Estimation of Benefits from Demonstrating Advanced Wet/Dry Cooling Technology: A Framework and Partial Analysis

by
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September 1977

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- If commercialization of ammonia cooling could be achieved only by a public investment in demonstration, the expected gross benefits from the demonstration are estimated to be \$71 million for 50 percent wet systems and \$98 million for 20 percent wet systems.

The estimated benefits varied significantly, depending on whether or not the occurrence of ammonia cooling without public participation in a demonstration is assumed. Hence, rigorous investigation of the hypothesis that some form of advanced wet/dry cooling will be commercialized in the absence of a publicly-funded demonstration is recommended. This should provide important information to ERDA on the program direction that could yield the highest net social benefits.

CONTENTS

SUMMARY	iii
LIST OF FIGURES.	vii
LIST OF TABLES	vii
INTRODUCTION	1
CONCLUSIONS AND RECOMMENDATIONS	3
ANALYTICAL FRAMEWORK	5
LEARNING THEORY	5
TECHNOLOGICAL DIFFUSION	6
MODEL DESCRIPTION	8
Probabilities and the Future Wet/Dry Market	11
Benefit Equations	14
Other Assumptions	17
MODEL VERIFICATION	17
RESULTS	19
CASE I: SOA VERSUS NH ₃ WITH INSTANTANEOUS LEARNING	19
CASE II: SOA VERSUS NH ₃ WITH LEARNING	19
CASE III: NH ₃ WITH DIFFERENT GROWTH	22
MODEL SENSITIVITY	23
PROBABILITY ANALYSIS	23
REFERENCES	25
APPENDIX A - THERMAL ELECTRIC AND DRY COOLING ADDITIONS TO THE YEAR 2000	A-1
APPENDIX B - PROBABILITY ANALYSIS CURVES	B-1

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FIGURES

1	Market Penetration Rate	7
2	Twenty Percent Wet System Learning Curves	10
3	Fifty Percent Wet System Learning Curves	10
4	Benefits if 20 GWe by Year 2000, 20 Percent Wet	20
5	Benefits if 20 GWe by Year 2000, 50 Percent Wet	21
B-1	Case I, 20 Percent Wet	B-1
B-2	Case II, 20 Percent Wet	B-2
B-3	Case III, 20 Percent Wet, $Z = 0.7$	B-3
B-4	Case III, 20 Percent Wet, $Z = 0.85$	B-4
B-5	Case III, 20 Percent Wet, $Z = 0.95$	B-5
B-6	Benefits if 50 GWe by Year 2000, 20 Percent Wet	B-6
B-7	Case I, 50 Percent Wet	B-7
B-8	Case II, 50 Percent Wet	B-8
B-9	Case III, 50 Percent Wet, $Z = 0.7$	B-9
B-10	Case III, 50 Percent Wet, $Z = 0.85$	B-10
B-11	Case III, 50 Percent Wet, $Z = 0.95$	B-11
B-12	Benefits if 50 GWe by Year 2000, 50 Percent Wet	B-12

TABLES

1	Market Level Fractions and Assigned Probabilities of Attainment for Wet/Dry Cooling Technology	12
2	Expected Values and Standard Deviations of Gross Benefits for Cases II and III	24
A-1	Thermal Electric Additions, 1981-2000	A-1
A-2	Projected Additions to Dry-Cooled Electric Generation (Percent of New Thermal Additions)	A-2
A-3	Additions to Dry-Cooled Electric Generation, MWe	A-3

ESTIMATION OF BENEFITS FROM DEMONSTRATING ADVANCED WET/DRY
COOLING TECHNOLOGY: A FRAMEWORK AND PARTIAL ANALYSIS

INTRODUCTION

This study was conducted as part of the ERDA Dry Cooling Tower Program at the Pacific Northwest Laboratory (PNL). The purpose of the analysis was to estimate the reductions in power generation costs expected to occur with a proposed demonstration of advanced wet/dry cooling technology. Experience gained by the electric power industry in building and operating new facilities can result in more efficient future production. If the information describing the experience were widely disseminated, many utilities could realize cost reductions. These cost reductions (benefits) to others would, of course, be external to the individual utility's decision whether or not to demonstrate advanced wet/dry cooling technology (and hence provide the experience). Without some means of internalizing these future cost reductions, private decisions based solely upon private benefits and costs may be inefficient from a social viewpoint. Therefore, information contained in this report is intended to assist ERDA in deciding the extent to which the public should participate in demonstrating an ammonia (NH_3) cooling concept.

