Comparative Cost Study of Four Wet/Dry Cooling Concepts that Use Ammonia as the Intermediate Heat Exchange Fluid

September 1978

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COMPARATIVE COST STUDY OF FOUR WET/DRY
COOLING CONCEPTS THAT USE AMMONIA AS
THE INTERMEDIATE HEAT EXCHANGE FLUID

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FOREWORD

The Dry Cooling Enhancement Program at Pacific Northwest Laboratory (PNL) 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 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 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.

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. DeSteele 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.

ALUMINUM ALLOY PERFORMANCE UNDER DRY COOLING TOWER CONDITIONS. A. B. Johnson, Jr., S. Begaj, M. W. Martini, and R. P. May, PNL-2392, December 1977.

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 been issued that serves the dual purpose of: 1) developing cost optimization models for dry cooling systems based on available technology and 2) 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, Daniel 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.

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, Daniel J. Braun, Warren V. De Mier, D. W. Faletti and L. E. Wiles, BNWL-2180, January 1977.

COMPARATIVE COST STUDY OF FOUR WET/DRY COOLING CONCEPTS THAT USE AMMONIA AS THE INTERMEDIATE HEAT EXCHANGE FLUID. R. D. Tokarz, Daniel J. Braun, B. M. Johnson, R. T. Allemann, David J. Braun, H. L. Parry, G. C. Smith and F. R. Zaloudek, PNL-2661, September 1978.

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

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, June 1977.

ESTIMATION OF BENEFITS FROM DEMONSTRATING ADVANCED DRY COOLING TECHNOLOGY: A FRAMEWORK AND PARTIAL ANALYSIS. J. W. Currie and T. J. Foley, BNWL-2182, April 1977.

ACKNOWLEDGMENTS

This report contains an account of the work sponsored by the Division of Advanced Systems and Materials Production of the U.S. Department of Energy (DOE) under the Dry Cooling Enhancement Program at PNL. This work was completed under the direction of I. Helms, Project Officer; W. F. Savage, Manager of Advanced Concepts Evaluation Branch, DOE Division of Nuclear Research and Applications; and B. M. Johnson, Manager of the Dry Cooling Enhancement Program at PNL.

The authors wish to acknowledge the assistance received from the S&Q Engineering Corporation in the preparation of the cost estimates used in this study.

As in the preceding report, A Study of the Comparative Costs of Five Wet/Dry Cooling Tower Concepts (BNWL-2122), this report benefited from input from the following cooling tower manufacturers and their representatives: M. Larinoff and E. C. Smith of Hudson Products, R. Landon and R. Cates of Marley Company, and G. Westman of the Ecodyne Cooling Products Company. Public Service Company of New Mexico provided information on the site characteristics of the San Juan site upon which this study is based and their assistance and interest is gratefully acknowledged.

Technical editing of this report was done by M. K. Dunstan and word processing was done by R. A. Keefe, M. J. Rockford and P. Goodenough.

SUMMARY

The projected costs of five alternative wet/dry power plant heat rejection concepts were studied under conditions imposed by hypothetical use in association with the San Juan Unit 3 plant. Four of the systems use ammonia as a heat transfer medium between the steam condenser and the heat rejection tower, while the fifth uses the condenser cooling water for heat transport. The four alternative concepts were:

- the HÖTERV plate fin with deluge augmented cooling (vertical round towers),
- the HÖTERV plate fin with deluge augmented cooling (horizontal configuration),
- the separate channel augmented tower (SCAT); a Curtiss-Wright extruded tube with integral fins, augmented with water flowing internally through separate channels,
- the augmenting ammonia condenser (AAC); Curtiss-Wright tube augmented with a separate water-cooled condenser close-coupled to a conventional wet tower,

and the state-of-the-art method:

- the integrated wet/dry tower currently being constructed at the San Juan Unit 3 station.

The comparable capital cost of the five concepts, i.e., the sum of the estimated capital cost (less escalation and contingency allowances) and the capitalized operating cost (obtained by dividing the annual operating costs by the annual fixed charge rate of 18%) are as follows:

<u>Heat Rejection Concept</u>	<u>Estimated Capital Cost</u>	<u>Capitalized Operating Cost</u>	<u>Comparable Capital Cost</u>
integrated wet/dry	23,407,000	9,586,000	32,993,000
vertical HÖTERV tower	24,795,000	3,138,000	27,933,000
horizontal HÖTERV tower	21,590,000	3,102,000	24,692,000
SCAT tower	21,493,000	2,969,000	24,462,000
augmenting ammonia condenser	19,765,000	4,167,000	23,932,000

Fuel savings resulting from using the advanced concept vis-a-vis the reference integrated wet-dry cooling towers, expressed in barrels of oil per year can be calculated on the basis of the established designs although these do not represent designs which maximize fuel savings.

FUEL SAVINGS: ADVANCED CONCEPTS VIS-A-VIS INTEGRATED WET/DRY SYSTEM

<u>Heat Rejection Concept</u>	<u>Fuel Savings, bbl/yr</u>
Vertical HÖTERV	299,000
Horizontal HÖTERV	292,000
SCAT Tower	312,000
Augmenting Ammonia Condenser	250,000

This study indicates that the ammonia system with either the deluge scheme for wet/dry cooling, using the HÖTERV plate fin heat exchanger, or the Curtiss-Wright chipped-fin surface, (using either the SCAT arrangement or the separate water-cooled ammonia condenser for augmentation) are potentially more cost-effective than the state-of-the-art system for use in a power plant heat rejection system. This has been shown specifically only under conditions imposed by the site at the San Juan plant near Farmington, New Mexico.

Included in this report are two estimates for the integrated tower--one provided by the Vitro Engineering Company and previously reported in BNWL-2122, the other provided by S&Q Engineering Corporation, who also provided most of the information included in the other four estimates. The two estimates are included to provide an indication of the degree to which the estimate in this report and the former study (BNWL-2122) can be related to each other.

The integrated wet/dry tower concept has been chosen for service at San Juan Unit 3 and was included in the concepts under study for reference purposes. The San Juan Unit 3 is a 550-MWe facility currently under construction near the "Four Corners" area of New Mexico by the Public Service Company of New Mexico.

All systems were conceptually designed and estimated using the same bases and uniform practices. Each system was assumed to use all water allocated for consumptive use in Unit 3. Emphasis was placed on using components, equipment and materials that are currently available from established sources.

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1.0 INTRODUCTION

This report describes a cost study that compared the economics of four dry/wet cooling tower concepts for power plant cooling. These concepts were selected as a result of a series of preliminary studies of their potential thermodynamic and economic benefits. All comparisons were made on the basis of a common plant site--the Public Service Company of New Mexico, San Juan Unit 3, located in the "Four Corners" area of New Mexico.

An earlier report (BNWL-2122) summarized a similar study of five dry/wet concepts. Four of these were based on the conventional "indirect cooling" arrangement in which steam from the last stage of the low-pressure turbine is condensed in a surface condenser by circulating water which, in turn, is cooled by combined dry (air-cooled) and wet (evaporative-cooled) heat rejection systems. Different arrangements of wet and dry cooling systems and different heat transfer surfaces were studied. One concept was based on the use of ammonia as a heat transfer medium together with the evaporation of water flowing over the dry cooling heat exchanger surface to augment the cooling during times of high ambient temperature.

This report extends the study of the ammonia heat transport approach and evaluates four different concepts of dry/wet cooling and compares them to the integrated dry/wet system being constructed at the San Juan Unit 3 station.

The four ammonia systems and their main features are:

1. HÖTERV (Heller-Fargo plate fin) vertical

The HÖTERV surface arranged in vertical stacks around the periphery of circular towers. The HÖTERV plate fin surface is ideally adapted to deluge cooling because of its physical design. This method of deluge offers higher rates of evaporation per cubic foot of cooling surface than a conventional wet tower.

2. HÖTERV horizontal

The HÖTERV surface arranged as A-frames in horizontal configuration under the induced draft fans seemed to offer significant savings in tower structural costs but at the expense of more costly arrangement of the water cooling system.

3. The Separate Channel Augmented Tower (SCAT)

A modified extruded tube with integral fins (Curtiss-Wright tubes) with a manifold system, which allows water to flow in some of the internal channels, provides a means of combining dry cooling with tube-to-tube water cooling in a single heat exchanger. The cooling water is close-coupled with a conventional evaporative cooling tower.

4. The Ammonia Augmenting Condenser

A logical alternative to using the dry surface in the dual capacity for both dry and wet cooling is to provide a separate conventional shell and tube condenser to handle the ammonia that cannot be condensed by air cooling at high ambient temperatures. Close coupling the wet tower with condenser provides economies similar to those of the SCAT concept.

1.1 BACKGROUND

In recent years, interest in the use of dry cooling towers for steam power plant cooling has increased. One principal reason for this interest is the projected increase in competition for existing water supplies among a growing population, industry and agriculture. In certain locations of the U.S., where water is sufficiently scarce, the building of power plants with dry cooling towers has become mandatory.

One of the problems in using dry cooling towers for power plants is the severe economic penalties associated with the unavoidably higher heat rejection temperature in warm weather compared with an equivalent wet cooling tower. These higher heat rejection temperatures increase the plant heat rate, making power more costly. With conventional turbine designs, plant output must be reduced on hot summer days when the power demands in the U.S. are likely to be highest. This loss of capacity would have to be compensated for by the availability of excess capacities in the plant or within the utility's system, or through the purchase of power.

Because of these economic penalties, there are strong incentives to augment the dry cooling towers through evaporative cooling on hot days using any inexpensive water that may be available at the plant site. By such use of dry/wet cooling systems, both the plant efficiency and power loss problems can

be ameliorated for the price of only a relatively small consumptive use of the available water resource as compared to usage of all-wet cooling towers. In a 1974 survey of utilities having potential problems with availability of cooling water, it was found that most saw the dry/wet cooling system as the most attractive option for plant construction in the 1980-2000 period.

A number of methods exist to combine dry and wet cooling systems. These methods include: 1) separate dry and wet towers, 2) integrated dry and wet towers, 3) dry tower/cooling pond arrangements, 4) water spray augmentation, 5) water deluge augmentation, and 6) water augmented dry towers with passive or active heat transport systems. Many factors must be considered in selecting the most economically advantageous option for a given plant site. These include water availability, fuel costs, water costs, elevation, and climatology. Other, less tangible factors, such as the availability of a power state-of-the-art technology, must also be considered. Recently, several articles and reports^(1,2,3) have elucidated the economics of state-of-the-art integrated dry/wet tower and separate dry and wet tower systems. In this report, the economics of four additional "advanced" system concepts are considered.

1.2 DOE/PNL DRY COOLING TOWER ENHANCEMENT PROGRAM

The objective of the Department of Energy/Pacific Northwest Laboratory (DOE/PNL) Dry Cooling Tower Enhancement Program is to develop, demonstrate and disseminate to potential users dry and wet/dry cooling tower technology that can be applied to conserve scarce water resources, increase flexibility in siting power plants, and result in a minimum degradation of annualized power plant performance.

As currently planned, the Dry Cooling Tower (DCT) Program is divided into five general areas:

- Assessment of the role of dry cooling in meeting national energy needs
- Cooperative testing and evaluation of dry cooling
- Critical appraisal of new technology
- Development and testing of unique design features
- Large-scale testing of an advanced concept.

This report presents the results of critical appraisals of new technology or design concepts. Continuing appraisals, similar to the one reported here, will be performed through analytic evaluation, design studies, and economic evaluation to normalize and compare claims of costs and performance of competing concepts. The results of this task will be used to identify the most advantageous concepts for further large-scale testing.

2.0 BASES FOR COMPARISON

Economic comparisons of the various concepts under study were performed on the basis of "comparable capital costs," based on 1976 dollars. This is defined as the sum of the estimated capital costs of the cooling tower installation plus the capitalized operating cost. The capitalized operating cost was based on an annual fixed charge rate of 18%.

Capital costs included all engineering, construction and material costs associated with the cooling towers, condenser, water treatment equipment and related piping and pumps. Construction costs included the contractor's profit and overhead, but excluded any escalation or contingencies. Operating costs included the cost of auxiliary power for pumps and fans, maintenance, and water treatment.

Credit was taken for improvements in plant heat rate associated with lower back pressures made possible by the advanced designs. However, no credit was taken for increases in load that may have been made possible by back pressures lower than the design values of the reference plant.

To assure the validity of the comparisons, every effort was made to use uniformity in the conceptual designs and cost estimation of each concept.

All estimates were prepared by an architect-engineer subcontractor^(a) from preconceptual design descriptions prepared for each concept. All design descriptions used a common reference plant location, the San Juan Unit 3 of the Public Service Company of New Mexico. This plant (described in Section 3 of this report) was selected as the reference plant for this study because a plant with integrated dry/wet cooling towers is currently under design and construction at this location. As a result, adequate data were already available on which to base the preconceptual designs of the advanced alternatives and to validate cost estimates. By basing the cost estimates on this common reference plant, it was possible to obtain common, representative values for the important design variables, including:

(a) S&Q Engineering Corporation

- meteorology,
- fuel costs,
- water availability and quality,
- onsite construction costs,
- transportation costs,
- power costs, and
- site characteristics.

Each of the dry/wet systems was conceptually designed and estimated using the same procedure, including the integrated wet/dry concept used in the reference plant. No cost or detail design information was obtained from the utility about the integrated wet/dry concept, so it, too, was designed and costed on the same basis as the other four considered. This cost comparison study applies only to the reference plant design conditions. Other sites would have different conditions that could markedly affect the resulting comparison.

2.1 CONCEPTUAL DESIGN BASES

The conceptual designs of the three cooling tower concepts were based on performance requirements established by the Public Service Company of New Mexico for the San Juan Unit 3. These requirements are listed below.

1. The heat rejection capability of the cooling system shall be 2.462×10^9 Btu/hr over a yearly cycle.
2. The cooling system shall accommodate the meteorological profile of Farmington, NM. (This profile is given in Subsection 3.1).
3. The turbine shall be operated at or below a back pressure of 4.5 in. Hg at an ambient temperature of 95°F or below. Above 95°F, the turbine back pressure shall be allowed to increase to a maximum of 5.0 in. Hg.
4. The maximum amount of water available annually for consumptive use is 1900 acre-ft or 5.12×10^9 lb.
5. The maximum instantaneous flow rate of consumptive water due to evaporation shall be 2.0×10^6 lb/hr (4000 gpm).

6. The temperature range on the condenser cooling water shall be held constant at 24°F, resulting in a cooling water flow rate of about 1.0958×10^8 lb/hr.

The San Juan River was assumed to be the source of water to the plant. Water treatment requirements for closed-loop recirculating systems associated with dry towers were assumed to include demineralization, vacuum deaeration, corrosion inhibition and pH control (pH 8.5). Open-loop systems used in wet and wet/dry towers were assumed to require lime-soda softening (side stream), scale inhibition and biofouling control. Delugeate treatment to maintain a Langlier saturation index of zero or slightly negative was assumed.

All conceptual designs were assumed to reflect current industrial practice for similar units. The design of the integrated dry/wet towers was as close to the existing design of the San Juan Unit 3 towers as available information permitted. All towers were conceptually designed to use components and materials, available from existing sources, of standard sizes and capacities.

The concepts have not been optimized from the standpoint of all variables involved. Specifications for required "dry" performance were fixed by analysis of the anticipated deluge performance and an evaluation of the hours of the year and the ambient temperature range over which water would be available to augment performance. A computer code PLDEL was developed at Pacific Northwest Laboratory (PNL) to establish the design point for all dry operation. Design details were not exhaustively optimized because of the preconceptual nature of the design activity. The details were principally governed by equipment and component sizes and capacities easily available from existing manufacturers and presently used in steam power generation design or in related areas.

3.0 REFERENCE PLANT DESCRIPTION

3.1 LOCATION AND METEOROLOGY

The San Juan power station is located at Fruitland, NM. It is owned and operated by the Public Service Company of New Mexico. Two units are currently operating at the site and two additional units, including the reference unit (No. 3), are under design and construction. The units under construction, each 500 MWe (nominal), 462 with SO₂ scrubbing, are expected to be in operation in 1979 and 1980. Units 1 and 2 are cooled by wet cooling towers. Units 3 and 4 will be cooled by Marley wet/dry units and are expected to save 60% of the water consumed by an all-wet tower.

The meteorological profile of the Fruitland plant site resembles that of nearby Farmington, described in Table 3-1. The site is at an elevation of approximately 5500 ft and has an average barometric pressure of 0.815 atm.

3.2 DESCRIPTION OF REFERENCE STEAM TURBINE

The San Juan Unit 3 will incorporate the first wet/dry towers used in this country for water conservation. These towers are rated at 2.5×10^9 Btu/hr over the yearly cycle and are designed to save roughly 80% of the water consumed by an all-wet tower of similar rating. The steam turbine is a conventional unit with allowable back pressure in the range of 1.0 to 5.0 in.-Hg. Back pressure will be maintained at 4.5 in.-Hg at ambient temperatures below 95 F, but will be allowed to rise to 5.0 at temperatures above 95 F. The unit will be provided with a precipitator and SO₂ scrubber.^(a)

3.3 WATER AVAILABILITY AND QUALITY

Approximately 1900-acre-ft of water are available annually from the San Juan River for consumptive use in the cooling towers of Unit 3. The water has the following assumed analysis:

(a) The Public Service Company of New Mexico provided much of this information on the San Juan Unit 3.

