cooling systems which were evaluated in depth. Using the conventional (expensive) finned tube SOA system as a base and a nominal power production cost of 22 mills/kWh, the potential for cost savings given in Table 6 was obtained.

TABLE 6. Comparison of Incremental Cost Savings
for Advanced All-Dry Cooling Systems

<u>Cooling System</u>	<u>Percent Reduction in Incremental Power Production Cost</u>	<u>Percent Reduction in Total Power Production Cost</u>
SOA Conventional	0	0
SOA Inexpensive Tubes	11.1	1.5
PLASTIC	22.2	2.8
NH_3	34.2	4.1

Table 7 is a tabulation of the cost comparisons of the near-optimum designs of each concept. These comparisons show the incremental unit energy costs associated with each aspect of the analysis (e.g., incremental energy costs attributed to capital cost of the system, the capital cost of scaling up the plant, the operating and maintenance of the cooling system, the energy penalty, etc.). Table 7 also shows the estimated capital cost of the various subsystems for each of the alternatives. The cost models and algorithms used to develop these costs are explained and summarized in Reference 5.

FIGURE 7. Comparison of Incremental Power Production Costs

TABLE 7. Near-Optimum Designs Cost Comparison

Unit Energy Costs (mills/kWh)	SOA (Expensive tube)	SOA (Inexpensive tube)	Plastic	NH ₃
Cooling System Capital	2.33	1.96	1.76	1.45
Capacity Penalty	0.27	0.27	0.27	0.26
Base Plant Scaling	0.22	0.23	0.15	0.12
Energy Penalty	0.09	0.09	0.09	0.09
Additional Base Plant Fuel	0.15	0.16	0.12	0.10
O&M	<u>0.13</u>	<u>0.11</u>	<u>0.10</u>	<u>0.08</u>
Total Incremental Power Production Costs	3.19	2.82	2.49	2.10
<u>Capital Costs x 10⁶ \$</u>				
Heat Exchanger				
Tubes	19.49	10.20	3.49	7.62
Spacers, etc.	1.16	1.27	2.04	0.88
Headers	1.98	1.88	4.28	1.75
Frame and Assembly	3.15	3.01	6.55	2.20
Ship and Erect	3.09	1.97	1.94	1.50
Louvers	4.13	3.99	3.1	--
Hail Screens	--	--	--	0.75
Plenum	0.20	0.19	0.15	0.13
Structure	5.94	5.55	4.47	3.96
Foundation	0.52	0.49	0.72	0.32
Piping and Pumps	16.44	15.85	14.80	10.40
Condenser	7.01	6.67	6.48	7.85
Fan System	13.12	13.09	9.37	10.15
Cap. Charge	8.79	8.80	8.75	8.64
Plant Scaling	<u>7.18</u>	<u>7.40</u>	<u>4.97</u>	<u>3.78</u>
TOTAL	92.20	81.36	71.11	59.93

The economic advantages of the NH_3 system are evident from the results in these tables. The 34-percent reduction in incremental power production cost accrues mainly from the lower cost of the heat exchanger of the cooling tower (because of the higher temperature difference) and the piping and pumps required to circulate the NH_3 . The full advantage of avoiding all concern for freeze-up in the tower (e.g., avoiding the need for louvers, controls, quick draining, etc.) cannot be shown in the economic evaluation.

Table 8 provides the complete listing of the design parameters which compose the near-optimum configuration of each of the alternatives. Further detailed discussion on the sensitivity of incremental cost of electricity to the more significant parameters listed here is included in Reference 6.