Wet/dry cooling technology is not generally used by the U.S. electric power industry because lower-cost options are available. For example, it is less expensive to the industry to acquire water rights and install wet cooling technology, even if doing so necessitates increased expenditures for transmitting electricity from the plant to the market or for transporting water to the plant. However, if technological improvements were to reduce either the average costs of wet/dry-cooled power generation or the uncertainty surrounding these costs, benefits could eventually accrue to electricity consumers through such cost reductions.

To demonstrate the technical and economic feasibility of one advanced concept, construction of a wet/dry-cooled demonstration unit equipped with

an ammonia cooling loop has been proposed. To be erected by 1981 near Bakersfield, California, the unit would have a capacity of 6 to 10 MWe. Testing would be completed by 1983. The total cost, including testing, is estimated at \$10 million.

Cost reductions expected to occur with demonstration of the NH_3 concept can be interpreted as benefits from "learning by doing", as well as benefits from reducing the uncertainty of performance, and, ultimately, costs associated with ammonia-cooled power generation systems. The extent to which consumer benefits would accrue is, of course, dependent upon the magnitude and timing of the cost reductions, as well as the fraction of thermal electric additions that would use wet/dry cooling. This study considers these cost reductions, but does not represent a comprehensive benefit-cost analysis. Hence, other significant benefits and costs, such as the value to society of the environmental impacts of wet/dry cooling versus those of other cooling technologies, are not quantified.

This report describes the analytical framework and data used in developing the model for analyzing expected cost reductions. The model and its limitations are discussed. Results of the analysis are presented by individual case and recommendations for future work are included.

CONCLUSIONS AND RECOMMENDATIONS

It was concluded that the benefits, in the form of future cost reductions, would probably exceed the expected costs of the proposed advanced wet/dry cooling technology demonstration.

- If commercialization of ammonia (NH_3) cooling were to result without a public investment in demonstration for 50 percent wet systems, the expected gross benefits from demonstration range from \$2 million to \$33 million, depending on market penetration rates. For 20 percent wet systems, the expected gross benefits range from \$8 million to \$48 million.
- If commercialization without the demonstration were to proceed at a rate of 15 percent less than with demonstration, there is an approximately 80 percent chance that the benefits from demonstration would exceed \$8 million.
- If commercialization of NH_3 cooling could only be achieved with a publicly-funded demonstration, the expected gross benefits from demonstration are estimated to be \$71 million for 50 percent wet systems and \$98 million for 20 percent wet systems.

These numbers represent best estimates. However, the reader is cautioned that the benefit estimates are extremely sensitive to small changes in the engineering-estimated learning functions, the market penetration rate of wet/dry cooling and the discount rate.

No conclusions were drawn regarding commercialization of ammonia cooling without demonstration. However, based on this analysis and a review of theoretical and empirical work on technological substitution and diffusion, it is hypothesized that ammonia cooling or some form of advanced wet/dry cooling technology will eventually be commercialized without public investment in demonstration. Hence, it is recommended that the above hypothesis be rigorously investigated. Such an investigation would necessitate studying the fundamental causes for technological diffusion,

the willingness to pay (economic demand) for cooling water and the role of information in imperfectly competitive markets. This investigation should be supported by:

- an analysis of the rates of diffusion of new capital intensive technology in other similarly-structured markets;
- estimates of the future economic supply (price-quantity relationships) of cooling water on a regional basis; and
- estimates of the monetary value to society of the environmental impacts from different cooling alternatives.

These efforts should result in either acceptance or rejection of the hypothesis as well as better overall estimates of the future wet/dry cooling market with and without demonstration.

ANALYTICAL FRAMEWORK

A comprehensive benefit-cost analysis of a proposed wet/dry cooling demonstration would include:

- the cost reductions and future savings that may accrue to wet/dry cooling users as a result of the knowledge acquired during the demonstration project;
- monetary quantification of the opportunity costs of the resources used in the demonstration;
- the values of the environmental impacts of dry cooling and alternative cooling technologies;
- the value of the demonstration to other RD&D;
- estimates of the optimal size of the demonstration investment; and
- estimates of the year in which the investment would maximize net social benefits.