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 3-1. Meteorological Profile at Farmington, NM

<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

4.0 ALTERNATIVE DRY/WET COOLING TOWER CONCEPTS

The purpose of this document is to provide a preconceptual design and cost estimate of four approaches to dry/wet cooling that use ammonia as the heat transfer medium. To relate these results with those presented in an earlier report, A Study of the Comparative Costs of Five Wet/Dry Cooling Tower Concepts (BNWL-2122),⁽⁴⁾ the description of the conceptual design of the integrated dry/wet cooling tower concept is repeated. This is the configuration of the cooling system being constructed by Public Service Company of New Mexico for the San Juan Unit 3 plant. The preconceptual design and cost estimates included here were developed without obtaining the design details or cost from either the owner or the manufacturer of that system. (Consequently, all systems were estimated by the same method and from similar data bases.) The design for the integrated dry/wet system was reestimated by the architect-engineering firm that contributed to this study, S&Q Engineering Company, Inc. of San Francisco, to provide a normalizing indicator between this study and the earlier one.

4.1 AMMONIA HEAT TRANSFER CONCEPT

The four cooling concepts principally studied in this report utilize the ammonia liquid-vapor phase change to transfer heat from the steam turbine outlet to the cooling towers. The portions of the system that are common to all three cooling tower concepts are described here and will not be repeated in the SCAT or horizontal tower descriptions.

Exhaust steam from the last stage of the turbine is condensed in the condenser/reboiler located directly below the turbine. Liquid ammonia is partially evaporated as it is pumped through the tubes of the reboiler. The flow rate of ammonia is regulated to yield outlet vapor qualities of 50 to 90%. The vapor is separated from the mixture and piped to the direct condensing cooling tower; the remaining liquid is recycled through the reboiler. The driving force for the ammonia vapor transport from the reboiler to the condenser is the difference between the saturation pressures in these components. Condensed liquid

ammonia is returned to the reboiler by gravity. The ammonia reboiler, vapor separator, piping to the tower area and ammonia pumps are common to all these tower concepts.

4.1.1 Vapor Separator/Reboiler Supply Tank

A conceptual design of the vapor separator/reboiler supply tank is shown in Figure 4-1. The tank is to be located as close to the steam condenser/ammonia reboiler exit as possible. The upper portion of the tank acts as a cyclone separator to remove liquid ammonia carried over in the vapor leaving the reboiler. The lower portion of the tank acts as a reservoir for supplying the reboiler injection pumps and also provides system surge capacity. The lower portion of this tank has sufficient volume to contain the inventory of two tower quadrants if it becomes necessary to evacuate them for maintenance or in case of leaks.

The piping for the system consists of vapor transport piping, vapor distribution piping, condensate collection piping, and condensate return piping. Associated with this system are tower condensate return pumps, a combination vapor separator/reboiler supply tank, reboiler reinjection pumps, and storage tanks and drain pumps as well as elbows, tees, reducers, and valves. All of these components must be designed to withstand a maximum system pressure of 350 psi and 150°F. All joints must be welded with a minimum of 5% x-ray inspection of the welds. The material for all piping and tanks is carbon steel (ASTM A-53, grade B; or ASTM A-139, grade B; or equivalent). Fittings are to be carbon steel-ASTM A-234, ANSI B16.9, or MSS SP-48. Valves are flanged carbon steel-API 6D, modified for anhydrous ammonia service. Stainless steel bellows are to be used for expansion joints where necessary.

4.1.2 Storage Tanks

Excess storage capacity will be provided by ten 7750-gal pressure tanks. These tanks will store the entire quantity of ammonia if it becomes necessary to evacuate the system for maintenance or in case of emergency. The tanks are interconnected and are vented to the main system by 3-1/2-in. pressure equalizer lines shown in Figure 4-2. The system is drained and filled through 8-in. lines by means of a 2500-gpm (at 50 ft TDH) pump.

FIGURE 4-1. Vapor Separator/Ammonia Reboiler

FIGURE 4-2. Ammonia Piping System

4.1.3 Steam Condenser/Ammonia Reboiler

The steam condenser is composed of horizontal tube bundles, with steam condensation on the shell side, and anhydrous ammonia evaporation on the tube side. Design tube side maximum pressure is 350 psig, 135°F. Construction is according to TEMA BEM standards (TEMA Class R, single pass, bonnets, stationary tubesheet, welded tube to tubesheet joints, cross baffles). Tubes are aluminum (ASME SB-234), with the following dimensions:

tube length	50 ft
tube OD	1 in.
tube gauge	12 BWG
tube pitch	1.5 in.
total number of tubes	15,100

The tube is enhanced on the outside for condensation and on the inside for boiling with proprietary Union Carbide Company/Linde enhanced condensation surface. The tubesheets are aluminum (ASME SB-241), and the condenser is equipped with impingement protection where necessary.

The air removal section of the condenser is stainless steel.

The performance and cost of this component are significant uncertainties in this study. The cost algorithms developed for computer optimization studies on the basis of laboratory data indicated its cost would be very nearly similar to that of a conventional turbine condenser. The estimate developed by the architectural engineer and used in this study, reflected the lack of firm data from similar equipment. The architectural engineer estimated the equipment to be 50% more costly than a conventional condenser.

4.1.4 Pumps

Each of the two condensate return pumps has a capacity of 10,000 gpm at 27 ft NH_3 TDH. Each of the two reboiler injection pumps has a capacity of 20,000 gpm at 30 ft NH_3 TDH. The drain and fill pump has a capacity of 2500 gpm at 50 ft NH_3 TDH.

4.1.5 Purge System

A nitrogen purge system will be required to flush the air from the system before filling it with ammonia. The total volume of the system is approximately 50,000 ft³. Nearly all oxygen must be removed from the system before filling it with ammonia in order to prevent the possibility of stress corrosion cracking of the steel components. This is to be accomplished by filling with nitrogen at one end of the system while venting to the atmosphere at the other end until the system is satisfactorily flushed of oxygen. If a tower quadrant is shut down and drained of ammonia for maintenance or repair, it will be required that that quadrant be flushed of oxygen before refill.

4.1.6 Tower Vent and Flare System

Located at the topmost point of each tower quadrant is a vent port and solenoid valve through which the quadrant can be evacuated of ammonia vapor after it has been isolated by closing the isolation valves in the quadrant supply and drain lines. Lines with 1/2-in. diameters connect the quadrant top vent ports to a flare station on top of the tower where the escaping ammonia vapors can be flared off.

4.2 VERTICAL HÖTERV PLATE-FIN TOWER WITH DELUGE

The initial design using the HÖTERV plate-fin heat exchangers was arranged in a configuration of round towers with fans over the top and the heat exchangers around the periphery. This arrangement was felt to be very cost effective for long fin-tube heat exchangers as conceptualized in the previous study⁽⁴⁾ and was being used as the preferred configuration in the design optimization code for dry/wet systems that is currently being developed in the Dry Cooling Enhancement Program at PNL. However, as the result of the design study described herein, we questioned the cost effectiveness of this configuration when applied to the HÖTERV bundles arranged horizontally to accommodate deluging. Therefore, a second configuration was scoped out and estimated in which the heat exchangers were arranged as A-frames on a plane below the fans. This provided a lower cost system and is described in Subsection 4.3.

4.2.1 Cooling Towers

This design features three round towers with plate-fin bundles horizontally disposed and stacked vertically around the periphery of each tower. A sketch of one of the three proposed cooling towers is shown in Figure 4-3. Each circular tower is capable of handling 1/3 of the heat load. The three cooling towers are located as shown in Figure 4-2. The spacing between towers is a minimum of 120 ft.

The cooling tower is designed to operate as a completely dry system during the cooler periods of the year. When the air temperature is sufficiently high, a portion of the heat exchanger surface is deluged with water on the outside of the plate fins to increase heat rejection capability. In this way, sensible heating of the air is augmented by heat transfer to the air by evaporation of the deluge water. The overall tower design is based upon the maximum use of available water for augmentation with minimum amount of heat exchange surface area. With this particular design, all the heat load from the power plant can be rejected at ambient temperatures of 55°F or below. Above 55°F, sections of the tower(s) must be augmented (deluged) to meet the load.

The airflow through each tower is induced by 19 fans (28-ft diameter) mounted at the top of the tower structure. The heat exchanger bundles (240 tubes/bundle) are arranged around the periphery of the towers as shown in Figure 4-3. Augmentation water is distributed to uniformly deluge the tubes and plate fins. Protection of the heat exchanger surfaces is provided by hail screens mounted directly to the face of each bundle. Table 4-1 gives specific information on the cooling tower system at design point conditions.

4.2.2 Heat Exchangers

The heat exchangers may be described as plate-fin bundles which are 47.6 ft (15 m) long, 7.8 ft (2.3 m) high, and 5.9 in. (15 cm) deep in the direction of airflow. There are 16 bundles/tower quadrant, 96 bundles/tower, and 288 bundles total. Each bundle contains 240 tubes and 4977 plate fins. The tubes are in six staggered rows. The distance between rows is 0.98 in., and the tubes in each row are 2.36 in. apart. The tubes are arranged for single

FIGURE 4-3. Vertical HOTERV Tower

TABLE 4-1. Vertical HÖTERV Tower Design Parameters

Parameter	Description
dry tower design ambient temperature (100% dry operation)	55°F
ammonia reboiler exit temperature	124.8°F
tower inlet temperature	122°F
overall design ITD	69.8°F
tower design ITD	67°F
heat of vaporization of ammonia steam	452.6 Btu/lb
ammonia flow rate	5.4×10^6 lb/hr
air stream exit temperature	108.2°F
airflow rate (100% dry operation)	1.93×10^8 lb/hr
air side static pressure drop across bundle	0.356 in. H ₂ O
frontal area of heat exchanger	1.072×10^5 ft ²
mass flow of air (dry operation)	1799 lb/hr-ft ²
mass flow of air (wet operation)	900 lb/hr-ft ²
face velocity (velocity immediately upstream of tube bundle)	8 ft/sec
log mean temperature difference	33.5°F
overall heat transfer coefficient	7.57 Btu/hr-ft ² -°F
total surface area	9.71×10^6 ft ²
tube length	47.6 ft
total number of heat exchanger tubes	69,120
number of towers	3
number of bundles per tower	96
number of bundles per tower per quadrant	16
total number of bundles	288
number of tubes per bundle	240
number of passes	1
tube and fin material	aluminum
tube OD	0.78
tube ID	0.699
fin thickness	0.013 in.
fin spacing	0.113 in. (106 fins/ft)
free area fraction for airflow	0.612
number of rows deep	6
bundle width	7.87 ft
tube geometry	staggered rows
tube transverse pitch (perpendicular to airflow)	2.36 in.
tube longitudinal pitch (in direction of airflow)	0.98 in.
total number of fans	57
number of fans per tower	19
fan diameter	28 ft

pass with appropriate header design. The bundle tubes are 47.6 ft long, and the overall bundle length is approximately 48.5 ft. The bundles are 7.87 ft wide. They are mounted as shown in Figure 4-3. The tubes are sloped at a 5 degree angle to promote drainage of the condensed ammonia. The bundles are also canted forward as shown in Section B-B of Figure 4-3 to promote uniform deluging of the plate fins during wet operation.

4.2.3 Fans, Motors, and Controls

The fan selection for the ammonia cooling system is shown in Table 4-2. The fans will be remotely controlled from the power house. For airflow control, one or more fans can be started or stopped.

TABLE 4-2. Fan Design Parameters for Vertical HÖTERV Design

<u>Parameter</u>	<u>Description</u>
fan diameter	28 ft
blade material	fiberglass
number of blades	6
blade angle	12 degrees
flow rate/fan	9.81×10^5 cfm
total pressure	0.464 in. H ₂ O
HP/fan	80.3 hp
inlet bell	5 ft long 6.9-ft radius maximum diameter 31.5 ft
velocity recovery stack	18 ft long 7 degree angle
stack construction	fiberglass
bell construction	carbon steel
number of fans per tower	19
total number of fans	57
fan packing arrangement	see Figure 4-3
blades	fixed pitch
motor	single speed ac motor (480 V)
direct drive	gear train

4.2.4 Hail Screens

The ammonia condensing system requires no louvers for airflow control since there is no problem from excess cooling and freezing of the ammonia. Simple hail screens mounted to the face of each individual tube bundle provide adequate protection against hail and debris.

4.2.5 Piping System

A schematic of the vapor piping system is shown in Figures 4-2 and 4-4. All of the vapor transport piping lies above grade. The main vapor line transports ammonia vapor from the vapor separator to the general area of the cooling towers through a 48-in. diameter pipe approximately 1000-ft long. At the end of this main line the flow splits into three 30-in. lines, one to each tower as shown in Figure 4-2. At the tower, the 30-in. line feeds into four 16-in. lines, one leading to each tower quadrant. Each 16-in. line runs along the ground until it reaches the center of the tower quadrant that it supplies. It then splits into two 12-in. lines, each supplying half of the quadrant, as shown in Figure 4-4. The 12-in. lines rise vertically up the tower, feeding vapor directly to four bundles each. They are then reduced to 10-in. lines and feed four more bundles. These lines are then reduced to 8 in. to supply four more bundles each. Each bundle header is connected to this main header system by 4-in. lines.

The condensed liquid ammonia is drained from the low end of each bundle through a 2-1/2-in. diameter drain pipe into a riser that drains to a collection header located about 3-1/2 ft below the bottom of the lowest bundle. This collection pipe runs around the inside periphery of the tower alongside the deluge collection basin channel (see Figures 4-2 and 4-4). Six bundles from the two farthest quadrant risers drain into two 5-in. diameter lines which then enlarge to 10 in. to drain the next 12 bundles. The lines next enlarge to 12 in. to drain the next 12 bundles, and finally to 16 in. to drain the remaining bundles. The two 16-in. lines then combine into an 18-in. line which drains to the main condensate return line.

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4.2.6 Deluge System

The deluge system is capable of augmenting the entire heat exchanger surface, although the maximum design wet area is probably less than 67%. Augmentation of the plate-fin surfaces is accomplished by allowing an approximate water flow rate of 2 gpm/ft of heat exchanger or 600 gpm/quadrant to run down the plate fins. This water is supplied by perforated pipe headers to the splash plate at the top of each six-bundle stack (see Figure 4-4). It then runs down the splash plate directly onto the plate fins of the uppermost bundle. After flowing over the uppermost bundle, the deluge water flows onto another splash plate. A small perforated pipe header adds water to the splash plate to make up for the deluge water evaporated in the previous bundle. The water then flows down the splash plate onto the next bundle and this same process continues down the stack of bundles.

The deluge piping system is composed of three separate piping networks, one for each tower (see Figure 4-4). A common link exists between these three networks in the water treatment and blowdown system. Bleed and feed lines of polyethylene will provide the link from the water treatment area (in the center of the tower area) to each tower.

Each deluge piping network contains the following items:

- two deluge pumps (vertical sump),
- deluge storage sump,
- distribution piping, and
- deluge distribution headers and splash plates.

Each deluge pump will have a capacity of 1200 gpm at 80 ft of H_2O (two pumps per tower). The suction side of the vertical sump pump will be immersed in a circular concrete channel that catches all the water falling from the tube bundles. This channel not only serves as a collection basin, but also as a storage area when the tower is being operated dry. A 16-in.-diameter line is connected to the pump discharge header and is then split into four 8-in. lines, one for each quadrant. Each 8-in. line rises to the top of the tower in the center of each quadrant and then splits into two 5-in. perforated lines, as shown in Figure 4-4. Each 5-in. line supplies deluge water to an uppermost

bundle and is then reduced to 4 inches. Each 4-in. line then supplies one more uppermost bundle. Makeup water is supplied to the top of each lower bundle by perforated 1-1/2-in. and 1-in. lines branching from the 8-in. quadrant riser. All deluge piping in the quadrants is constructed of polyethylene.

4.2.7 Deluge Water

A maximum of 6.15×10^8 gal is available annually from the San Juan River for use in the deluge system. Maximum instantaneous consumptive use is approximately 4000 gpm. Because the system is open, no deoxygenation is specified; water treatment will consist of sulfuric acid addition to control pH to 7.6-7.8 and blowdown (800 gpm) to maintain a sufficiently low dissolved solids concentration. The blowdown will undergo lime softener treatment, and the effluent from the treatment plant will be recycled into the deluge system. Sludge from the softener (85 gpm) will be discarded to the effluent pond. See Subsection 5.3 for water treatment details.

4.2.8 Tower Control

The overall control of the cooling tower is accomplished through the use of a microprocessor. Important control functions include:

- fan control,
- ammonia leak detection,
- liquid ammonia level control,
- reboiler exit vapor quality control,
- dry/wet split control,
- water use monitoring,
- meteorological measurement,
- back pressure control, and
- emergency shutdown procedures

The ammonia cooling system will operate in an automatic mode with the aid of a microprocessor when the ambient air temperature and relative humidity are within certain limits. At an ambient temperature of 55°F or below, the system will automatically be operated dry at the lowest possible back pressure. Above this temperature, the control system will automatically determine the amount of wet operation required.

In this automatic mode the microprocessor will receive input information including the following items:

- turbine back pressure,
- plant power level,
- ambient air temperature,
- relative humidity,
- tower status,
- current amount of wet operation,
- cumulative water usage,
- selected temperatures and pressures throughout the system,
- selected flow rates,
- selected liquid level, and
- leak detection monitoring.

The microprocessor will analyze input data and take appropriate action to maintain the desired back pressure and economic water use. The control system will record system components or segments that are out of service.

The control system will have set procedures established for routine shutdown and evacuation, emergency shutdown in case of a hazardous ammonia leak, and startup. If a dangerous ammonia leak is detected, the control system will sound an alarm and initiate the shutdown and isolation of the particular tower, quadrant, or component in question. Detection of ammonia leakage into the condenser steam will initiate shutdown of the system.

If ambient temperatures become too high for the system to maintain sufficiently low back pressure, the control system will sound an alarm.