TABLE 8. Comparison of Design and Operating Parameters for Near-Optimum Designs

	SOA (Exp. tube)	SOA (Inexp. tube)	Plastic	NH ₃
<u>Temperatures</u>				
TTD1, °F (Condenser)	5	5	5	4.3
TTD2, (NH ₃ Supply Pipe)	--	--	--	3.6
ITD, °F	45.6	45.6	45.6	45.0
LMTD, °F	21.3	20.6	17.4	24.8
Range _{air} , °F	26.1	25.4	30.6	33.1
Range _{H₂O} , °F	22.5	24.5	25.5	--
<u>Velocities</u>				
V _{air max.} , ft/sec	18.6	18.3	10.3	19.2
V _{H₂} , H.X. ft/sec	4.6	4.9	1.8	--
V _{NH₃} , H.X. ft/sec	--	--	--	16.7
<u>Heat Transfer Coefficients</u>				
U, Btu/hr-ft ² -°F	6.1	5.4	13.6	5.7
h _{H₂O} , Btu/hr-ft ² -°F	1094	1170	713	--
h _{NH₃} , Btu/hr-ft ² -°F	--	--	--	1304
h _{air} , Btu/hr-ft ² -°F	8.0	7.5	15.7	8.0
<u>Heat Exchanger Dimensions</u>				
A _{H.T.} , ft ²	42.4x10 ⁶	49.4x10 ⁶	24.2x10 ⁶	36.6x10 ⁶
A _{frontal} , ft ²	4.0x10 ⁵	3.9x10 ⁵	6.0x10 ⁵	2.8x10 ⁵
H.X. Rows Deep	4.0	4.0	26.0	4.0
H.X. Total Tubes	0.9x10 ⁵	0.8x10 ⁵	4.7x10 ⁶	0.6x10 ⁵
Width-H.X., ft	5010	4844	7530	3540
<u>Towers</u>				
Dia., Tower, ft	199	193	196	188
Number Towers	8	8	6	6
<u>Auxiliaries</u>				
Fan Power, MWe	16.9	17.9	11.9	14.9
Pump Power, MWe	6.8	6.2	6.7	0.3
Fans - number	197	182	147	133
ΔP _{air} , total lbs/in ²	0.018	0.019	0.015	0.021
ΔP _{fan dis} , lbs/in ²	0.005	0.006	0.006	0.006
ΔP _{air} H.X. lbs/in ²	0.013	0.013	0.009	0.014
ΔP _{pump} lbs/in ²	28.6	28.6	32.0	11.3
ΔP _{H₂O} H.X. lbs/in ²	6.1	7.1	8.4	--
ΔP _{NH₃} H.X. lbs/in ²	--	--	--	0.21

6.2 CONCEPTUAL DESIGNS FOR FIVE DRY/WET SYSTEMS

A summary of the estimated capital costs of constructing the five alternative heat rejection concepts for the San Juan Plant Unit 3 is provided in Table 9.

TABLE 9. Results of Capital Cost Estimates of Alternative Heat Rejection Concepts for San Juan Unit 3

	<u>Estimated Capital Cost</u>	<u>Escalation</u>	<u>Contingency</u>	<u>Total</u>
Integrated Dry/Wet (Baseline)	\$22,789	\$5,638	\$8,573	\$37,000
Separate Dry/Wet	29,276	7,243	10,981	47,500
Metal Fin-Tube - Deluge	28,882	7,145	10,773	46,800
Plastic Tube - Deluge	24,311	6,014	9,075	39,400
Deluge - Ammonia Heat Transport	23,128	5,721	8,651	37,500

All estimates summarized in Table 9 are subject to the validity of assumptions defined in Section 4.2. The integrated dry/wet concept is considered as a baseline for comparison because it represents current practice. The San Juan Plant Unit 3 is currently being constructed with a heat dissipation system of this type. However, the estimate of the integrated dry/wet concept was performed without the benefit of knowledge of actual construction costs or bid costs of San Juan Unit 3 and may or may not correspond to actual costs.

A breakdown of the costs summarized in Table 9 is provided in Table 10. Additional details may be requested from the PNL Dry Cooling Tower Project.

The annual operating costs for the five dry/wet cooling tower concepts under study were estimated using assumptions and data provided in Section 4.2. The results of these estimates are summarized in Table 11.

It should be specifically noted that the costs given in Table 11 include only those costs associated with the dry/wet cooling tower operation. These costs were credited for savings resulting from predicted lower back pressure than anticipated for the San Juan Unit 3 design developed herein.

ERRATA

This page replaces the page 37 bound in this document, BNWL-2120. Costs underscored with the dashed line (---) were updated after the original printing.