Although extensive theoretical and applied literature exists on all of these items,⁽¹⁻¹⁰⁾ only the first falls within the scope of this analysis. If it is assumed that the sum of the net benefits on the items not addressed is non-negative, it is possible to evaluate (from an expected improvement in economic efficiency) the demonstration plant by estimating benefits in the form of future cost reductions accruing to users of wet/dry cooling as a direct result of the demonstration project.

To estimate these benefits, elements of learning theory and the theory of technological diffusion were incorporated into a stochastic model. This model estimates a distribution of benefits from learning over time and discounts these benefits back to the beginning of the demonstration project.

LEARNING THEORY

Learning by doing is an important concept when estimating the benefits from technology RD&D, and an extensive literature exists on this subject.⁽¹¹⁻¹⁸⁾ The problem has been cast in proper economic perspective by Arrow, who views it as encompassing intertemporal and international shifts in production functions.⁽¹⁶⁾

Several available empirical studies have estimated the increase in productivity from learning as a function of capacity, output, and duration of production time.^(17, 19-23) Much early empirical work centered on labor productivity in the airframe industry. In 1936, Wright⁽¹⁹⁾ demonstrated that the number of labor-hours expended in producing an airframe is a decreasing function of the total number of airframes of the same type previously produced. In 1949, Alchian⁽²¹⁾ performed a statistical analysis on airframe data to estimate several different functions to be used in estimating production costs. He found a significant negative relationship between per unit costs and quantity produced.

Only recently has learning theory within a rigorous economic analysis been empirically applied to new technology. Rausser et al.⁽²²⁾ investigated external benefits from a water desalting plant. The analysis incorporated Bayesian methods using both prior and posterior information. Willis performed a similar analysis on the production of methane from chicken waste.⁽²³⁾ He also made use of prior and posterior information.

Methodology and findings of this previous research were freely employed in estimating the benefits from learning expected to result from demonstrating advanced wet/dry cooling technology. The benefits are estimated as distributions, thus providing information on the expected value of benefit estimates as well as the variance about the expected values. No other benefits and costs are quantified in this analysis.

TECHNOLOGICAL DIFFUSION

The theory of technological diffusion, that is, the examination of the rapidity of, and underlying reasons for, industry adoption of new technology, is also well-documented.^(18, 24-30) Technological adoption tends to proceed along a logistics or S-shaped curve, slowly at first and then more rapidly, slowing again as it approaches its ceiling or ultimate equilibrium level. In Figure 1, T represents the diffusion period or the time required to reach ultimate equilibrium. The vertical axis usually

FIGURE 1. Market Penetration Rate

measures cumulative adoption as a percentage of ultimate equilibrium level. Historically, diffusion periods have ranged from 9 years for detergents to substitute for soap, to 18 years for synthetic fibers to replace natural fibers in tires, to 75 years to substitute steam ships for sailing ships.

The driving forces for technological innovation in the past have been a technological achievement, a military threat or competition in business. Increasingly, however, it appears that technological innovation will be driven by environmental concerns and fears of resource depletion.⁽³¹⁾

Many reasons are postulated to explain why the diffusion processes proceed along an S-shaped curve rather than jumping immediately to an equilibrium level. Among these are: 1) imperfect flow of information from user to potential users, 2) age distribution of existing capital stock, 3) anticipation of changes in quality and price of new technology, and 4) supply bottlenecks.

In this analysis, a Gompertz curve having the form

$$y = \alpha \beta^t \quad (1)$$

was used to describe the rate of technological diffusion, where

y = the percentage of equilibrium attained in year t

α = constant < 1

β = constant < 1

t = time in years since the start of wet/dry cooling technology adoption.

MODEL DESCRIPTION

As stated earlier, the model is firmly based on learning theory literature. Much empirical evidence derived from statistical analysis supports the general learning theory hypothesis that unit costs of production decrease as the cumulative total of units produced or as the cumulative total of time spent in doing increases. The generally accepted form of the equation is

$$AC = e^a CAP^b + AS \quad (2)$$

where

AC = average cost per unit produced

a, b = parameters to be estimated

CAP = surrogate for cumulative production/time

e = the constant 2.718

AS = minimum average cost asymptote.

The preceding formulation lends itself to simple statistical estimation of the parameters after subtracting AS from both sides and taking logarithms. This yields

$$\ln(AC - AS) = a + b \ln CAP \quad (3)$$

Parameters a and b can then be estimated by regressing the log of $(AC - AS)$ on the log of cumulative capacity. In this equation, b represents the learning rate. It can be shown that doubling the cumulative capacity (or an appropriate surrogate) will lead to a cost decrease of $(1-2^b)100$ percent. A typical and often-quoted value for b is -0.322 ,⁽³²⁾ indicating a 20-percent reduction in costs per unit produced for each doubling of capacity.