The wet-dry split control will be initiated manually, but the control system will indicate this split through a preprogrammed routine.

Deluge water quality (pH and conductivity) will be monitored by the control system, and alarms will be actuated if these parameters exceed set limits.

4.2.9 Power to the Cooling System

Power will be provided to the components listed below. All 3-phase power is 480 V and all single-phase power is 220 or 110 V.

reboiler injection pumps	150 kWe
condensate return pumps	70 kWe
cooling tower fans	360 kWe
deluge water pumps	140 kWe
drain and fill pump	20 kWe

4.3 HORIZONTAL HÖTERV PLATE FIN AMMONIA COOLING SYSTEM

As previously stated, the horizontal arrangement of the HÖTERV heat exchanger was scoped and estimated because, within the constraints on the orientation of these heat exchanger elements with deluge operation, the horizontal arrangement appeared to be more compact and potentially less costly.

The cooling towers in this design are rectangular in geometry with the heat exchanger bundles elevated off the ground to obtain adequate airflow to the bundles. The heat exchanger is composed of the same HÖTERV slotted plate-fin tube bundles as in the previous design. The cooling tower design is based on the same assumptions as in the vertical configuration design; i.e., the cooling tower is designed to operate as a completely dry system during the cooler periods of the year, but when the air temperature is sufficiently high, a portion of the heat exchanger surface is deluged with water on the outside of the plate fins to increase heat rejection capability. In this way, sensible heating of the air is augmented by heat transfer to the air by evaporation of the deluge water. The overall tower design is based upon the maximum use of available water for augmentation with minimum amount of heat exchange surface area. The design parameters for the heat exchangers were kept the same as in the case of the vertical arrangement (Table 4-1).

4.3.1 Cooling Tower

A sketch of one of the two cooling towers is shown in Figure 4-5. Each rectangular tower is capable of handling one-half of the heat load. The two cooling towers are located as shown in Figure 4-6. The spacing between towers is a minimum of 200 ft. The airflow through each tower is induced by 28 fans (28-ft diameter) mounted at the top of the tower structure. The heat exchanger bundles (240 tubes/bundle) are arranged in a horizontal A-frame configuration

FIGURE 4-5. Horizontal HÖTERV Tower

PLAN-PIPING DIAGRAM

ISOMETRIC-AMMONIA SYSTEM PIPING
TYPICAL FOR TOWERS #1 & 2

ISOMETRIC-DELUGE WATER SYSTEM PIPING

TYPICAL FOR TOWERS #1 & 2

LINE LEGEND

---	NH ₃ VAPOR
---	NH ₃ LIQUID
---	WATER SUPPLY
---	WATER RETURN (BLOWDOWN)
---	P
---	PRESSURIZED EQUALIZER

FIGURE 4-6. Horizontal HÖTERV Piping Plan

as shown in Figure 4-5. Augmentation water is distributed to deluge the tubes and plate fins uniformly. Hail protection for the heat exchange surfaces is not required. Specific parameters of the cooling tower system at design point conditions are the same as provided in Table 4-1, with the following exceptions:

number of towers	2
number of bundles per tower	144
number of bundles per tower per quadrant	36
number of fans per tower	28

With this cooling system design, all the heat load from the power plant can be rejected at ambient temperatures of 55°F or below. Above 55°F, sections of the towers must be augmented (deluged) to meet load.

4.3.2 Heat Exchangers

The heat exchanger bundles are essentially the same as described in Section 4.2.2, with 36 bundles/tower quadrant, 144 bundles/tower, and 288 bundles total. Each bundle contains 240 tubes and 4977 plate fins. The tubes are in six staggered rows. The distance between rows is 0.98 in., and the tubes in each row are 2.36 in. apart. The tubes are arranged for single pass with appropriate header design. The bundle tubes are 47.6-ft long, and the overall bundle length is approximately 48.5 ft. The bundles are mounted as shown in Figure 4-5. The tubes are sloped at a 5 degree angle to promote drainage of the condensed ammonia. The bundles are also in an A-frame arrangement as shown in Section B-B of Figure 4-5 to promote uniform deluging of the plate fins during wet operation.

4.3.3 Fans, Motors, and Controls

The fan selection for the ammonia cooling system (shown in Table 4-3) is similar to that for the vertical system (Subsection 4.2.3, Table 4-2) except for one less fan in the total system; hence slightly higher horsepower per fan.

The fans will be remotely controlled from the power house. For airflow control, one or more fans can be started or stopped.

TABLE 4-3. Fan Design Parameters for Ammonia Cooling System

<u>Parameter</u>	<u>Description</u>
fan diameter	28 ft
blade material	fiberglass
number of blades	6
blade angle	12 degrees
flow rate/fan	1.028×10^6 cfm
total pressure	0.464 in. H ₂ O
HP/fan	82.3 hp
number of fans per tower	28
total number of fans	56
fan packing arrangement	see Figure 4-5

4.3.4 Piping System

The piping system between the plant and the towers is described in Sub-section 4.1. A schematic of the vapor piping system at the tower is shown in Figure 4-6. All of the vapor transport piping lies above grade. The main vapor line transports ammonia vapor from the vapor separator to the general area of the cooling towers through a 48-in.-diameter pipe approximately 1000-ft long. At the end of this main line the flow splits into two 34-in. lines, one to each tower. Each 34-in. line runs to the centerline of the tower. There they feed the main header, which runs along the ground the length of the tower. One-sixth down the length of the tower, the main header splits up into an 18-in. riser and a 24-in. header, and continues down the length of the tower. At the one-half point, the header splits up into an 18-in. riser and an 18-in. header running down another one-third of the tower. At the end of the main header, a third 18-in. riser rises to the height of the bundles. Each riser splits up into 12-in. pipes that run one-sixth the length of the tower in opposite directions. Each 12-in. pipe supplies 24 bundles through twelve 6-in. pipes. The 6-in. pipes are split up into 4-in. pipes that supply individual bundles at their base.

The condensed liquid ammonia is drained from the bottom of each header through a 2-1/2-in.-diameter drain pipe. The drain lines from a pair of bundles are combined to form a 5-in. line that leads into a 6-in. header. Each 6-in. header drains 12 bundles. Two 6-in. headers drain into each 8-in. riser. Six 8-in. risers exist per tower. Three risers feed into each main header running along the ground on each side of the tower. The main header increases in size from the end of the tower as it picks up each riser. It starts out as 8 in. in diameter, goes to 10 in. in diameter and then to 12 in. in diameter. The two main return headers combine to form an 18-in. pipe. The 18-in. line from each tower takes the condensate to the tower pump pit where it joins the flow from the other. The 18-in. tower drain lines are required to slope 2 ft in the 100-ft distance from the towers to the condensate return pumps to drain properly. The total flow is then pumped through a 24-in. line back to the reboiler supply tank as shown in Figure 4-6.

4.3.5 Deluge System

The deluge system is capable of augmenting the entire heat exchanger surface. Augmentation of the plate-fin surfaces is accomplished by allowing an approximate water flow rate of 85 gpm/bundle to run down the plate fins. This water is supplied by perforated pipe headers to the splash plate at the top of each set of bundles (see Figure 4-6). It then runs down the splash plate directly onto the plate fins of each bundle. After flowing over each bundle, the deluge water flows into a trough and back into the return piping for the deluge water system.

The deluge piping system is composed of 16 separate piping networks, eight for each tower (see Figure 4-6). A common link exists between these networks in the water treatment and blowdown system. Bleed and feed lines of polyethylene will link the water treatment area (in the center of the tower area) to each tower deluge system. Total flow in the system is about 20,000 gpm.

Each deluge piping network contains the following items:

- deluge pump (vertical sump),
- deluge storage sump,
- distribution piping, and
- deluge distribution headers and splash plates.

Each deluge pump has a capacity of 1300 gpm at 40 ft of H₂O (eight pumps per tower). The suction side of the deluge water pump is supplied by an 18-in. return line from the bundle troughs and a water makeup line. An 18-in. pipe rises from the discharge of the pump to a 12-in. header running perpendicular to the bundles near the centerline of the tower. The height of the header corresponds to that of the apex of the A-framed bundles. The header supplies 18 bundles with deluge water via 6-in. lines running along the apex of each set of bundles, as shown in Figure 4-6. The remaining deluge water coming out of the bundles is caught and collected by troughs. The water runs toward the outside of the tower and runs into a 12-in. header and then into the 18-in. return riser. All deluge piping is constructed of polyethylene.

4.3.6 Deluge Water

The water supply system and treatment is identical for this concept as for the vertical design (Subsections 4.2.7 and 5.3).

4.3.7 Ancillary Subsystems

All other ancillary subsystems are the same as for the vertical configuration, e.g., Tower Controls (Subsection 4.2.8) and Power Distribution (Subsection 4.2.9).

4.4 SEPARATE CHANNEL AUGMENTED TOWER (SCAT)^(a)

The heat exchanger in this concept is an adaptation of the Curtiss-Wright surface comprising integral fins chipped from an extruded multiport aluminum tube. Heat is transferred from the condensing ammonia within the channels to the air stream passing over the outside heat exchange surfaces. Additional cooling is provided by the separate channel augmented tower (SCAT) system, which uses selected channels within each Curtiss-Wright multichannel tube as water channels. When water is pumped through these channels, increased cooling of the ammonia occurs by heat transfer to the water. The heated water is piped

(a) This system is the subject of a DOE patent application.

to a wet cooling tower either inside the dry tower (this design), to a separate wet tower outside the dry towers, or to any other cooling system. The basic design parameters for the SCAT system are the same as the previous two concepts. The tower can reject the design heat load of 2.5×10^9 Btu/hr without the use of any water at a turbine exit temperature of 130°F, an ambient temperature of 55°F, and an 8°F temperature drop across the condenser/reboiler and the ammonia transport lines.

4.4.1 Cooling Tower

A sketch of one of the two cooling towers is shown in Figure 4-7. Each circular tower is capable of handling one-half of the heat load. The two cooling towers are located as shown in Figure 4-8. The spacing between towers is a minimum of 120 ft.

Each tower can be operated all dry or with additional SCAT cooling in the wet tower. The airflow through each tower is induced mechanically with 34 fans (28-ft diameter) mounted at the top of the tower structure. The heat exchanger bundles (80 tubes/bundle) are arranged around the periphery of the towers as shown in Figure 4-7. SCAT water is pumped from the center basin to the bottom header of each bundle, passing through five channels in each tube and out the top header to the wet tower inlet basin.

4.4.2 Heat Exchangers

The heat exchangers are bundles of multiport finned channels 50 ft x 12 ft x 1 ft (in the direction of airflow) of the integral chipped-fin type manufactured by Curtiss-Wright. The condensing tubes are vertical single pass with ammonia vapor entering at the top and saturated liquid ammonia emerging at the bottom. Each bundle consists of 80 tubes, 12.3 in. in depth and 50 ft long. Figure 4-9 shows the cross-section of the tubes and Figure 4-10 shows the header arrangement for the ammonia vapor inlet and circulating water outlet. For the purpose of sizing the tower, the fins over the back portion of the tube where the water channels are located are not included in the calculation of heat transfer to the air during wet operation but are included in the calculation for pressure drop.

FIGURE 4-7. SCAT Cooling Tower Design

FIGURE 4-8. Site Plan for Ammonia Concept

FIGURE 4-10. Header Arrangement of SCAT Heat Exchanger

Table 4-4 summarizes the design parameters for the SCAT concept operating in the all-dry mode.

For enhanced cooling, water is run through five alternating channels in the rear (relative to airflow) of the SCAT tube. The temperature range of this water, the overall heat transfer coefficient, and the effectiveness of this section of the bundle for heat transfer are calculated independently of any interaction with the airflow over the tube. This is justified by the fact that the air and the cooling water would be at approximately the same average temperature in this part of the bundle and the presence of the air would neither add nor subtract from the cooling action of the circulating water.

4.4.3 SCAT Wet Tower

The wet tower which provides cooling of the circulating SCAT water is integrated with the dry tower, and is located concentric and within this structure. A portion of the air drawn through the heat exchanger is taken on through the wet packing and exhausted by the wet tower fans. The rest of the air is exhausted by the dry-only fans arranged in the annular region between the respective peripheries of the wet and dry towers. When the tower is operated at less than fully enhanced cooling capacity, sections of the wet packing are not wetted; none are wetted during all-dry operation (below 55°F). The pressure drop through the dry packing of the wet tower has been neglected in the calculation of required fan horse power. The design parameters of the wet tower are listed in Table 4-5.

4.4.4 Fan and Motors

The fan selection for the cooling system is shown in Table 4-6. The fans will be remotely controlled from the power house. For airflow control, one or more fans can be started or stopped.

4.4.5 Ammonia Piping System

The piping system between the plant and the tower is as described in Subsection 4.1. A schematic of the vapor piping to the towers is shown in Figure 4-11. Vapor transport lines are above grade. The main line from the vapor separator to the general area of the cooling towers is a 48-in.-diameter

TABLE 4-4. SCAT Dry Tower Parameters

Parameter	Description
tower design ambient temperature (100% dry operation)	55°F
heat of vaporization of ammonia	452.6 Btu/lb
tower inlet temperature	122°F
overall design ITD	69.8°F
tower design ITD	67°F
ammonia reboiler exit temperature	124.8°F
ammonia flow rate	5.46×10^6 lb/hr
air stream exit temperature at 55°F ambient	107.1°F
airflow rate	1.97×10^8 lb/hr
air side static pressure drop across bundle	0.281 in. H ₂ O
air side static pressure drop (total)	0.384 in. H ₂ O
frontal area of heat exchanger	0.732×10^5 ft ²
face velocity (velocity immediately upstream of tube bundle)	12 ft/sec
log mean temperature difference	34.7°F
overall heat transfer coefficient	8.0 Btu/hr-ft ² -°F
total surface area	8.91×10^6 ft ²
tube length	50.0 ft
total number of heat exchanger tubes	9,760
number of towers	2
number of bundles per tower	61
number of bundles per tower per quadrant	15 or 16
total number of bundles	122
total number of tubes per bundle	80
number of passes	1
fin length	0.707 in.
fin thickness	0.012 in.
fin spacing	10.6 fins/in.
free area fraction for airflow	0.73
bundle depth	12.3 in.
bundle width	12 ft
tube geometry	single row multichannel
tube transverse pitch perpendicular to airflow	1.8 in.
total number of fans	48
number of fans per tower	24
fan diameter	28 ft
fan horsepower	60 hp/fan

TABLE 4-5. SCAT Wet Tower Parameters

Parameter	Description
ambient air temperatures	97°F dry bulb 62°F wet bulb
air temperatures into wet tower (inside dry tower)	113.6°F dry bulb 67.5°F wet bulb
inlet water temperature	107.8°F
outlet water temperature	90°F
range	17.8°F
approach	22.5°F
tower diameter	135 ft
structure	partial inverted truncated cone
fill	depth, 16 ft height, 32 ft
composition	asbestos-cement slats, ABC splash bars in noncombustible GRP support grids
fill supports	fiberglass webbing
drift eliminators	asbestos-cement V-slats, ABC eliminators in noncombustible GRP support forms
partition walls (top of wet tower roof and segments between tower halves)	asbestos-cement sheeting and louvers, ABC perimeter and shield
SCAT piping	Schedule 40 PVC piping

pipe approximately 1000 ft long. At the end of this main line, the flow splits into two 36-in. lines, one to each tower. At the tower, the 36-in. line splits into four 20-in. lines, one leading to each tower quadrant. This 20-in. line runs along the ground until it reaches the center of the quadrant that it supplies, where it rises vertically to the top of the quadrant and splits into two 14-in. lines. Each 14-in. line feeds vapor directly to one bundle and is then reduced to 12 in. to supply the next three bundles. It is then further reduced to 10 in. to handle two more bundles, then to 8 in. to supply two bundles, and finally to 6 in. to feed the last two bundles of the branch.

TABLE 4-6. SCAT Tower Fans

Parameter	Description
fan diameter	28 ft
blade material	fiberglass
number of blades	6
blade angle	10 degrees + 22 degrees
flow rate/fan	9.32×10^5 cfm + 1.635×10^6 cfm
total pressure	0.384 in. H ₂ O
HP/fan	48 at 60 hp + 8 at 150 hp
velocity recovery stack	18 ft long 7 degree angle
stack construction	fiberglass
number of fans per tower	28
total number of fans	56
fan packing arrangement	see Figure 4-7
blades	fixed pitch
motor	single speed ac motor (480 V)
direct drive	gear train

The condensed liquid is drained from the bottom of each bundle through a 4-in.-diameter drain pipe into a collection header located about 3-1/2 ft below the bottom of the bundle. This collection pipe runs around the periphery of the tower. Two bundles from each quadrant drain into a 6-in.-diameter line that then enlarges to 8 in. to drain the next three bundles. The 8-in. line enlarges to 10 in. to drain five more bundles of the quadrant; it then enlarges to 12 in. to drain all remaining quadrant bundles. The 12-in. line continues to follow the periphery of the tower until lines from all four tower quadrants join a common collection header, which combines the tower flow into a 20-in. line. The 20-in. line from each tower flows the condensate to the tower pump pit where it joins the flow from the other tower. The 20-in. drain lines are required to slope 3 ft in the 60-ft distance from the towers to the condensate return pumps in order to drain properly. The total flow is then pumped through a 22-in. line back to the reboiler supply tank. The condensate return piping is also shown in Figure 4-11.