TABLE 10. Breakdown of Capital Costs of Alternative Concepts

<u>Item</u>	<u>Integrated Dry/Wet</u>	<u>Separate Dry/Wet</u>	<u>Metal Fin- Tube Deluge</u>	<u>Plastic Tube Deluge</u>	<u>Deluge Ammonia System</u>
Steam Condenser	1,740	2,848	1,740	1,740	2,653
Cooling System					
Piping	1,631	2,089.6	1,439	928.5	1,275
Tanks		573.5	573.5	714	310
Pumps	338	610	375.5	381	262
System Subtotal	1,969	3,273.1	2,388	2,023.5	1,847
Fill and Drain System					
Piping	245.4	493.1	447	143	232
Tanks					514
Pumps	13.5	60.2	51	78	35
System Subtotal	258.9	553.3	498	221	781
Water Quality Control					
Water Treatment	495.3	409	554	554	290
Demineralized Water		264	187	270	167
Piping and Pumps		325.3	316.9	226.1	334.7
System Subtotal	495.3	998.3	1,057.9	1,050.1	791.7
Cover Gas System		136	140.8	143	143
Cooling Towers					
Structural Work	1,647	1,557	1,728	1,525	1,334
Piping	1,160	1,996	<u>2,483.2</u>	2,603	984
Pumps			152	58	106
Heat Transfer	<u>4,686</u>	<u>3,825</u>	5,440	4,006	3,976
Fans	2,046	2,415	1,908	1,142	1,742
Louvers		686	744	720	
System Subtotal	9,539	10,479	12,455.2	10,054	8,142
Buildings	52	71	52	52	52
Electrical Work	2,014.9	2,246	1,907.1	1,810.6	1,665.6
SUBTOTALS	16,069.1	20,604.7	20,239	17,094.2	16,075.3
Contractors' OH and Profit	2,921.9	3,791.3	3,829	3,164.8	3,198.7
Eng. and Constr. Mgt.	3,798	4,880	4,814	4,052	3,854
Escalation	5,638	7,243	7,145	6,014	5,721
Contingency	8,573	10,981	10,773	9,075	8,651
TOTALS	37,000	47,500	46,800	39,400	37,500

TABLE 10. Breakdown of Capital Costs of Alternative Concepts

Item	Integrated Dry/Wet	Separate Dry/Wet	Metal Fin- Tube Deluge	Plastic Tube Deluge	Deluge Ammonia System
Steam Condenser	1,740	2,848	1,740	1,740	2,653
Cooling System					
Piping	1,631	2,089.6	1,439	928.5	1,275
Tanks		573.5	573.5	714	310
Pumps	338	610	375.5	381	262
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Tanks					514
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System Subtotal	258.9	553.3	498	221	781
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Water Treatment	495.3	409	554	554	290
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Cooling Towers					
Structural Work	1,647	1,557	1,728	1,525	1,334
Piping	1,160	1,996	4,211.2	2,603	984
Pumps			152	58	106
Heat Transfer	3,786	3,855	5,440	4,006	3,976
Fans	2,046	2,415	1,908	1,142	1,742
Louvers		686	744	720	
System Subtotal	9,539	10,479	12,455.2	10,054	8,142
Buildings	52	71	52	52	52
Electrical Work	2,014.9	2,246	1,907.1	1,810.6	1,665.6
SUBTOTALS	16,069.1	20,604.7	20,239	17,094.2	16,075.3
Contractors' OH and Profit	2,921.9	3,791.3	3,829	3,164.8	3,198.7
Eng. and Constr. Mgt.	3,798	4,880	4,814	4,052	3,854
Escalation	5,638	7,243	7,145	6,014	5,721
Contingency	8,573	10,981	10,773	9,075	8,651
TOTALS	37,000	47,500	46,800	39,400	37,500

TABLE 11. Estimated Annual Operating Costs (\$/year)