The absence of previous experience with advanced wet/dry cooling technology necessitated employing available engineering cost estimates. Comparisons of incremental power production costs of wet/dry cooling system options⁽³³⁻³⁵⁾ indicated that average costs of cooling decrease as the percentage of wet to dry increases for a given system.

Using these estimates, three basic assumptions were formulated for this model:

- Initially, incremental power production costs for NH_3 systems would be the same as those for state-of-the-art metal finned tube (SOA) systems; those costs would reduce to the estimated advanced system costs only after equipping 1500 MWe of electric generating capacity with NH_3 cooling.
- With continued learning, the NH_3 system added cost could be expected to decrease asymptotically to approximately 85 percent of the cost at 1500 MWe installed capacity.
- Incremental power production costs for SOA systems would be reduced asymptotically to approximately 85 percent of current costs.

The learning curves for 20 and 50 percent wet systems are shown in Figures 2 and 3. Curve B represents the SOA cooling system learning curve; Curve D represents the NH_3 system learning curve. The case in which no learning occurs in SOA dry cooling systems is illustrated by Curve A. Curve C represents the occurrence of instantaneous learning and costs do not decrease with increases in installed capacity.

Market penetration is depicted in this model with an S-shaped curve approaching a predetermined ultimate equilibrium level over time. The diffusion period (i.e., time required to reach equilibrium) is approximately

FIGURE 2. Twenty Percent Wet System Learning Curves

FIGURE 3. Fifty Percent Wet System Learning Curves

40 years but by the 12th year one-half the ultimate equilibrium has been attained. A Gompertz function was used and has the form

$$y = \alpha \beta^t \quad (4)$$

where

$$\alpha = 0.01$$

$$\beta = 0.85.$$

When t is equal to 12 as stated above, $y = 0.52$, or 52 percent of the ultimate equilibrium level has been attained.

Probabilities and the Future Wet/Dry Market

Considerable uncertainty exists in estimating the learning function parameters and the expected future wet/dry cooling technology market. Probability functions are recommended to explicitly account for this uncertainty.⁽³⁶⁾ Accounting for the uncertainty permits the analyst to report sensitivity of benefit estimates to changes in specific model parameters in terms of benefit probability and expected value. The learning curve parameters were estimated by using a pseudo random number generator to draw random deviates from probability density functions with means equal to the parameters as shown in Figures 2 and 3. The parameter b was chosen from a gamma density function because this form does not allow for negative learning and agrees with information derived by other researchers.⁽²²⁾ The parameter a was calculated by first selecting a random deviate b from the gamma distribution, then selecting a random deviate, AA , from a normal distribution with a mean equal to the difference between the initial incremental cost of wet/dry cooling and the expected minimum cost. The parameter a is then

$$a = \ln AA + b \ln (31.536) \quad (5)$$

where 31.536 is the number of kWh (millions) generated by a 6-MWe demonstration plant with a capacity factor of 0.6 and AA is equal to $(AC - AS)$ in Equation (3).

The rate of wet/dry cooling technology commercialization was also treated probabilistically. Each of fifteen different ultimate market equilibrium levels was assigned a probability of attainment with the sum of the fifteen probabilities equal to one. This required choosing a probability distribution and appropriate parameters. The probability of attainment distribution was assumed to be skewed similar to a gamma distribution (see Table 1). Next, the mode and range were chosen. This step required information on the expected future demand for wet/dry cooling or, as a minimum, a subjective evaluation of the future wet/dry cooling market. The approach used was to relate the future market of wet/dry cooling to national market forecasts of thermal electric additions to the year 2000.

TABLE 1. Market Level Fractions and Assigned Probabilities of Attainment for Wet/Dry Cooling Technology

Ultimate Equilibrium (Fraction of New Cooling Capacity)		Fraction of Thermal Electric Additions 1985-2000 (Low Growth)	Probability of Attainment
$t = \infty$	$t = 15$		
.02	.01	.007	.0025
.04	.03	.014	.0100
.06	.04	.020	.0400
.08	.06	.028	.1000
.10	.07	.034	.1500
.12	.09	.041	.3000
.14	.10	.048	.1500
.16	.11	.054	.1000
.18	.13	.062	.0400
.20	.14	.069	.0300
.22	.16	.075	.0250
.24	.17	.083	.0200
.26	.19	.089	.0150
.28	.20	.096	.0125
.30	.21	.103	.0050

Two recent studies have used this approach. Proceeding from national forecasts of thermal electric additions, both studies regionalized and compared water consumption requirements of these forecasts to projected unallocated regional water supplies to the year 2000.