FIGURE 4-11. SCAT Ammonia Piping

4.4.6 SCAT System

The SCAT system is shown in Figure 4-12 and consists of 16 pumps (eight per tower). Each pump is to be 12,000 gpm at 35-ft head and requires a 185 hp motor. The pumps will be set in wells around the circumference of the wet tower collection basins. Taking their intake from the basin, each pump draws water through a 24-in. line into a distribution header where the water distributes into 8-in. lines, one running to the base of each heat exchanger tube bundle. The water flows upward through the bundle-tube SCAT channels, being heated by the ammonia in the adjacent channels; 8-in. lines carry the heated water along the roof of the tower and down to the wet tower distribution basin. As the water falls through the wet tower splash packing, fans (four 150-hp fans per wet tower) draw air through the packing and upward out of the wet tower.

4.4.7 SCAT Water

A maximum of 6.15×10^8 gal of water is available annually from the San Juan River for use in the SCAT system. Maximum instantaneous consumptive use is approximately 3200 gpm. Because the system is open, no deoxygenation is specified; water treatment will consist of chemical addition to control pH to 7.6-7.8 and blowdown as required to maintain a sufficiently low dissolved solids concentration. The blowdown may undergo lime softener treatment, and the effluent from the treatment plant will be sent to the settling pond.

4.4.8 Ancillary Subsystems

All other ancillary subsystems are very similar to the vertical configuration, as discussed in Subsections 4.2.8 and 4.2.9. The power requirements of the SCAT system are slightly different from those of the vertical system (as listed below) due to the different configurations of the two systems.

reboiler injection pumps	150 kWe
condensate return pumps	70 kWe
cooling tower fans	3729 kWe
SCAT water pump	2200 kWe
drain and fill pump	20 kWe

100

100

FIGURE 4-12. SCAT Water Piping

4.5 AUGMENTING AMMONIA CONDENSER ENHANCEMENT

Other concepts for enhanced dry cooling using ammonia could logically include the use of a "split waterbox" turbine condenser with both ammonia and water as coolants. Another possibility is the use of a water-cooled ammonia condenser, located at the dry tower, to handle ammonia vapor which could not be condensed by the dry tower, thereby augmenting the dry tower on a hot day. This latter approach was chosen for scoping for three reasons:

1. Primarily, since the water-cooled ammonia condenser is the simplest alternative to the SCAT system, i.e., it provides water cooling capability external to the dry surface rather than integrally, and thus addresses the question of cost effectiveness of dual-purpose surfaces such as the SCAT configuration.
2. The water-cooled ammonia condenser probably offers fewer design uncertainties than does the "split waterbox."
3. The loss of temperature difference incurred by going through the ammonia as an intermediate heat-transfer medium may be offset by the close proximity of the condenser to the wet tower, hence lower piping cost.

The water-cooled condensers (individual ones for each quadrant of the dry tower) are designed to "float" on the system. That is, they are designed to function in parallel with the dry tower to maintain the pressure in the ammonia system at a prescribed level in the same manner as with the SCAT design. Thus, they are designed to allow the cooling tubes to reach the ammonia temperature, and the amount of water circulation and evaporative cooling in the wet tower is controlled by the turbine back pressure at a level dictated by the plant operator. Since the operation of the dry tower is unaffected by the operation of the condenser (unlike the deluge approach), evaporative cooling is not substituted for dry cooling, and the dry tower can be somewhat smaller for the same water allotment. Like the integrated tower, described in Section 4.6, it is designed for an ambient air temperature of 35°F (ITD = 87°F) rather than 55°F (ITD = 67°F) for the other three systems.

4.5.1 Cooling Tower

A sketch of one of the two cooling towers is shown in Figure 4-13. Placement, spacing, and general configuration is similar to the SCAT towers. However, the higher design ITD and simpler tube configuration result in a smaller tower as shown in Figure 4-13. The heat exchanger bundles (80 tubes/bundle) are arranged around the periphery of the towers as shown, and the water-cooled condenser (four in each tower) are hung within the annular space between the periphery of the dry and wet towers. The enhancement cooling water is pumped from the center basin to the top header of each of the condensers, passes down and back up through the cooling tubes and out the top header to the wet tower inlet distribution box. The augmenting ammonia condenser water piping system is shown in Figure 4-14.

4.5.2 Heat Exchangers

The heat exchangers are bundles of multiport finned channels 50 ft x 12 ft x 7.2 in. (in the direction of airflow) of the integral chipped-fin type manufactured by Curtiss-Wright. Each bundle consists of 80 tubes 50 ft long.

Table 4-7 summarizes the design parameters for the dry tower.

Table 4-8 summarizes the design parameters for the eight water-cooled condensers. These are tube-in-shell pressure vessels designed for 350 psi at 150°F with ammonia on the shell side. Each is 8 ft in diameter and contain 875 U-bend aluminum tubes 1 in. in diameter 50 ft long. Maximum flow through each is 25,000 gpm.

4.5.3 Wet Towers

The wet tower which provides cooling for the circulating water is integral with the dry tower and is located concentric within this structure essentially the same as with the SCAT concept. The design parameters are the same as those listed in Table 4-5.

FIGURE 4-13. Augmenting Ammonia Condenser Cooling Tower Design

FIGURE 4-14. Augmenting Ammonia Condenser Water Piping System

TABLE 4-7. Augmenting Ammonia Condenser Dry Tower Design Parameters

Parameter	Description
tower design ambient temperature (100% dry operation)	35°F
heat of vaporization of ammonia	452.6 Btu/lb
tower inlet temperature	122°F
overall design ITD	89.8°F
tower design ITD	87°F
ammonia reboiler exit temperature	124.8°F
ammonia flow rate	5.4×10^6 lb/hr
air stream exit temperature at 35°F ambient	95.5°F
airflow rate	1.70×10^8 lb/hr
air side static pressure drop across bundle	0.243 in. H ₂ O
air side static pressure drop (total)	0.463 in. H ₂ O
frontal area of heat exchanger	0.522×10^5 ft ²
face velocity (velocity immediately upstream of tube bundle)	14.0 ft/sec
log mean temperature difference	50.9°F
overall heat transfer coefficient	9.1 Btu/hr-ft ² -°F
total surface area	5.41×10^6 ft ²
tube length	50.0 ft
total number of heat exchanger tubes	6960
number of towers	2
number of bundles per tower	0.44
number of bundles per tower per quadrant	11
total number of bundles	88
total number of tubes per bundle	80
number of passes	1
fin length	0.707 in.
fin thickness	0.012 in.
fin spacing	10.6 fins/in.
free area fraction for airflow	0.73
bundle depth	7.7 in.
bundle width	12 ft
tube geometry	single row multichannel
tube transverse pitch perpendicular to airflow	1.8 in.
total number of fans	26
number of fans per tower	13
fan diameter	28 ft
fan horsepower	105 hp/fan

TABLE 4-8. Augmenting Ammonia Condenser Design Parameters for Water-Cooled Condensers

Parameter	Description
water inlet temperature	90°F
design ITD	32°F
ammonia flow rate	3.88×10^6 lb/hr
exit temperature of water	108°F
water flow rate	9.75×10^7 lb/hr
water velocity	7.0 ft/sec
log mean temperature difference	21.8°F
overall heat transfer coefficient	420
total surface area	1.83×10^5 ft ²
tube length	50 ft
total number of heat exchanger tubes	14,000
number of shells	8
number of shells per tower	4
number of tubes per shell	1750
number of passes per tube	2
diameter of shells	8.0 ft
diameter of tubes	1 in.
inside diameter of tubes	0.902 in.

4.5.4 Fans and Motors

The fans selected for this system, summarized in Table 4-9, are very similar to those for the SCAT systems (Table 4-6).

4.5.5 Ammonia Piping System

The piping system for this concept is identical to that for the SCAT with the exception of the connection to the water-cooled condensers which are in parallel to the dry-cooled tower. A 14-in. line continues over from the main supply line to each quadrant of the towers to the vertical water-cooled condenser, and a 6-in. condensate line issues from the bottom of the condenser to the main condensate collection line for each quadrant. All other piping is identical to the SCAT piping.

TABLE 4-9. Fans for Augmenting Ammonia Condenser System

Parameter	Description
fan diameter	28
blade material	fiberglass
number of blades	6
blade angle	16 degrees + 22 degrees
flow rate/fan	1.38×10^6 cfm + 17.1×10^6 cfm
total pressure	0.463 in. H ₂ O
HP/fan	26 at 105 hp + 8 at 150 hp
velocity recovery stack	18 ft long
stack construction	fiberglass
number of fans per tower	17
total number of fans	34
fan packing arrangement	see Figure 4-13
blades	fixed pitch
motor	single speed ac motor (480V)
direct drive	gear train

4.5.6 Water System

The water system is also closely similar to that of SCAT (described in Subsection 4.4.6) except that four pumps per tower are used, each of 25,000 gpm at 50 ft head and 550 hp. Each takes its intake from the basin through a 34-in. line which runs directly to the top of the condenser. A second line runs from the condenser water box to the distribution box of the wet tower.

Water treatment is identical to that for SCAT as described in Subsection 4.4.7.

4.5.7 Ancillary Subsystems

All other ancillary subsystems are very similar to those previously described in Subsections 4.2.8 and 4.2.9. Power requirements are slightly different, as follows, due to small differences in configuration:

reboiler injection pumps	150 kWe
condensate return pumps	70 kWe
cooling tower fans	2900 kWe
water pump	2600 kWe
drain and fill	20 kWe

4.6 INTEGRATED DRY/WET COOLING TOWER CONCEPT

This heat rejection concept is currently planned for use in the San Juan Unit 3. It was included in this study to provide a basis for comparing these alternative concepts to previous design concepts and to each other.⁽⁴⁾ To assure the validity of the comparisons, this concept, which is believed to approximate the system actually being constructed at the site, was conceptually designed and estimated using the same bases as the other concepts. The attempt was made to make this conceptual design resemble the San Juan Unit 3 cooling towers with respect to physical arrangement and performance as closely as was possible with the limited information provided by the utility and cooling tower supplier. That is, this concept was estimated without reference to actual cost figures to make the comparison on the same basis.

The heat rejection system uses water as the cooling medium. The cooling water receives thermal energy from condensing steam in a surface condenser. The heated cooling water is then transmitted to the cooling towers via a large diameter piping system. Two rectangular cooling towers house the heat exchange surface. The heat exchanger is composed of spiral-wrapped finned tubes tilted 25 degrees from horizontal above an array of wet tower packing. Heat is transferred from the cooling water to the air stream passing over the outside heat exchange surfaces, and the cooled water is then dumped directly into the wet towers. The cooling tower is designed to operate as a completely dry system during the cooler periods of the year by turning off the fans above the wet portion of the tower. When the air temperatures are sufficiently high, the fans above the wet portion of the tower are turned on to increase cooling capacity.

4.6.1 Cooling Tower

A sketch of the cooling tower is shown in Figure 4-15. Each rectangular cooling tower is capable of handling 50% of the heat load. The two cooling towers are located between north coordinates 2,112,800 and 2,113,800 and east coordinates 322,300 and 323,500, as shown on the site plan, Figure 4-8.

Each tower can be operated all-dry, all-wet (no airflow through the fin tubes), or fractions thereof. The airflow through each dry tower is induced by twenty 32-ft-diameter fans mounted at the top of the tower structure, and through the wet sections by five 26-ft-diameter fans. The exchanger bundles (groups of 1448 tubes/96-ft bundle) are arranged in flat sections tilted 25 degrees from horizontal. Table 4-10 summarizes the tower design parameters.

The design was based on the assumption that the total heat load could be rejected by the dry portion of the tower at ambient temperatures of 35°F or below. Above 35°F, sections of the wet tower(s) must be activated to dissipate the specified quantity of heat. This design condition was determined through the use of a PNL code which determined the integrated amount of water required to augment the cooling capability of a dry tower of a prescribed size. Thus, a dry tower capable of handling the entire plant heat load at 35°F would require the available 1900 acre-ft of water to meet the power requirements under the meteorological conditions at Farmington, NM.

4.6.2 Heat Exchangers

There are 10 heat exchanger units per tower, two units in each bay. Specifications for these exchangers are included in Table 4-10. The spiral-wrapped fin tubes are 1 in. in diameter, of admiralty metal, with the thin (0.018-in.) aluminum fin wound as a single leg wrap around the tube. They are arranged in a staggered equilateral close-packed spacing three rows deep. The two pass arrangement is accommodated by splitting the direction of flow through the middle row.

FIGURE 4-15. Integrated Dry/Wet Tower Plan, Section and Elevation

TABLE 4-10. Interated Dry/Wet Tower Design Parameters

Parameters	Description
number of towers	2
dry tower design ambient temperature	35°F
tower design ITD	89.8°F
cooling water flow rate	1.096×10^8 lb/hr
cooling water range	22.5°F
airflow rate dry section	2.196×10^8 lb/hr
airflow temperature range	46.6°F
airflow rate wet section (full capacity)	2.37×10^7 lb/hr
mass flow of air, dry section	2382 lb/hr-ft ²
mass flow of air, wet section	1580 lb/hr-ft ²
air side pressure drop	0.345 in. H ₂ O (corrected to exhaust air temperature and elevation)
frontal area of heat exchanger, total	9.216×10^4 ft ²
total surface area	7.206×10^6 ft ²
overall heat transfer coefficient	6.41 Btu/hr-ft ² -°F
number passes	2
fin design	single-leg wrapped
fin material	aluminum
tube material	Admiralty
tube OD	1.07 in.
tube ID	0.93 in.
fins/in.	10
fin OD	2.25 in.
fin thickness	0.018 in.
fin spacing	0.082 in.
width of one unit	96 ft in 12-ft-wide sections
depth of one unit	10 in.
length of one unit	48 ft
number of tubes/96-ft unit	1448
tube geometry	staggered, equilateral
transverse tube pitch	2.345 in.
number of units/tower	10
number of passes	2

4.6.3 Fans

A total of 25 induced draft fans were specified for each tower, 20 in the dry section and 5 in the wet section. Specifications for these fans are provided in Table 4-11.

Louvers have not been specified although they may be required for airflow control during high winds and for equalizing flow into each bay to avoid local freezing.

4.6.4 Piping System

The piping system for the cooling towers consists of cooling water pumps, concrete distribution piping between the condenser and heat exchange headers (collection basin and return), water treatment, elbows and tees, reducers and valves and is shown schematically in Figure 4-16.

TABLE 4-11. Integrated Dry/Wet Tower Fan Specifications

Parameter	Dry Sections	Wet Sections
fan diameter	30 ft	24 ft
blade material	fiberglass	fiberglass
number of blades	8	6
blade angle	14 degrees	16 degrees
fan speed	120 rpm	156 rpm
flow rate/fan	1,542,000 cfm at 80°F	702,000 cfm at 109°F
HP/fan	145	90
bell material	steel	steel
velocity recovery stack	18 ft	18 ft
stack material	fiberglass	fiberglass
number of fans/tower	20	5
total number of fans	40	10
blades	manually adjusted	manually adjusted
drive	gear train	gear train

Diagram illustrating the components and dimensions of a box header assembly:

- BOX HEADER** (8" REMOVABLE TOP PLATE FABRICATED FROM 1/2" PLATE)
- BUNDLE SUPPORT** (PRISM FABRICATED FROM 1/2" PLATE)
- FINNED JOINTS** (ROLLED AT HEADERS TO FORM WATER TIGHT JOINT)
- Dimensions:**
 - Overall width: 24"
 - Header width: 10"
 - Header height: 4"
 - Support height: 3"

UPPER HEADER
INTERNAL - STEEL UNLESS NOTED

LOWER HEADER

NONFERAL - STEEL UNLESS NOTED

LOWER HEADER DIVIDER PLAN

FIGURE 4-16. Integrated Dry/Wet Tower Cooling Water Piping System

The piping system supplies cooling water to the general area of the cooling towers through 96-in.-diameter buried concrete pipe that is approximately 1400-ft long. The return line is similar. During cold weather, the towers can be bypassed completely to allow a reasonable temperature rise in the water before entering the towers. At the tower end of the 96-in. line, the flow is first separated into two 72-in. lines. The 72-in. lines are then split into two 48-in. lines for each of the two towers.

The 48-in. lines (two per tower running parallel down the tower length) supply circulating water to 6-in.-diameter lines every 12 ft along the length of two bays, 192 ft. At this point the lines are reduced to 36-in. in diameter for the remaining 288 ft, again with 6-in.-diameter lines off the 36-in.-diameter lines. Each 6-in.-diameter line goes to a 12-ft-wide, two-pass, three-row bundle containing 182 tubes. After passing through the bundle, the circulating water may either be distributed into the wet sections in the center of each group of 8- to 12-ft-wide bundles, or it may be bypassed through two 24-in. wet section bypasses, one on either side of the wet section. The water is collected in the tower basin and flows to a sump where it is pumped to the condenser through a 96-in.-diameter line by three 73,000-gpm (77-ft head) vertical well pumps.

The basin has the capacity to hold more than 150,000 gal of water or the entire inventory of the cooling tower. When the cooling system goes off-line, the water in the cooling tower will drain into the tower basin. The 122,000-gal addition should raise the water level in the basin about 1.0 ft. The water in the basin may be drained to the influent pond by operating the makeup drain pump. The water in the remaining piping is gravity drained by a separate line from the lowest point (near the condenser) to the influent pond. The makeup line also acts as the fill piping and is capable of providing sufficient operating water in about 7 hours.

The San Juan River will provide makeup water for the recirculating water system. A flow of 4000 gpm will be pumped to the influent pond to allow settling of solids. Makeup water will be taken from the pond. Water treatment will be performed in a side-stream treatment plant with 1000-gpm capacity.

Treatment will consist of lime-soda softening dispersant addition (phosphonate and polyacrylate), scale inhibition (H_2SO_4) and biofouling control (chlorine plus supplemental quaternary ammonium/tributyl tin oxide). The treatment facility will consume 85 gpm for washing and dilution.