<u>System</u>	<u>Circulation Pump Cost</u>	<u>Induced Draft Fan Cost</u>	<u>Reduced Back Pressure Savings</u>	<u>Water Treatment Cost</u>	<u>Deluge Pump Cost</u>	<u>Total Cost</u>
Integrated Dry/Wet	628,400	1,227,600	-55,597	330,000	-0-	2,130,403
Separate Dry/Wet	967,450	1,311,600	-55,597	356,000	-0-	2,579,453
Deluge/Finned Tube	782,550	1,016,900	-230,422	130,000	13,130	1,712,158
Plastic Tube	650,400	598,000	-234,877	131,000	7,530	1,152,053
Ammonia	34,300	1,047,350	-220,257	75,000	25,130	961,523

To facilitate comparison of the total costs of the dry/wet cooling tower concepts under study, a "comparable capital cost" was calculated for each concept. Comparable capital cost was defined as the sum of the estimated basic capital cost (i.e., estimated capital cost less escalation and contingency) and the capitalized annual operating cost. The capitalized annual operating cost was based on estimated annual operating costs summarized in Table 11 and on a fixed charge rate of 18 percent. The comparable capital costs of the five concepts considered in this report are summarized in Table 12.

TABLE 12. Summary of Comparative Capital Costs

	<u>Basic Capital Cost</u>	<u>Capitalized Operating Cost</u>	<u>Comparable Capital Cost</u>
Integrated Dry/Wet	\$ 22,789,000	11,836,000	34,625,000
Separate Dry/Wet	29,276,000	14,330,000	43,606,000
Deluge/Finned Tube	28,882,000	9,512,000	38,394,000
Plastic Tube	24,344,000	6,400,000	30,744,000
Ammonia	23,152,000	5,342,000	28,494,000

7.0 DISCUSSION

Table 12 shows that, on the basis of conditions associated with the San Juan Plant Unit 3, two of the alternative dry/wet concepts considered have a potential of lower cost than the integrated dry/wet concept (the concept chosen as the basis for comparison and the one under construction for use in San Juan Unit 3). The deluge/ammonia concept shows significantly lower cost.

Both the conceptual design study and the design optimization results show similar ranking of the systems involving ammonia (NH_3) as an intermediate heat transfer fluid, whether they are designed for all-dry or dry/wet operation. The comparative advantage of the NH_3 system over the SOA approach using inexpensive tubes is about 25 percent in the all-dry system and about 20 percent in the dry/wet system.

Although the ammonia concept requires a rather expensive ammonia reboiler in place of a simple condenser, and a complex pressurized ammonia fill and drain system, it has a number of important cost advantages associated with the evaporation-condensation heat transfer system. Among these are the enhanced heat transfer in the condenser and cooling tower, resulting in a substantial saving in tower costs. Also, the existence of natural forces to transmit vapor from the reboiler to the cooling tower eliminates some pump work. Only small pumps are required to return the ammonia to the reboiler and to provide forced recirculation. Water treatment plant costs are also less because of the need for treating only the deluge water.

Operating costs for the deluge/ammonia system are substantially less than the other concepts because 1) very little power is required to operate recirculation pumps and 2) fuel savings from lower back pressure result from the somewhat larger dry cooling tower inherent in the use of the deluge concept which requires that dry cooling be removed from the system as wet cooling is brought into operation. The advantage of avoiding all concern for freeze-up cannot be quantitatively assessed. However, it could be significant and greatly affect the general acceptance of dry-cooled power plants by the utility industry.

A discussion of the sources of the cost difference for the other alternative systems is included in References 6 and 7.

Although the results of this study have identified two concepts which have the potential for lower costs than the integrated dry/wet system selected for use in the San Juan Unit 3, it is not inferred that an inappropriate selection was made there. In fact, the results of this study support the application of the integrated dry/wet concept for the San Juan Plant because it was shown to be the least costly of the concepts investigated which are state-of-the-art or resemble state-of-the-art. The lower cost plastic deluge and deluge/ammonia concepts are developmental in nature and have not been subjected to conditions existing in commercial power operation. Therefore, unknown problems not adequately reflected in this study may exist with these concepts. Additional testing and demonstration is required before a selection of these concepts for commercial power applications can be confidently made.

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