The first study, prepared by the General Electric Company (GE), projected 6 to 23 GWe of wet/dry cooling for nuclear power plants by the year 2000.⁽³⁵⁾ No estimate was given for fossil-fired plants. However, Hendrickson used the GE data to derive an estimate of 5 to 19 GWe for fossil-fired plants.⁽³⁶⁾ Combining the two estimates yields a total projected addition of 11 to 42 GWe by the year 2000.

The second study,⁽³⁷⁾ by Petersen and Sonnichsen of the Hanford Engineering Development Laboratory (HEDL), used power projections normalized to forecasts published in Nuclear Power Growth, 1973-2000, WASH-1139. These projections were then dispersed into localized patterns and assigned to Water Resource Regions and Subregions. The authors assumed that a maximum of 10 percent of the once-in-ten-year monthly low flow would be available for thermal power plant consumptive use. Using this and information on institutional constraints, the authors made a judgmental forecast of expected future occurrences of dry and wet/dry cooling in each region. They estimated between 24 and 44 MWe of wet/dry cooling nationally by the year 2000.

Both studies assumed no water transfers from other uses to power plant cooling. Hendrickson found that, on the average, water is worth at least five times as much to a utility as to a farmer.⁽³⁶⁾ He also found that institutional constraints to water rights transfers currently exist in two western states, California and Montana. Over half the projected future use of wet/dry cooling is in California. However, if water rights transfers continue to be allowed in other states, the future additions of wet/dry cooling will probably be at the lower end of the above estimates. Hendrickson, in fact, suggests 20 GWe by the year 2000 as a reasonable estimate.

The national forecast of thermal electric additions used in this analysis is the low growth forecast of Table A-1. This forecast is consistent with current econometric estimates and with intentions to add capacity noted in recent issues of Electric World. By summing the thermal additions over all Water Resource Regions for the HEDL low growth case a national forecast is available for comparison. The low growth case of the GE report may be compared directly with the additions to 2000 used in this report. Both the HEDL and GE forecasts of thermal electric additions on which the forecasts for wet/dry cooling were based are twice those used in this analysis. Thus, Hendrickson's estimate of 20 GWe of wet/dry cooling by the year 2000 was chosen as the most likely to occur. This was assigned the highest probability of attainment, 0.30, at an ultimate equilibrium of 0.12. Thus, it is estimated that, at time equals infinity, there is a 30 percent chance that wet/dry cooling will capture 12 percent of the cooling market of the additions to thermal electric capacity. Further, this represents 20 GWe. It is also estimated that wet/dry cooling has a 30 percent chance of capturing 9 percent of the new market in the year 2000 ($t = 15$). Between the years 1985 and 2000 it is estimated that wet/dry cooling has a 30 percent chance of capturing 4.1 percent of the additions to thermal electric capacity. The yearly fraction that would accrue to wet/dry cooling for each equilibrium level is given in Appendix A.

Benefit Equations

Given the learning curves shown in Figures 2 and 3, the market penetration rates as calculated by the Gompertz function, projections of additions to thermal electric generating capacity, estimated probabilities of attaining selected ultimate market equilibrium levels, average life of new thermal generating plants and the discount rate, equations can now be written for estimating benefits from learning that accrue to a demonstration of a plant equipped with an NH_3 cooling loop.

Benefits were estimated for three separate cases characterized by differing assumptions on ultimate equilibrium levels for SOA and NH₃ cooling.