4.6.5 Condenser

A single water box condenser is used and has a heat rejection capacity of 2.462×10^9 Btu/hr with a water flow rate of 219,000 gpm. Particulars regarding the condenser are provided in Table 4-12.

4.6.6 Ancillary Subsystems

All other ancillary subsystems are similar to those described in Subsection 4.2, specifically, the tower controls in Subsection 4.2.8. The power required by each of the various systems does differ significantly as follows:

circulating water pumps	4000 kWe
cooling tower fans	4400 kWe

TABLE 4-12. Integrated Dry/Wet Tower Condenser Details

<u>Parameter</u>	<u>Description</u>
tube diameter	1 in.
tube length	35 ft
tube gauge	20 BWG
tube material	Admiralty
air removal section	stainless steel
number of tubes	28,500
tube geometry	square

5.0 BASES FOR COST ESTIMATES

The cost estimates for construction and annual operation were based on a variety of sources. S&Q Engineering Company, Inc, San Francisco, CA, architect-engineers, provided the four conceptual cost estimates for the Dry Cooling Enhancement Development program. These estimates were based on the facility descriptions and conceptual sketches provided by PNL.

Sections of the three advanced systems and the state-of-the-art system have been previously estimated by Vitro Engineering Company, Richland, WA.⁽⁴⁾ S&Q did not reestimate these sections; however, S&Q did provide independent cost estimates for:

- a) main vapor distribution and condensate collection piping,
- b) circulation pumps,
- c) cooling towers,
- d) electrical/instrumentation, and
- e) water quality control.

S&Q reviewed the Vitro cost estimates to ensure that their own estimates were comparable. The capital cost estimates provided by S&Q should be considered as "preconceptual" estimates. They are intended for use for comparative evaluation of the systems investigated.

All cost data were normalized to mid-1976 dollar values.

5.1 CONSTRUCTION COSTS

Construction costs for the three concepts described in Section 4.0 were estimated from conceptual designs prepared from system descriptions. Copies of these system descriptions may be obtained from PNL. Construction costs estimates were performed by S&Q Engineering Corporation.

Costs for material and equipment were obtained from phone discussions with suppliers and vendors and from S&Q purchase order files. Medium range or "average" prices were used from the cost data sources. PNL provided costs for heat exchanger bundles and tower fans.

Labor costs for the work to be accomplished were derived from such sources as S&Q estimating files and R. S. Means Co., Inc. Area craft rates were secured from the Federal Register to reflect the geographical location under consideration.

Engineering services and construction management costs were estimated at 10% of the direct construction cost.

Although no escalation or contingency values are used in any of the comparable cost listings of the five systems, these items are shown on summary work sheets of the S&Q estimates shown in Appendix A. They include an escalation of 9.9% for 2.5 years and a contingency of 30% to reflect the preconceptual nature of the estimate.

5.2 ANNUAL OPERATING COSTS

The preconceptual designs which have been developed and evaluated in this report are not the optimal design for each system, i.e., they are not designs which have been coordinated with the design and sizing of the steam supply to give the lowest cost of busbar electricity. Instead, they are designs which fit a stipulated set of conditions with respect to ambient temperature and heat rejection capability.

Optimization studies of dry (and dry/wet) systems generally compare the "operating costs" of alternative systems in terms of several "penalty costs." These "penalty costs" represent the incremental increases in plant operating costs resulting from the use of the dry cooling system in relation to a reference system with a once-through flow of cooling water. Included in the list of penalty costs may be the following:

- Energy Penalty. This is the cost of electricity which cannot be exported by the dry-cooled plant in relation to the reference plant, because 1) it is used internally to power auxiliary fans and pumps not required in the reference plant, and 2) the gross plant output is lower than the reference plant due to high heat sink temperature (i.e., the ambient temperature) and lower turbine efficiency. It is assumed this unavailable power must be supplied from some other source and the cost is assessed against the dry cooling system. Several different rationales have been used in setting the cost of this power.⁽⁵⁾

- Capacity Penalty. This is the capital cost of the source of power to supply the difference in net plant output at the hottest hour. The difference in net plant output of the dry-cooled plant in relation to the reference plant, at the highest annual ambient temperature must be available from some power source. The capital cost of having this source (peaking reserve) on hand is assessed to the dry cooling system. The two sources of energy deficiency just noted translate into corresponding needs for additional generating capacity to supply: 1) the power required by the cooling system auxiliaries (fans and circulating pumps), and 2) the power deficiency arising from the lower plant efficiency at the hottest hour of the dry-cooled plant.
- Makeup Water Penalty. This is the sum of the capital cost for the makeup water system, pumping costs, and water purchase and treatment costs. The bases for estimating the treatment costs are provided in Subsection 5.3. The capital cost of the water treatment system is included in the system cost estimate.

An "optimized" design represents a trade-off between a larger-sized cooling system which has small energy and capacity penalties and a smaller-sized cooling system which has larger penalties.

With the present comparison of four systems (and the previous comparison of five systems in BNWL-2122) there were no such trade-offs involved in the designs. All were sized to meet stipulated parameters of inlet temperature difference, heat rejection capability and annual water rate. Thus, the gross plant output is approximately the same from a plant equipped with each cooling system. However, the total penalties would differ with each design depending on the characteristics of each with respect to: 1) the power required for fans and water/ammonia recirculating, 2) the capacity penalty for this power, i.e., the cost of the peaking reserve required to supply this power, and 3) water treatment and pumping power required for the enhanced (evaporative) cooling system.

In addition, there is a negative energy penalty which may arise from increased output in cold weather which differs in each case. All plants have been designed to reject the stipulated heat load at a particular design ambient temperature. At temperatures below this, the plant is capable of producing more than the rated power--or operating at rated output with lower fuel consumption because of higher turbine efficiency (lower back pressure). The assumption is made in this study that no market exists for excess power generation in the winter and consequently credit is taken only for fuel savings from the higher plant efficiency. The four alternatives (and the previous five alternatives--BNWL-2122) are not designed to the same reference ambient temperature. This situation arises because they do not all use water at the same rate, yet each system may use only the stipulated annually available water. The systems relying on deluge cooling for enhancement are different from those in which the dry and wet systems are essentially independent. With the deluge systems, dry surface is lost from service as evaporative cooling is added. Consequently, to maintain the same annual water use rate, the dry tower with deluge cooling must be larger (designed for a higher ambient temperature) than a similar tower with separate evaporative cooling. Hence, in this study the deluged systems designed are designed for a 55°F ambient and separate systems for 35°F. This requirement calls for a larger tower with deluge cooling but has the compensating effect that the plant can operate at a lower back pressure in the winter and thus use slightly less fuel. Credit is taken for this difference.

In summary, in this study the differences in "penalties" among the various alternatives are accounted for by evaluating five "operating" cost terms and a sixth capital cost term. Those six cost terms are:

- power for the main circulating system,
- power for the fans,
- water treatment operating costs,
- power for pumping deluge water,
- fuel savings resulting from the capability to operate at lower than the reference turbine back pressure at temperatures below the design ambient, and

- capital cost of peaking reserve capability to provide auxiliary power to the cooling system.

To combine these "operating" and other penalty costs with the capital costs of the plant, the former are "capitalized" by dividing by an annual fixed-charge rate of 18% and adding them to the capital cost. (Table 6-2, together with the footnotes, summarizes these estimates.)

5.3 WATER TREATMENT COST

A maximum total volume of 6.15×10^8 gal of water from the San Juan River is available for use in any of the wet/dry cooling systems each year. The assumed water quality parameters for the makeup water are shown below:

total hardness	20 to 40 mg/l as CaCO_3
calcium hardness	15 to 30 mg/l as CaCO_3
total alkalinity	10 to 25 mg/l as CaCO_3
sulfate	10 to 15 mg/l as CaCO_3
total dissolved solids	50 to 100 mg/l as CaCO_3
silica	11 ppm
pH	6.5 to 7.5

The water treatment assumed can be grouped into two processes for the five systems being compared (four ammonia systems and the reference integrated dry/wet system).

The water treatment for the deluge systems, i.e., those using HÖTERV surface in either the vertical or horizontal arrangement, will include scale inhibition by pH adjustment with sulfuric acid and biofouling control with chlorine. Blowdown will be treated by lime softening to remove dissolved solids with return of the effluent to the water supply together with drying and impounding of the sludge. In addition, provision is made to supply demineralized water from zeolite softeners to flush the surface after each use.

The water treatments for the SCAT and AAC systems as well as the reference integrated system, are very similar to those for the deluge systems except no demineralized flush water is needed. The blowdown volume is also somewhat

smaller since higher concentrations of dissolved solids are believed to be allowable. However, greater quantities of chlorine to combat biofouling are needed because of the much larger inventory of water.

5.3.1 Deluge Water Treatment

To avoid scale formation on the fin surfaces, the deluge water should be maintained with a Langlier saturation index of zero or slightly negative. The following water quality parameters satisfy this requirement:

calcium hardness	100 mg/l as CaCO_3
total alkalinity	89 mg/l as CaCO_3
total dissolved solids	400 mg/l
pH	7.3

The listed water qualities for the delugeate and its makeup are maintained if about 6 cycles of concentration are allowed. However, due to the relatively low temperature of the delugeate (80 to 90°F), a less stringent makeup water quality and a greater number of concentration cycles may be allowed.⁽⁶⁾

River water, requiring pH control only, will supply the required makeup water for the deluge system. Addition of sufficient sulfuric acid solution to lower the pH to 7.6 through 7.8 will set the maximum allowable dissolved solids concentration level at about 6 cycles. At the maximum evaporation rate of 4000 gpm, a blowdown rate of 800 gpm will be required to maintain the dissolved solids concentration at this level. Since the system is open, no attempts to deoxygenate the water will be made.

Biofouling control by chlorination will be used, although the quantity actually required is not known because the biomass is unknown. Typical chlorination, and that assumed here, occurs when the total inventory is raised to 2.5 mg/l and this quantity is consumed per minute for 1/2-hour treatment of the plant water. This treatment is assumed to be done once a day.

Because discharge of the blowdown is unacceptable, it will be necessary to circulate the 800 gpm blowdown from the deluge basins through a lime softener station to remove the dissolved solids. Two hundred (200) lb/day of lime,

1730 lb/day of soda ash, and 95 lb/day of alum are required in the softening process. Eighty-five gpm of sludge is pumped from the softener to the effluent pond. The remaining 715 gpm leaves the softener as softened water and is joined to a flow of 4085 gpm (slightly more than the 4000 allowed for calculational convenience) of untreated river makeup water to form a stream of 4800 gpm. Before being pumped into the deluge system, 66°F baume (97%) H_2SO_4 solution is added to this stream at a rate of 375 gal/12-hour day in order to lower the pH to the required level for inhibition. A schematic of the deluge water treatment is shown below. It is expected that a single 4800 gpm capacity pump will be sufficient to circulate the treatment and makeup system flow.

Whenever a tower is changed from wet to dry operation, the extended surfaces will be flushed with 2500 gpm per quadrant of "zero hardness" water for about 3 minutes. Water containing less than 5 ppm calcium as $CaCO_3$ will be produced for all towers by passing a maximum of 50,000 gal/day of excess deluge makeup water through a sodium zeolite water softening system. The demineralized water produced by the system will then be stored in a central 50,000 gal steel or lined concrete open storage tank. Sixty thousand (60,000) gal will allow consecutive flushing of all eight cooling tower quadrants. One flushing pump rated at 2500 gpm at 80 ft of H_2O will be provided to serve all towers.

5.3.2 Water Treatment for SCAT, AAC and Integral Systems

The treatment schemes for these systems differ little from that used in the deluged systems except that the quantities of water circulated and the water inventories are considerably greater. However, the amount consumed over the year is the same for all cases.

The governing water quality limitations for water in the wet towers is given in Table 5-1. These criteria, together with the assumed water quality parameters for the raw river water, indicate a limit of 14 cycles of concentration dictated by the silica content. Probably the range of silica content would dictate a somewhat lower concentration. Allowable cycles of concentration are:

sulfate and calcium	20
silica	14
magnesium and silica	19

TABLE 5-1. Recirculating Water Quality Limitations⁽³⁾

Characteristic	Limitation	Comment
pH and hardness	Langlier saturation index = 0.1	Langlier saturation index = pH - pHs where
pH and hardness with addition of proprietary chemicals for deposit control	Langlier saturation index = 2.5	pH = measured pH pHs = pH at saturation with CaCO_3 see Sisson for nomograph solution
sulfate and calcium	$(C_{\text{SO}_4}) \times (C_{\text{Ca}}) = 500,000$	C_{SO_4} = concentration of SO_4 in mg/l C_{Ca} = concentration of Ca in mg/l as CaCO_3
silica	$(C_{\text{SiO}_2}) = 150$	C_{SiO_2} = concentration of SiO_2 in mg/l
magnesium and silica	$(C_{\text{Mg}}) \times (C_{\text{SiO}_2}) = 35,000$	C_{Mg} = concentration of Mg in mg/l as CaCO_3
suspended solids	$C_{\text{SS}} = 400 \text{ mg/l}$	C_{SS} = concentration of ss in mg/l

To keep the concentration at that level. 325 gpm is taken to a side stream treatment for reduction to a blowdown sludge. As in the deluge case, similar amounts of softener chemicals are used.

The Langlier saturation index, calculated using calcium at 66 ppm, solids at 390 ppm and alkalinity at 270 ppm in the river and pH 7.3 (adjusted) is 2.4 and would be within the guidelines as set by Table 5-1.

Scale inhibition and biofouling protection are provided in the same way as with the deluge system, through the use of H_2SO_4 and chlorine, respectively. Costs for these subsystems are very similar to those for the deluge systems as shown in Appendix C. These values are different from those given in BNWL-2122 for the integrated system because of a different cycle of concentration assumed to be possible in the wet towers and the time on stream assumed for the wet section.

Figures 5-1 and 5-2 show the treatment of water for the deluged systems (HÖTERV horizontal and vertical configurations) and for the SCAT and AAC systems. The close similarity is seen; the recirculating water flow is the only marked difference. Water treatment for the integrated system is nearly identical to that for the SCAT system.

6.0 RESULTS

The capital and operating costs determined in this analysis are presented in this section. Comparable capital costs for five concepts are also included.

6.1 CAPITAL COSTS OF ALTERNATIVE CONCEPTS

Estimated capital costs of constructing the four alternative heat rejection concepts for the San Juan Unit 3 plant are detailed in Table 6-1.

All estimates detailed in Table 6-1 are subject to the validity of assumptions defined in Sections 2.0 and 5.0. The integrated dry/wet concept is considered 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. The estimate of the integrated dry/wet concept was performed without the benefit of prior knowledge of actual construction costs of San Junit Unit 3 to put all estimates on the same relative basis and may or may not correspond to actual costs.

S&Q Engineering cost sheets for the four tower concepts are provided in Appendix A.

6.2 OPERATING COSTS

The annual operating costs for the four dry/wet cooling tower concepts under study were estimated using assumptions and data provided in Subsections 5.2 and 5.3. An outline of the calculations of these annual operating costs is shown in Appendix B. The results of these estimates are summarized in Table 6-2.

The costs specified in Table 6-2 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 present San Juan Unit 3 design.

TABLE 6-1. Capital Cost Estimate Comparison (\$1000)

		INTEGRATED DRY/WET SYSTEM FROM BNWL INTEGRATED 2122, BY VITRO ENGINEERING	INTEGRATED DRY/WET SYSTEM (STATE-OF-THE-ART) S&Q ENGINEERS	VERTICAL PLATE-FIN HOTERV DELUGE	SEPARATE CHANNEL CURTISS-WRIGHT AUGMENTATION	HORIZONTAL PLATE-FIN HOTERV DELUGE	AUGMENTING NH ₃ CONDENSER
STEAM CONDENSER ^(a)	E	1,411.0	1,411.0	2,150.0	2,150.0	2,150.0	2,150.0
	F1	113.0	113.0	172.0	172.0	172.0	172.0
	M	73.0	73.0	112.0	112.0	112.0	112.0
	L	143.0	143.0	219.0	219.0	219.0	219.0
		1,740.0	1,740.0	2,653.0	2,653.0	2,653.0	2,653.0
SUBTOTAL							
COOLING TOWER STRUCTURAL	SC	1,647.0	2,182.0	1,905.0	858.4	997.8	599.4
Vapor Distribution and Condensate Collection	M	840.6	672.0	115.5	75.6	34.9	54.0
Piping and Valves	L	193.4	254.6	91.3	64.9	31.9	46.6
	SC	126.0	288.8	101.4	72.1	35.5	51.5
		1,160.0	1,215.4	308.2	212.6	102.3	152.1
HEAT EXCHANGER DRY/ WET BRINDIES	M	3,608.0	3,608.0	5,287.4	4,700.0	4,898.9	2,530.6
	L	162.0	162.0	544.8	261.7	459.3	188.8
	SC	16.0	16.0	47.0	20.4	28.8	14.7
		3,786.0	3,786.0	5,874.2	4,982.1	5,387.0	2,734.1
COOLING WATER PIPING (AUGMENTATION/DELUGE)	M	-	-	192.3	44.5	205.4	30.6
	L	-	-	38.6	61.1	58.5	38.9
	SC	-	-	28.0	40.7	39.2	25.9
		-	-	258.9	146.3	303.1	95.4
COOLING WATER PIPING PUMPS	M	-	-	36.6	443.3	97.9	415.2
	L	-	-	8.4	84.0	18.5	96.0
	SC	-	-	1.4	14.0	3.1	16.0
		-	-	46.4	531.3	119.5	607.2
AUGMENTING NH ₃ CONDENSER	M	-	-	-	-	-	198.8
	L	-	-	-	-	-	206.0
	SC	-	-	-	-	-	1,157.5
		-	-	-	-	-	1,562.3
WET TOWER	SC	300.0	1,077.5	-	262.7	-	309.0
FANS	M	1,920.0	1,920.0	1,135.5	987.3	1,116.0	797.5
	L	114.0	114.0	60.2	71.8	60.8	71.8
	SC	12.0	12.0	9.0	10.7	9.0	10.7
		2,046.0	2,046.0	1,204.7	1,069.8	1,185.8	880.0

TABLE 6-1. (contd)

		INTEGRATED DRY/WET SYSTEM FROM BNWL INTEGRATED 2122, BY VITRO ENGINEERING	INTEGRATED DRY/WET SYSTEM (STATE-OF-THE-ART) S&Q ENGINEERS	VERTICAL PLATE-FIN HOTERV DELUGE	SEPARATE CHANNEL CURTISS-WRIGHT AUGMENTATION	HORIZONTAL PLATE-FIN HOTERV DELUGE	AUGMENTING NH ₃ CONDENSER
VENT AND FLARE SYSTEM	M	-	-	6.6	4.4	4.4	4.4
	L	-	-	3.6	2.4	2.4	2.4
	SC	-	-	4.8	3.2	3.2	3.2
				15.0	10.0	10.0	10.0
SUBTOTAL		9,539.0	10,306.9	9,612.4	8,073.2	8,105.5	6,949.5
MAIN COOLING SYSTEM							
Vapor Piping and Valves	M	901.7	763.1	213.1	249.7	230.9	249.7
	L	246.0	160.0	45.6	43.9	53.6	43.9
	SC	483.3	510.1	50.6	48.8	59.5	48.8
		1,631.0	1,433.2	309.3	342.4	344.0	342.4
CONDENSATE RETURN PIPING AND VALVES	M	(b)	(b)	234.6	119.5	93.3	119.5
	L			39.9	23.9	32.4	23.9
	SC			44.3	26.8	36.1	26.8
				318.8	170.2	161.8	170.2
CONDENSATE RETURN Pumps	E	270.0	450.0	54.0	54.0	54.0	54.0
	FI	22.0	22.0	4.0	4.0	4.0	4.0
	M	9.0	9.0	20.0	20.0	20.0	20.0
	L	37.0	37.0	25.0	25.0	25.0	25.0
		338.0	518.0	103.0	103.0	103.0	103.0
REBOILER INJECTION Pumps	E	-	-	82.0	82.0	82.0	82.0
	FI	-	-	7.0	7.0	7.0	7.0
	M	-	-	31.0	31.0	31.0	31.0
	L	-	-	39.0	39.0	39.0	39.0
				159.0	159.0	159.0	159.0
VAPOR SEPARATOR/ REBOILER	E	-	-	175.0	175.0	175.0	175.0
	FI	-	-	14.0	14.0	14.0	14.0
	M	-	-	45.0	48.0	48.0	48.0
	L	-	-	73.0	73.0	73.0	73.0
				310.0	310.0	310.0	310.0

TABLE 6-1. (contd)

		INTEGRATED DRY/WET SYSTEM FROM BNWL INTEGRATED 2122, BY VITRO ENGINEERING	INTEGRATED DRY/WET SYSTEM (STATE-OF-THE-ART) S&Q ENGINEERS	VERTICAL PLATE-FIN HOTERV DELUGE	SEPARATE CHANNEL CURTISS-WRIGHT AUGMENTATION	HORIZONTAL PLATE-FIN HOTERV DELUGE	AUGMENTING NH ₃ CONDENSER
SUBTOTAL		1,969.0	1,951.2	1,200.0	1,084.4	1,077.8	1,084.4
DRAIN AND FILL SYSTEM		(c)	(c)				
Piping	M	87.1	29.9	90.0	90.0	90.0	90.0
	L	45.8	14.7	52.0	52.0	52.0	52.0
	SC	112.5	26.4	90.0	90.0	90.0	90.0
		245.5	71.0	232.0	232.0	232.0	232.0
STORAGE TANKS							
	E	-	-	290.0	290.0	290.0	290.0
	FI	-	-	23.0	23.0	23.0	23.0
	M	-	-	79.0	79.0	79.0	79.0
	L	-	-	121.0	121.0	121.0	121.0
				513.0	513.0	513.0	513.0
DRAIN AND FILL PUMPS							
	E	7.0	11.1	18.0	18.0	18.0	18.0
	FI	0.6	0.7	1.5	1.5	1.5	1.5
	M	2.4	0.5	6.5	6.5	6.5	6.5
	L	3.5	2.8	9.0	9.0	9.0	9.0
		13.5	15.1	35.0	35.0	35.0	35.0
SUBTOTAL		258.9	86.1	780.0	780.0	780.0	780.0
TOXIC GAS SYSTEM							
	M	-	-	183.0	122.0	122.0	122.0
	L	-	-	14.0	9.0	9.0	9.0
	SC	-	-	14.0	12.0	12.0	12.0
				211.0	143.0	143.0	143.0
WATER QUALITY CONTROL							
Water Treatment Facilit.	SC	418.0	418.0	290.0	290.0	290.0	290.0
Demineralized Water	SC	-	-	135.5	135.5	135.5	135.5
	M	-	-	22.6	22.6	22.6	22.6
	L	-	-	8.9	8.9	8.9	8.9
				167.0	167.0	167.0	167.0
PIPING AND PUMPS	M	29.8	14.9	57.9	50.4	107.9	50.4

TABLE 6-1. (contd)

		INTEGRATED DRY/WET SYSTEM FROM BNWL INTEGRATED 2122, BY VITRO ENGINEERING	INTEGRATED DRY/WET SYSTEM (STATE-OF-THE-ART) S&O ENGINEERS	VERTICAL PLATE-FIN HOTERV DELUGE	SEPARATE CHANNEL CURTISS-WRIGHT AUGMENTATION	HORIZONTAL PLATE-FIN HOTERV DELUGE	AUGMENTING NH ₃ CONDENSER
L		21.0	6.1	28.0	22.7	39.7	22.7
SC		26.5	11.5	19.2	14.6	24.1	14.6
		77.3	32.5	105.1	87.7	171.7	87.7
SUBTOTAL		495.3	450.5	562.1	544.7	628.7	544.7
BUILDINGS		52.0	52.0	52.0	52.0	52.0	52.0
ELECTRICAL/INSTRUMENTATION	M	1,075.3	1,057.3	1,194.2	818.4	773.1	818.4
	L	487.6	491.6	563.2	418.3	397.2	418.3
	SC	115.0	119.8	139.8	136.4	138.1	136.4
		1,677.9	1,668.9	1,897.2	1,373.1	1,308.4	1,373.1
OH&P/S		337.0	325.2	369.1	259.7	254.7	259.7
SUBTOTAL		2,014.9	1,994.1	2,263.3	1,632.8	1,554.1	1,632.8
SUBTOTAL		16,069.0	16,584.0	17,334.0	14,963.0	14,994.0	13,840.0
CONTRACTORS OH + PROFIT		2,922.0	2,921.0	3,329.0	2,948.0	2,998.0	2,631.0
ENG AND CONST MGT		3,798.0	3,902.0	4,132.0	3,582.0	3,598.0	3,294.0
TOTAL CAPITAL COST (Less Contingency & Escalation)		22,798.0	23,407.0	24,795.0	21,493.0	21,590.0	19,762.0
ESCALATION ^(d)		5,638.0	5,791.0	6,134.0	5,317.0	5,341.0	4,890.0
CONTINGENCY ^(d)		8,573.0	8,759.0	9,279.0	8,043.0	8,079.0	7,397.0
TOTAL CAPITAL COST		37,000.0	37,957.0	40,208.0	34,853.0	35,010.0	32,052.0

(a) The steam condenser for the advanced ammonia systems consists of a steam condenser/ammonia reboiler that requires an ammonia vapor separator. Saturated ammonia is recirculated through the ammonia reboiler.

(b) The cost of the condensate return piping and valves is included in the vapor piping and valves cost figure.

(c) The drain and fill system for the integrated cooling tower includes the piping, pump and valves to fill and drain the cooling water sump. The drain and fill for the ammonia systems consists of storage tanks. Piping, pumps and valves to maintain the inventory of ammonia in the main cooling system.

(d) Figures shown include escalation and contingency of engineering and construction management.

E = Equipment; FI = Freight & Insurance; M = Field Material; L = Field Labor; SC = Subcontract; ST = Sub Total; OH&P/S = Overhead & Profit on Subcontract

TABLE 6-2. Estimated Annual Operating Costs (\$/Year)

System	Circulation Pump Cost(a)	Fan Cost(b)	Fuel Savings from Reduced Back Pressure(c)	Water Treatment Cost(d)	Deluge Pump Cost(e)	Annual Charge on Peaking Capacity(f)	Total Cost
integrated dry/wet	694,000	798,000	-55,600	105,000	0	184,000	1,725,400
vertical HÖTERV tower	38,500	588,900	-235,000	79,000	10,100	83,300	564,800
horizontal HÖTERV tower	38,500	571,600	-235,000	79,000	19,600	84,700	588,400
SCAT tower	38,500	435,400	-235,000	89,000	110,900	95,600	534,400
Ammonia Augmenting Condenser	38,500	433,300	-55,600	105,000	130,900	98,000	750,100

(a) Circulation pump cost = pump power (kW) x hr/yr x capacity factor x power cost

(b) Fan cost = fan power (dry) x hr/yr x capacity factor x fraction use (dry) x power cost

Fan cost = fan power (wet) x hr/yr x capacity factor x fraction use (wet) x power cost

(c) Fuel savings from reduced back pressure = (heating rate)_{4.5 in.} - (heating rate)_{op.} (power output) dt x fuel cost

(d) Water treatment costs = chlorination + scale inhibition + blowdown + demineralized flush (deluge only)

(e) Deluge pump cost = pump power x hr/yr x capacity factor x fractional use x power cost

(f) The capital needed for the Capacity Penalty is annualized in this column by applying 18% of the capital needed for the increased generating capability.

Parameters:

plant size: 500,000 kWe (Nominal)

capacity factor: 0.758

cost of power: 24.7 mills/kWh

turbine rated back pressure: 4.5 in. Hga

minimum turbine back pressure: 1.0 in. Hga

standard heat rate: 8168 Btu/kWh

fuel cost: 81¢/MMBtu

maintenance: pump, 7.5% of capital

fans and towers, 1.5% of capital

6.3 COMPARATIVE CAPITAL SAVINGS

To facilitate comparison of the total costs of the dry/wet cooling tower concepts under study, a "comparative capital cost" was identified for each concept. Comparable capital cost was defined as the sum of the estimated basic capital cost (i.e., estimated 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 6-2, and on an annual fixed charge rate of 18%.

The comparable capital costs of the four concepts considered in this report are summarized in Table 6-3.

TABLE 6-3. Summary of Comparative Capital Costs

<u>Cooling Tower Concept</u>	<u>Basic Capital Cost</u>	<u>Capitalized Operating Cost</u>	<u>Comparable Capital Cost</u>
integrated dry/wet	23,407,000	9,586,000	32,993,000
vertical HÖTERV tower	24,795,000	3,138,000	27,933,000
horizontal HÖTERV tower	21,590,000	3,102,000	24,692,000
SCAT tower	21,493,000	2,969,000	24,462,000
Augmenting Ammonia Condenser	19,765,000	4,167,000	23,932,000

7.0 DISCUSSION

Results of the analysis are discussed in further detail in this section, followed by conclusions and recommendations. Operating parameters of the five systems are presented in Appendix D.

7.1 POTENTIAL COST SAVINGS OF ALTERNATIVE CONCEPTS

Table 6-3 shows that, on the basis of conditions associated with the San Juan Unit 3 Plant, all four of the alternative dry/wet concepts considered have a potentially lower cost than the integrated dry/wet concept.

The ammonia systems were found to have potentially lower capital and operating costs than comparable capital cost for the integrated concept considered in this base study. The ammonia systems require: 1) an ammonia reboiler, which may be somewhat more complex and expensive than a simple condenser, and 2) a complex pressurized ammonia fill and drain system. However, the ammonia systems have a number of important cost advantages associated with the evaporation-condensation heat transfer system. Among these advantages is the enhanced heat transport from the reboiler to the cooling tower. The cost of the ammonia condenser/reboiler was conservatively estimated to be significantly greater than a conventional turbine condenser but there is reason to question that estimate. Only small pumps are required to return the ammonia to the reboiler and to provide forced recirculation. Water treatment capital costs are also less because of the need for treating smaller quantities of water.

Operating costs for the ammonia systems are substantially less than the integrated concept because: 1) very little power is required to operate recirculation pumps, and 2) fuel savings from lower back pressure result from the more efficient use of available water.

Of the three deluge concepts, the vertical HÖTERV deluged tower is more expensive in capital cost but significantly less expensive to operate. This is primarily due to the differences in deluge pump cost.

Although the results of this study have identified four basic concepts which have the potential for lower costs than the integrated dry/wet system selected for the San Juan Unit 3, it is not implied that an inappropriate

selection was made. In fact, the results of BNWL-2122 support the application of the integrated dry/wet concept for the San Juan plant since it was shown that it is the least costly of concepts investigated which are (or are similar to) state of the art. The lower cost deluge/ammonia and SCAT concepts are developmental in nature and have not been subjected to conditions existing in commercial power operation. Therefore, unknown problems may exist with these concepts which have not been adequately reflected in this study. Additional testing and demonstration is required before a selection of these concepts for commercial power applications can be confidently made.

The costs presented in this report for all concepts studied are necessarily approximate in nature. It was not considered feasible or cost effective to research all site-related factors which could influence construction costs in light of the uncertainties involved in preconceptual cost estimates. Also, none of the concept designs were fully optimized from the standpoint of all parameters involved that are described in Section 3.0. However, all designs and estimates were arrived at utilizing the same bases and uniform procedures. It is not anticipated that exhaustive optimization would change the relative ranking of the concepts with regard to comparative capital costs. Therefore, it is believed that the results of this study are valid for the comparative purposes of this report. It is not recommended that cost figures presented in this report be used out of context of the comparisons intended.

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 5.0. They are applicable only to conditions existing at the San Juan Unit 3 site and the results may change if the same study is performed in the context of another site. The San Juan site cannot be said to be "typical." Its fuel costs are low and transportation costs high. However, the results of the study indicate that there may be economic incentives for developing advanced systems such as the horizontal HOTERV, the SCAT, and the AAC concepts. Each site has its own requirements and any system would have to be designed and optimized for the particular site. The delay in utilizing attractive advanced concepts such as identified here will largely be due to engineering conservatism concerning new systems. The proof that advanced concepts can be successfully operated

probably depends on the outcome of tests proving the reliability and performance of the concepts. The beneficiary of the success of these tests will be the public, for, until then, all dry cooling will be slower in coming and will result in more expensive plants and/or more water consumption.

7.2 CONCLUSIONS AND RECOMMENDATIONS

The results of this study indicate that the HÖTERV finned surface with deluge augmentation and Curtiss-Wright finned surface with either SCAT augmentation or the AAC as described in Subsections 4.4 and 4.5 of this report, respectively, have potential cost advantages for use in power plant cooling applications under conditions imposed by the San Juan site. It is recommended that additional consideration be given to these concepts by industry and particularly by the DOE/PNL Dry Cooling Tower Enhancement Program to further quantify potential benefits within the context of other sites and to work toward providing the experimental data and operating experience required to demonstrate their performance and reliability.

REFERENCES

1. M. W. Larinoff and L. L. Forster, Dry and Wet-Peaking Tower Cooling Systems for Power Plant Applications. ASME-Paper-No-75 WA-PWR-2, 1975.
2. M. C. Hu and G. A. Englessen, Wet/Dry Cooling Systems for Fossil-Fueled Power Plants. EPA-600-7-77-137, United Engineers and Constructors, Philadelphia, PA, November 1977.
3. B. M. Johnson, R. T. Allemann, D. W. Faletti, B. C. Fryer, and F. R. Zaloudek, Dry Cooling of Power Generating Stations. A Summary of the Economic Evaluation of Several Advanced Concepts via a Design Optimization Study & A Conceptual Design and Cost Estimate. BNWL-2120, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, September 1976.
4. R. T. Allemann et al., Study of the Comparative Costs of Five Wet-Dry Cooling Tower Concepts, BNWL-2122, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, September 1976.
5. B. C. Fryer, A Review and Assessment of Engineering Economic Studies of Dry Cooled Electrical Generating Plants, BNWL-1976, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, March 1976.
6. D. R. Pratt, Scale Formatin in Deluged Dry Cooling Systems, BNWL-2060, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, May 1976.

APPENDIX A

S&Q SUMMARY COST SHEETS FOR THE FOUR
TOWER CONCEPTS IN THIS STUDY

PROJECT COST ESTIMATE SUMMARY

TITLE	PREPARED FOR	PREPARED BY	CHECKED BY	PROJECT NO.	DATE
Vertical Hsterv					

	TITLE I	TITLE II	TITLE III	\$ TOTAL	
A. ENGINEERING					
ARCHITECT - ENGINEER				2,066,000	
OTHER ENGINEERING - SPECIFY				2,066,000	
SUBTOTAL				4,132,000	
ESCALATION I II III				1,022,000	
CONTINGENCY				1,546,000	
SUBTOTAL ENGINEERING				2,568,000	
OPERATING CONTRACTOR				6,700,000	
TOTAL A				6,700,000	
B. CONSTRUCTION					
(1) IMPROVEMENTS TO LAND					
(2) BUILDINGS					
BUILDING NO. _____ SQ. FT.					
BUILDING NO. _____ SQ. FT.					
(3) OTHER (DETACHED) STRUCTURES					
(4) SPECIAL FACILITIES AND INSTAL.				20,603,000	
(5) UTILITIES					
(6) OPERATING EXPENSE CHARGES					
(7) CONTRACT ADMINISTRATION					
(8) STATE TAX					
SUBTOTAL				5,112,000	
ESCALATION 7.896% 2.5 YEARS				773,000	
CONTINGENCY 30%				33,508,000	
TOTAL B					
C. STANDARD EQUIPMENT					
TOTAL C					
D. TRANSFERRED CAPITAL PROP. OR EQUIPMENT					
CURRENT ENR. COST INDEX	BUILDING _____	CONSTRUCTION _____	TOTAL PROJECT ESTIMATE		40,208,000

PROPOSED FUNDS ALLOCATION			TYPE OF ESTIMATE:		REMARKS:
FUNDS PURPOSE	OPER CONTR.	ERDA -RL	APPROVALS	DATE	
ENGINEERING					
PROCUREMENT					
CONSTRUCTION					
ESCALATION					
CONTINGENCY					
TCP/TCE					
WASH STATE TAX			PROJECT MANAGER		
TOTAL			CLIENT ENGINEER		

ESTIMATE SHEET _____ OF _____

JOB LOCATION

Vertical Interval

Done at PNL

TAKE OFF

APPROVED

PRICED O.T.R.

DATE 4/28/78

CHECKED

SHEET 1[illegible]

PROJECT COST ESTIMATE SUMMARY

TITLE <i>Horizontal Hater</i>	PREPARED FOR	PREPARED BY <i>PJ. B</i>	CHECKED BY	PROJECT NO.	DATE <i>4/28/78</i>
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	TITLE I	TITLE II	TITLE III	\$ TOTAL	
A. ENGINEERING					
ARCHITECT - ENGINEER				<i>1,799,000</i>	
OTHER ENGINEERING - SPECIFY				<i>1,799,000</i>	
SUBTOTAL				<i>3,598,000</i>	
ESCALATION <i>24.24</i> %				<i>870,000</i>	
CONTINGENCY <i>30</i> %				<i>1,346,000</i>	
SUBTOTAL ENGINEERING				<i>2,236,000</i>	
OPERATING CONTRACTOR				<i>5,834,000</i>	
TOTAL A				<i>5,834,000</i>	
B. CONSTRUCTION					
(1) IMPROVEMENTS TO LAND					
(2) BUILDINGS					
BUILDING NO. _____ SQ. FT.					
BUILDING NO. _____ SQ. FT.					
(3) OTHER (DETACHED) STRUCTURES					
(4) SPECIAL FACILITIES AND INSTAL.				<i>1,799,000</i>	
(5) UTILITIES					
(6) OPERATING EXPENSE CHARGES					
(7) CONTRACT ADMINISTRATION					
(8) STATE TAX					
SUBTOTAL				<i>4,451,000</i>	
ESCALATION <i>7.55</i> % <i>2.5</i> YEARS				<i>6,733,000</i>	
CONTINGENCY <i>30</i> %				<i>29,176,000</i>	
TOTAL B					
C. STANDARD EQUIPMENT					
TOTAL C					
D. TRANSFERRED CAPITAL PROP. OR EQUIPMENT					
CURRENT ENR COST INDEX				BUILDING _____ CONSTRUCTION _____	TOTAL PROJECT ESTIMATE <i>35,010,000</i>

PROPOSED FUNDS ALLOCATION			TYPE OF ESTIMATE:		REMARKS: <i>Dollars rounded to the nearest \$1000</i>
FUNDS PURPOSE	OPER CONTR	ERDA - RL	APPROVALS	DATE	
ENGINEERING					
PROCUREMENT					
CONSTRUCTION					
ESCALATION					
CONTINGENCY					
TCP/TCE					
WASH. STATE TAX					
TOTAL					

PROJECT COST ESTIMATE SUMMARY

TITLE <u>SCAT</u>	PREPARED FOR	PREPARED BY <u>D. J. B.</u>	CHECKED BY	PROJECT NO.	DATE <u>4/28/78</u>
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	TITLE I	TITLE II	TITLE III	\$ TOTAL
A. ENGINEERING				<u>1791000</u>
ARCHITECT - ENGINEER				<u>1791000</u>
OTHER ENGINEERING - SPECIFY				<u>3582000</u>
SUBTOTAL				<u>886000</u>
ESCALATION <u>24.74</u> % <u> </u> % <u> </u> %				<u>1340000</u>
CONTINGENCY <u>30</u> % <u> </u> % <u> </u> %				<u>2226000</u>
SUBTOTAL ENGINEERING				<u>5808000</u>
OPERATING CONTRACTOR				<u>5808000</u>
TOTAL A				<u>5808000</u>
B. CONSTRUCTION				
(1) IMPROVEMENTS TO LAND				
(2) BUILDINGS				
BUILDING NO. <u> </u> SQ. FT. <u> </u>				
BUILDING NO. <u> </u> SQ. FT. <u> </u>				
(3) OTHER (DETACHED) STRUCTURES				
(4) SPECIAL FACILITIES AND INSTAL.				<u>17911000</u>
(5) UTILITIES				
(6) OPERATING EXPENSE CHARGES				
(7) CONTRACT ADMINISTRATION				
(8) STATE TAX				
SUBTOTAL				<u>4431000</u>
ESCALATION <u>9.896</u> % <u>2.5</u> YEARS				<u>6203000</u>
CONTINGENCY <u>30</u> %				<u>27045000</u>
TOTAL B				
C. STANDARD EQUIPMENT				
TOTAL C				
D. TRANSFERRED CAPITAL PROP. OR EQUIPMENT				
CURRENT ENR. COST INDEX	BUILDING <u> </u>	CONSTRUCTION <u> </u>	TOTAL PROJECT ESTIMATE	<u>34853000</u>

PROPOSED FUNDS ALLOCATION			TYPE OF ESTIMATE:		REMARKS: <u>Dollars Rounded to the Nearest \$1000</u>
FUNDS PURPOSE	OPER. CONTR.	ERDA -RL	APPROVALS	DATE	
ENGINEERING					
PROCUREMENT					
CONSTRUCTION					
ESCALATION			ESTIMATING		
CONTINGENCY			PROJECT MANAGER		
TCP/TCE			CLIENT ENGINEER		
WASH. STATE TAX					
TOTAL					

PROJECT COST ESTIMATE SUMMARY

TITLE <i>Augmenting N/H₂ Condenser</i>	PREPARED FOR	PREPARED BY <i>D. J. E.</i>	CHECKED BY	PROJECT NO.	DATE <i>4/28/78</i>
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	TITLE I	TITLE II	TITLE III	\$ TOTAL
A. ENGINEERING				
ARCHITECT - ENGINEER				<i>1659000</i>
OTHER ENGINEERING - SPECIFY				<i>1659000</i>
SUBTOTAL				<i>3318000</i>
ESCALATION <u>24.24</u> %				<i>821000</i>
CONTINGENCY <u>30</u> %				<i>1242000</i>
SUBTOTAL ENGINEERING				<i>2003000</i>
OPERATING CONTRACTOR				
TOTAL A				<i>5381000</i>
B. CONSTRUCTION				
(1) IMPROVEMENTS TO LAND				
(2) BUILDINGS				
BUILDING NO. _____ SQ. FT.				
BUILDING NO. _____ SQ. FT.				
(3) OTHER (DETACHED) STRUCTURES				
(4) SPECIAL FACILITIES AND INSTAL				<i>16593000</i>
(5) UTILITIES				
(6) OPERATING EXPENSE CHARGES				
(7) CONTRACT ADMINISTRATION				
(8) STATE TAX				
SUBTOTAL				<i>4105000</i>
ESCALATION <u>7.55</u> % <u>2.5</u> YEARS				<i>6209000</i>
CONTINGENCY <u>30</u> %				<i>26907000</i>
TOTAL B				
C. STANDARD EQUIPMENT				
TOTAL C				
D. TRANSFERRED CAPITAL PROP. OR EQUIPMENT				
				<i>32288000</i>
CURRENT ENR COST INDEX				
BUILDING _____ CONSTRUCTION _____				
TOTAL PROJECT ESTIMATE				<i>32288000</i>

PROPOSED FUNDS ALLOCATION			TYPE OF ESTIMATE:		REMARKS: <i>Dollars Rounded to the Nearest \$1000</i>
FUNDS PURPOSE	OPER CONTR	ERDA - RL	APPROVALS	DATE	
ENGINEERING					
PROCUREMENT					
CONSTRUCTION					
ESCALATION					
CONTINGENCY					
TCP TCE					
WASH. STATE TAX					
TOTAL			PROJECT MANAGER		
			CLIENT ENGINEER		
					ESTIMATE SHEET ____ OF ____

JOB LOCATION

Augmenting NH₃ Condensate

Different PNL

TAKE OFF _____ APPROVED _____

PRICED D. J. R. DATE 4/28/78

CHECKED _____ SHEET 1

[illegible]

PROJECT COST ESTIMATE SUMMARY

TITLE	PREPARED FOR	PREPARED BY	CHECKED BY	PROJECT NO.	DATE
COMBINED SYSTEM	Battelle	D. J. B.		0396-350	4/28/78

	TITLE I	TITLE II	TITLE III	\$ TOTAL
A. ENGINEERING				
ARCHITECT - ENGINEER				1951000
OTHER ENGINEERING - SPECIFY				1951000
SUBTOTAL				3902000
ESCALATION 24.74 %				765000
CONTINGENCY 30.0 %				1460000
SUBTOTAL ENGINEERING				2425000
OPERATING CONTRACTOR				
TOTAL A				6327000
B. CONSTRUCTION				
(1) IMPROVEMENTS TO LAND				
(2) BUILDINGS				
BUILDING NO. _____ SQ. FT.				
BUILDING NO. _____ SQ. FT.				
(3) OTHER (DETACHED) STRUCTURES				
(4) SPECIAL FACILITIES AND INSTAL.				19505000
(5) UTILITIES				
(6) OPERATING EXPENSE CHARGES				
(7) CONTRACT ADMINISTRATION				
(8) STATE TAX				
SUBTOTAL				4826000
ESCALATION 9.896 % 2.5 YEARS				7299000
CONTINGENCY 30 %				31630000
TOTAL B				
C. STANDARD EQUIPMENT				
TOTAL C				
D. TRANSFERRED CAPITAL PROP. OR EQUIPMENT				
CURRENT ENR. COST INDEX				
BUILDING _____ CONSTRUCTION _____				
TOTAL PROJECT ESTIMATE				37957000

PROPOSED FUNDS ALLOCATION			TYPE OF ESTIMATE:		REMARKS: Dollars Rounded to the Nearest \$1000
FUNDS PURPOSE	OPER. CONTR.	ERDA -RL	APPROVALS	DATE	
ENGINEERING					
PROCUREMENT					
CONSTRUCTION					
ESCALATION			ESTIMATING		
CONTINGENCY			PROJECT MANAGER		
TCP/TCE			CLIENT ENGINEER		
WASH. STATE TAX					
TOTAL					

SPE CORPORATION

Job No. and Title

0396-300

Take Off

SPE

Approved

Client

BATELLE

Priced

Date

12/10/72

Job Location

Checked

Sheet

1 of 30

ITEM AND DESCRIPTION			SHEET	UNIT	Unit Cost		Man Hours		TOTAL COST				
			Quantity		\$	C	Unit	Total	\$	Mat	Labor	Sub-Contr	Total
CONSTRUCTION COSTS													
MAIN STEAM CONDENSER			2						15920.00	1300.00	1300.00		17420.00
COOLING WATER SYSTEM			3						12140.00	1910.00	5090.00		19140.00
FILL & DRAIN SYSTEM			6						4200.00	1800.00	2700.00		8700.00
WATER QUALITY CONTROL			9						15000.00	6000.00	43000.00		45100.00
COOLING TOWER SUMMARY			13						62310.00	53400.00	35810.00		103460.00
BUILDINGS			20								5200.00		5200.00
A114	ELECTRICAL SUMMARY			21							19400.00		19400.00
	SUBTOTAL								90390.00	87900.00	66060.00		165840.00
	GENERAL CONT. BURR. 14% LAB									1230.00			1230.00
	SUBTOTAL								90390.00	100200.00	66060.00		167070.00
	OVERHEAD 10% LAB, MAT								9100.00	10000.00			10100.00
OVERHEAD 5% of Sub											3300.00		3300.00
SUB TOTAL									100090.00	110200.00	69360.00		180470.00
PROFIT 10% LABOR, MAT									10040.00	11000.00			11100.00
PROFIT 5% Subs											3470.00		3470.00
TOTAL (EXCLUDING TAX)									110100.00	121200.00	72830.00		195050.00
Code													

APPENDIX B

ANNUAL OPERATING COSTS

APPENDIX B

ANNUAL OPERATING COSTS

INTRODUCTION

As discussed in Section 6, the comparable capital cost of the five systems is evaluated by adding a capitalization of annual operating cost to the estimated capital cost of each concept. This appendix outlines the calculation of these annual operating costs. The six terms stipulated in Section 6 and listed in Table 6-2 are evaluated by the following expressions.

- a) Circulating pumping costs = pump power (kW) x operating hour/yr x power cost
- b) Fan power costs = fan power (dry) x operating hours/yr x fraction used (dry fans) x power cost + fan power (wet) x operating hours/yr x fraction used (wet fans) x power cost
- c) Fuel savings from reduced back pressure = $\int [\text{operating rate}) dt - (\text{heating rate})] - \text{operating pressure @ 4.5 inch back pressure} \times (\text{power output}) dt \times \text{fuel cost}$
- d) Water treatment costs = [chlorination + scale inhibition + blowdown + demineralized flush]
- e) Deluge pump costs = pump power x operating hours/yr x fractional use x power costs
- f) Annual charge for peaking capacity = power rating of fans and pumps (circulating and deluge) x 122/kW x 0.18 (afcr)

WATER USE AT SAN JUAN

Water use for dry/wet concepts using deluge cooling is based on a design point of 55°F for all-dry operation, while those concepts using separate augmentation systems are based on a dry tower design point of 35°F. The following calculations indicate how these assumptions are translated into duty cycles for the pumping systems supplying cooling water.

35°F

1900 acre ft - total available supply

4000 gpm - maximum allowable rate of water consumption

Number of days at maximum water rate

$$= \frac{1900 \times 3,295 \times 10^5}{4000 \times 60 \times 24} = 108 \text{ days @ 4000 gpm}$$

Duty Cycle: at San Juan, 6789 hrs above 35°F

with Capacity Factor 0.748 = 5146 hrs = 214 days

108/214 ~ 0.5 = 50% duty cycle

55°F

Duty Cycle: at San Juan, 5917 hrs

with Capacity Factor 0.748 = 4426 = 184 days

108/184 ~ 58% duty cycle

INTEGRATED DRY/WET TOWER

a) Circulation pumping

$$\frac{219,000 \text{ gpm} \times 77 \text{ TDH} \times 8.34 \text{ lb/gal} \times 0.746 \text{ kW/HP}}{33,000 \text{ ft lb/sec HP} \times 0.8 \text{ (efficiency)}} = 3995 \text{ kW}$$

$$3995 \text{ HP} \times 6640 \text{ hrs/yr} \times 24.7 \times 10^{-3} \$/\text{kWh} = \$655,000$$

$$\text{Maintenance @ 7.5\% of Capital} = \$39,000$$

$$\text{Total} = \$694,000$$

b) Fan power costs

$$\text{Dry 40 @ 145 HP} \times 0.746 \text{ kW/HP} = 4330 \text{ kW}$$

$$\text{Wet 10 @ 90 HP} \times 0.746 \text{ kW/HP} = 670 \text{ kW}$$

$$\text{Dry Fans - 1971 hr below 35°F} \times \text{Cap. Factor} = 1494 \text{ hrs}$$

$$\text{- 6789 hr above 35°F} \times \text{Cap. Factor} = 5146 \text{ hrs}$$

Assume 50% duty cycle below 35°F and 100% above 35°F

$$\text{Wet Fans - 6789 hrs above 35°F} \times \text{Cap. Factor} = 5146 \text{ hrs}$$

Assume 50% of dry fans are on above 35°F

Fan power costs =

$$\{(1494 \times 0.5 + 5146)(4330 + 670 \times 0.5)\} \times 0.0247 = \$680,000$$

$$\text{Maintenance at 1.15\% Tower Capital} = \$118,000$$

$$\text{Total} = \$798,000$$

c) Fuel savings from reduced back pressure	= \$ 55,600
d) Water treatment costs	= \$105,000
e) Deluge pumping costs - N.A.	
f) Annual charge for peaking capacity 8375 x 122 \$/kW x 0.18 (afcr) ^(a)	= <u>\$184,000</u>
Total	<u>\$1,725,400</u>

VERTICAL HÖTERV TOWER (DELUGED)

a) Circulation pumping - 190 kW total (same as Horizontal HÖTERV)	= \$ 38,500
b) Fan power costs - 3500 kW total - 2213 hr below 55°F @ 50% duty cycle - 4426 hr above 55°F @ 100% duty cycle (2213 x 0.5 + 4426) x 3500 x 0.0247 Maintenance at 1.15% Tower Capital	= \$478,390 = <u>\$110,500</u>
Total	= <u>\$588,890</u>
c) Fuel savings from reduced back pressure	= \$235,000
d) Water treatment costs	= \$ 79,000
e) Deluge pumping cost - 104 kW Assume 58% duty cycle for hrs above 55°F 4426 x 0.58 x 104 x 0.0247 Maintenance @ 7.5% of pump capital	= \$ 6,600 = <u>\$ 3,500</u>
Total	= <u>\$ 10,100</u>
f) Annual charge for peaking capacity 3794 kW x 122 \$/kW x 0.18 (afcr)	= \$ 83,300
Total	= <u>\$564,800</u>

(a) afcr = annual fixed charge rate.

HORIZONTAL HÖTERV TOWER (DELUGE)

- a) Circulating pumping - 190 kW total
(same as Vertical HÖTERV)
 $190 \times 6640 \text{ hr/yr} \times 0.0247 \text{ \$/kWh} = \$ 30,800$
Maintenance @ 7.5% of Pumping Capital = \$ 7,700
Total = \$ 38,500
- b) Fan power costs - 3500 kW total
(same as Vertical HÖTERV) = \$478,400
Maintenance @ 1.15% Tower Capital = \$ 93,200
Total = \$ 571,600
- c) Fuel savings from reduced back pressure = \$235,000
(same as Vertical HÖTERV)
- d) Water treatment costs = \$ 79,000
(same as Vertical HÖTERV)
- e) Deluge pumping costs - 167 kW
Assume 58% duty cycle for hrs above 55°F
 $4426 \times 0.58 \times 167 \times 0.0247 = \$ 10,600$
Maintenance @ 7.5% of pump cost = \$ 9,000
Total = \$ 19,600
- f) Annual charge for peaking capacity
 $3857 \text{ kW} \times 122 \text{ \$/kW} \times 0.18 \text{ (afcr)} = \$ 84,700$
Total = \$ 558,400

SCAT TOWER

- a) Circulation pumping (ammonia) - 190 kW
(same as Vertical HÖTERV) = \$ 38,500
- b) Fan power costs -
Dry 48 @ 60 HP = 2148 kW
Wet 8 @ 150 HP = 895 kW
Total = 3043 kW

Dry Fans - 2213 hrs below 55°F @ 50% duty cycle	
- 4426 hrs above 55°F @ 100% duty cycle	
Wet Fans - 4426 hrs above 55°F @ 50% duty cycle	
$\{(2213 \times 0.5 + 4426) 2148 + 4426 \times 0.5 \times 895\} \times 0.0247$	= \$342,500
Maintenance @ 1.15% of Tower Capital	= \$ <u>92,900</u>
Total	= <u>\$435,400</u>
c) Fuel savings from reduced back pressure	= \$235,000
d) Water treatment costs	= \$ 89,000
e) Augmented cooling pumping cost - 1120 kW	
4426 hrs/1/n x 0.58 duty cycle x 1120 x 0.0247 \$/kWh	= \$ 71,000
Maintenance @ 7.5% of Pumping Capital	= \$ <u>39,900</u>
Total	= <u>\$110,900</u>
f) Annual charge for peaking capacity	
4353 kW x 122 \$/kW x 0.18	= \$ 95,600
Total	= <u>\$534,400</u>

AMMONIA AUGMENTING CONDENSER

a) Circulation pumping (ammonia) - 190 kW	
(same as Vertical HÖTERV)	= \$ 38,500
b) Fan power costs	
Dry 26 @ 105 HP = 2037 kW	
Wet 8 @ 150 HP = <u>895 kW</u>	
Total = 2932 kW	
Dry Fans - 1494 hrs below 35°F @ 50% duty cycle	
- 5146 hrs above 35°F @ 100% duty cycle	
Wet Fans - 5146 hrs above 35°F @ 50% duty cycle	
$\{(1494 \times 0.5 + 5146) 2037 + 5146 \times 0.5 \times 895\} \times 0.0247$	= \$353,400

Maintenance @ 1.15% x Tower Capital	= \$ 79,900
Total	= <u>\$433,300</u>
c) Fuel savings from reduced back pressure	= \$ 55,600
d) Water treatment costs	= \$105,000
e) Augmented cooling pumping cost	
200,000 gpm @ 35 TDH - 1342 kW	
5146 x 0.5 x 1343 x 0.0247	= \$ 85,400
Maintenance @ 7.5% of Pumping Capital	= \$ 45,500
Total	= <u>\$130,900</u>
f) Annual charge for peaking capacity	
4464 kW x 122 \$/kW x 0.18 (afcr)	= \$ 98,000
Total	= <u>\$750,100</u>

APPENDIX C

WATER TREATMENT COSTS

APPENDIX C

WATER TREATMENT COSTS

HÖTERV WATER TREATMENT

Flow rate = 21,000 gpm

Volume = 3×10^5 gal

Evaporation rate = 4000 gpm

1. Water Treatment

a) Side Stream Treatment (800 gpm)

Capital Cost = $\$2.6 \times 10^5$ installed

Operating Cost = $\$5.0 \times 10^4$ /year

b) Scale Inhibition

Capital Cost = $\$2.9 \times 10^4$ installed

Operating Cost = $\$1.9 \times 10^4$ /year

2. Zero Hardness Flush Water

Water Treatment - Sodium Zeolite Softening, 50,000 gpd

Capital Cost = $\$1.5 \times 10^5$ installed

Operating Cost = $\$4.0 \times 10^3$ /year

3. Delugeate Biocide Cost (Chlorine)

These costs are approximated from bids on large chlorination units, chlorine consumption and labor rates - \$15/hour

a) Basis

1) 1 chlorination per day when deluging

2) 1 chlorination per week when running dry tower only

3) Total volume in system, 100,000 gal

4) Chlorine use rate 2.5 mg/e - minimum for 30 minutes

b) Chlorine Requirements per Year

$$100,000 \text{ gal} \times 8.344 \frac{\text{lb}}{\text{gal}} \times \frac{2.5}{10^6} \frac{\text{lb Cl}_2}{16 \text{ H}_2\text{O min}} \times 30 \frac{\text{min}}{\text{day}} \left(215 \frac{\text{days}}{\text{year}} + 20 \frac{\text{weeks}}{\text{year}} \right) = 14706 \text{ lb/year using a 480 lb/day system}$$

Capital cost of such a system can be estimated from cost of a 20,000 lb/day system.

$$\text{Capital Cost} = \left(\frac{480}{20,000} \right)^{0.6(a)} \times \$100,000 = 10,669.0 \quad \underline{\underline{\$11,000}}$$

Operating Costs

Typical costs at a Washington site	Cl ₂ cost	\$2.08/ton
	shipping	\$2.00/100 lb
	cylinder wt.	1500 lb
	cylinder full wt. shipping	3500 lb

Return cylinder shipping \$30/ton

$$\text{Cost per lb Cl}_2 = \frac{2.08 + 70 + 30}{2000 \text{ lb/ton}} = \$0.155/\text{lb}$$

$$\text{Labor } 1 \text{ hr/day} \times 235 \text{ days/year} \times \$15/\text{hour} = 3525$$

$$\text{Total} = 5804$$

$$+ \text{electricity/pumping} = \underline{\underline{6000}}$$

Total Cost of Deluge Treatment

$$\text{Capital Cost} = \$4.5 \times 10^5$$

$$\text{Operating Cost} = 7.9 \times 10^4$$

COMBINED WET-DRY WATER TREATMENT

Dry recirculation system

Flow rate 200,000 gpm.

1. Biofouling Control

a) Basis

- 1) 1 chlorination per day when using wet section
- 2) 1 chlorination per week bypassing wet section
- 3) Total volume in system 10^6 gal
- 4) Chlorine use rate 2.5 mg/e minimum for 30 minutes

(a) 0.6 = assumed scale-up exponent.

b) Chlorine Requirements per Year

Ten-times the volume of the deluge system or $10 \times 14706 =$

147,060 lb/year using a 4800 lb/day system

Capital cost estimated from cost of a 20,000 lb/day system. (a)

$$\text{Capital} = \left(\frac{4800}{28000} \right)^{0.6} \times 100,000 = 42,474 \quad \underline{\underline{40,000}}$$

Operating Costs

Cl_2 cost + shipping

Ten times deluge requirements = \$22,740/year

Labor 1 1/2 hour/day $\times$ 235 days $\times$ \$15/hr = 5287

\$28,000/year

2. Wet-Dry Operation (b) Side Stream Treatment

a) Lime-Soda Softening

Capital Cost = $\$1.5 \times 10^5$ installed

Operating Cost = $\$5.4 \times 10^4$ /year

b) Scale Inhibition

Capital Cost = $\$1.7 \times 10^5$ installed

Operating Cost = $\$2.3 \times 10^4$ /year

Total Cost of Water Treatment

Capital Cost = $\$3.6 \times 10^5$

Operating Cost = $\$10.5 \times 10^4$ /year

SCAT SYSTEM WATER TREATMENT

Flow rate - 170,000 gpm

Evaporation rate - 3200 gpm

Water Treatment - Wet-Dry Operation

(a) Wallace and Tieron estimate of \$100,000 for a 20,000 lb/dry unit.

(b) Operating costs are assumed to be the same as those for the deluge water treatment since the same amount of chemicals are used.

1. Side Stream Treatment

Capital Cost = $\$1.3 \times 10^5$ Installed

Operating Cost = 4.6×10^4 /year

2. Scale Inhibition

Capital Cost = $\$1.5 \times 10^5$ installed

Operating Cost = $\$2.0 \times 10^4$ /year

3. Biofouling Control

a) Basis

1) 1 chlorination per day when using wet section

2) 1 chlorination per week when running dry only

3) Total volume water in system 10^6 gal

4) Chlorine use rate 2.5 mg/e minimum for 30 minutes

b) Chlorine required and costs are on the same basis as for the combined tower.

Capital Cost = \$34,000

Operating Cost = \$23,000/year

Total Cost of Water Treatment

Capital Cost = 3.1×10^5

Operating Cost = 8.9×10^4

APPENDIX D

DESIGN PARAMETERS

TABLE D-1. Design Parameters

Tower	Vertical HÜTERV	Horizontal HÜTERV	SCAT Tower Design	Augmenting NH ₃ Condenser	Integrated Wet/Dry
Tower size (ft)	259 dia x 56 high	205 x 230 x 57 high	225 dia x 56 high	170 dia x 56 high	482 x 138 x 55 high
Tower Design Temp.	55°F	55°F	55°F	35°F	35°F
Design ITD, degrees	67	67	67 dry, 32 wet	87 dry, 32 wet	90 day, 30 wet
Number of Towers	3	2	2	2	2
Number of Bundles	288	288	122	88	320
Dimensions	47.6 ft x 8 ft x 6 in.	47.6 ft x 8 ft x 6 in.	50 ft x 12 ft x 1 ft	50 ft x 12 ft x 7.2 in.	48 ft x 72 ft x 10 in.
Total Surface Area, ft ²	9.71 x 10 ⁶	9.71 x 10 ⁶	8.91 x 10 ⁶	5.41 x 10 ⁶	7.206 x 10 ⁶
Frontal Area, ft ²	1.072 x 10 ⁵	1.072 x 10 ⁵	0.732 x 10 ⁵	0.522 x 10 ⁵	9.216 x 10 ⁴
Tube OD, inches	0.78	0.78	0.3	0.3	1.07
Fin Design	Rectangular Plate	Rectangular Plate	Integral	Integral	Single Leg Wrapped
Fin Dimensions	6 in. deep 7.87 ft high	6 in. deep 7.87 ft high	0.707 in. high 12 in. deep	0.707 in. high 12 in. deep	2.25 round
Fins Per Inch	9	9	10.6	10.6	10
Tube Material	Aluminum	Aluminum	Aluminum	Aluminum	Admiralty
Fin Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
Tube Geometry	Staggered Rows	Staggered Rows	Rectangular Aligned Channels	Rectangular Aligned Channels	Equilateral
Transfer Tube Pitch, Inches	2.36	2.36	NA	NA	2.35
Heat Transfer Coefficient Btu/hr- ft ² -°F	7.57	7.57	8	9.1	6.41
Frontal Velocity/ Internal Velocity, ft/sec.	8/13.3	8/13.3	12/16.4	14.0/19.1	10.5/15
Air Flow, lb/hr - Dry	1.93 x 10 ⁸	1.93 x 10 ⁸	1.97 x 10 ⁸	1.70 x 10 ⁸	2.196 x 10 ⁸
Air Flow, lb/hr - Wet	1.3 x 10 ⁸	1.3 x 10 ⁸	0.45 x 10 ⁸	0.47 x 10 ⁸	0.24 x 10 ⁸
Air Mass Flow Rate, - Dry lb/hr-ft ² - Wet	1.79 x 10 ³ 0.9 x 10 ³	1.79 x 10 ³ 0.9 x 10 ³	2.69 x 10 ³	3.26 x 10 ³	2.38 x 10 ³ 0.5 x 10 ³
Cooling Water Flow, GPM	7,000 (80 TDH)	21,000 (40 TDH)	170,000 (35 TDH)	200,000 (35 TDH)	219,000 (77 TDH)
Airside Heat Exchange/ΔP/ Total ΔP, Inches H ₂ O	0.356/0.464	0.356/0.464	0.281/0.384	0.243/0.358	0.345/0.538
Fans - Dry Wet	57	56	48 8	26 8	40 10
Fan Diameter, ft - Dry Wet	28	28	28	28	30 24
HP Per Fan - Dry Wet	82.3	82.3	50 150	105 150	145 90
Number of Blades - Dry Wet	6	6	6	6	8 6
Pitch, degrees - Dry Wet	12	12	10 22	16 22	14 16

APPENDIX E

FUEL SAVINGS IN BARRELS OF OIL
FOR THE ADVANCED DRY COOLING
TOWER DESIGNS

APPENDIX E

FUEL SAVINGS IN BARRELS OF OIL FOR THE ADVANCED DRY COOLING TOWER DESIGNS

The additional base plant fuel required (based on an assumed fuel cost of \$0.81/10⁶ Btu) is:

SOA

0.16 m/kWh

NH₃

0.10 m/kWh

Differential fuel cost $\Delta FC = 0.16 - 0.10 = 0.06$ m/kWh

Assuming the high heating value of oil = 15×10^4 Btu/gal

Then: barrels of oil/yr = $\Delta FC \times \frac{1}{RC} \times \frac{1}{HHV} \times \frac{\text{bbl}}{\text{gal}} \times \text{Cap Factor}$

$\times \text{hr} \times \text{plant power} \times \frac{1}{\text{eff}}$

Table 6-3, BNWL-2121

Therefore: $0.06 \times 10^{-3} \text{ $/kWh} \times \frac{10^6 \text{ Btu}}{0.81 \text{ $}} \times \frac{\text{gal}}{15 \times 10^4 \text{ Btu}} \times \frac{\text{bbl}}{42 \text{ gal}}$

$\times 0.758 \times 8760 \text{ hrs} \times 10^6 \text{ kW} \times 2.5 = 195,000 \text{ bbl/yr}$

for PNL-2661

INTEGRATED DRY/WET COOLING TOWER

Annual operating expenses less Peaking Capacity

charge =	\$1,541,400
VERTICAL HOTERV Tower =	481,500
HORIZONTAL HOTERV Tower =	503,700
SCAT Tower =	438,800
AAC Tower =	652,100

Additional base plant fuel required

= $\frac{\text{Annual Operating Expenses} \times \text{Cap Factor}}{\text{Plant Output} \times \text{hours}}$

$$\therefore FC = \text{Annual Operating Expenses} \times \frac{0.758}{0.5 \times 10^6 \text{ kW} \times 8760 \text{ hr}} = \$/\text{kWh}$$

$$\begin{aligned} \text{INTEGRATED} &= 2.667 \times 10^{-4} \text{ } \$/\text{kWh} \\ \text{VERTICAL HÖTERV} &= 8.3 \times 10^{-5} \\ \text{HORIZONTAL HÖTERV} &= 8.7 \times 10^{-5} \\ \text{SCAT} &= 7.5 \times 10^{-5} \\ \text{AAC} &= 1.128 \times 10^{-4} \end{aligned}$$

From BNWL-2121

$$\begin{aligned} \text{OIL SAVED} &= \Delta FC \times \left(\frac{1}{RC} \times \frac{1}{HHV} \times \frac{\text{bbl}}{\text{gal}} \times \text{Cap Factor} \right. \\ &\quad \left. \times \text{hours} \times \text{plant output} \times \text{eff.} \right) = (1.62 \times 10^9) \end{aligned}$$

FOR VERTICAL HÖTERV TOWER

$$\Delta FC_{\text{VH}} = 2.667 \times 10^{-4} - 8.2 \times 10^{-5} = 1.84 \times 10^{-4}$$

$$\text{OIL SAVED} = 1.84 \times 10^{-4} \times (1.62 \times 10^9) = 299.200 \text{ bbl of oil}$$

FOR HORIZONTAL HÖTERV TOWER

$$\Delta FC_{\text{HH}} = 2.667 \times 10^{-4} - 8.7 \times 10^{-5} = 1.79 \times 10^{-4}$$

$$\text{OIL SAVED} = 1.79 \times 10^{-4} (1.62 \times 10^9) = 292,200 \text{ bbl of oil}$$

FOR SCAT TOWER

$$\Delta FC_{\text{ST}} = 2.667 \times 10^{-4} - 7.5 \times 10^{-5} = 1.92 \times 10^{-4}$$

$$\text{OIL SAVED} = 1.92 \times 10^{-4} (1.62 \times 10^9) = 311,800 \text{ bbl of oil}$$

FOR AAC

$$\Delta FC_{\text{AAC}} = 2.667 \times 10^{-4} - 1.128 \times 10^{-4} = 1.54 \times 10^{-4}$$

$$\text{OIL SAVED} = 1.54 \times 10^{-4} (1.62 \times 10^9) = 250,300 \text{ bbl of oil}$$

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