Case 1: SOA Versus NH₃ with Instantaneous Learning

Case 1 is represented by Curves A and C in Figures 2 and 3. This is the most naive of the cases examined. Benefits from the demonstration can be defined as the cost differential (ammonia versus state-of-the-art) for each plant over its 40-year life discounted back to the start of the demonstration project (1979). Throughout all the analyses, benefits from only those plants projected to adopt wet/dry cooling between 1985 and 2000 were included. The benefits equation then is

$$BEN = \sum_{i=1985}^{2000} \sum_{j=i}^{j+39} \left(\frac{1}{(1+R)^j} \right)^{(j-1979)} (C_1 - C_2) NEWCAP_i \quad (6)$$

where

R = discount rate in real terms (i.e., inflation excluded)

C₁ = 1.86 for 20 percent wet; 1.52 for 50 percent wet

C₂ = 1.49 for 20 percent wet; 1.27 for 50 percent wet

NEWCAP_i = new wet/dry-cooled generation (10⁶ kWh) in year i and is calculated in the code as NEWCAP = αβ^t (TOTEL_i)(EQUIL)

where

TOTEL_i = projected additions to all thermal generation in year i (10⁶ kWh)

EQUIL = ultimate equilibrium level for wet/dry cooling as a percentage of total new thermal additions

α,β = parameters of the Gompertz function

t = (i - 1984).

Case II: SOA Versus NH₃ with Learning

Case II assumes learning as depicted by Curves B and D in Figures 2 and 3. The benefits equation is

$$BEN = \sum_{i=1985}^{2000} \sum_{j=1}^{i+39} \left(\frac{1}{(1+R)^j} \right)^{(j-1979)} NEWCAP_i \left[(e^{A2} DCCAP_i^{B2} + AS2) - (e^A DCCAP_i^B + AS) \right] \quad (7)$$

where R and $NEWCAP_i$ are as described in Case I and

$$DCCAP_i = \sum_{j=1985}^i NEWCAP_j$$

and A, A2, B and B2 are parameters, and AS2 and AS are asymptotes, from learning curves B and D in Figures 2 and 3.

Case III: NH₃ with Different Growth

Case III assumes learning as depicted by Curve C in Figure 2, but allows for the adoption of ammonia cooling at a reduced penetration rate even if there is no demonstration. Because of the different market penetration rates, the benefits from learning for each penetration rate relative to a no-learning case were measured separately. The benefit equation for this case is $BEN = BEN1 - BEN2$ where BEN1, the benefits from learning given a demonstration plant, is defined as

$$BEN1 = \sum_{i=1985}^{2000} \sum_{j=i}^{i+39} \left(\frac{1}{(1+R)^j} \right)^{(j-1979)} NEWCAP_i \left[C_1 - (e^A DCCAP_i^B + AS) \right] \quad (8)$$

and BEN2, the benefits from learning assuming no demonstration, is defined as

$$BEN2 = \sum_{i=1985}^{2000} \sum_{j=i}^{i+39} \left(\frac{1}{(1+R)^j} \right)^{(j-1979)} XNEWCAP_i \left[C_1 - (e^A XDCCAP_i^B + AS) \right] \quad (9)$$

where

R , $NEWCAP_i$ and $DCCAP_i$ are as defined in Cases I and II and

$$XNEWCAP = (NEWCAP)(Z)$$

$$Z = 0.7, 0.85 \text{ or } 0.95$$

$$XDCCAP_i = \sum_{j=1985}^i XNEWCAP_j$$

$AS = 1.31$ for 20 percent wet; 1.15 for 50 percent wet from Figures 2 and 3

A, B = parameters from learning curve D in Figures 2 and 3

$C_1 = 1.86$ for 20 percent wet; 1.52 for 50 percent wet.

Other Assumptions

In most analyses, the results are extremely sensitive to the assumptions used. For this reason, the other assumptions used in this analysis will now be explicitly defined.

The discount rate used in calculating the "best" estimates was 7 percent in real terms. This means that the effects of inflation are removed and the benefits and costs are in constant dollars.

The computer model adds wet/dry cooling capacity in units of 200 MWe. If actual capacity were added in units greater than 200 MWe, the benefits will have been slightly overestimated in this analysis. Table A-3 shows how much capacity is added in each year under assumptions of different growth rates.

MODEL VERIFICATION

Verification of the model was an important consideration. The first step was to hand-calculate the most naive case (Case I), instantaneous learning. The results were then compared with output from the computer algorithm for Case I.

Verification of Cases II and III was accomplished by performing several simulations while varying different parameters to see if the results "made sense" in relative terms. For example, an increase in the discount rate must result in a reduction of benefits, everything else being equal. When it appeared that the computer output was correct, a run was made for both Case II and III, printing out variables each time a calculation was made. The results were duplicated by hand calculations for a four-year time horizon in each case. This completed the model verification.

RESULTS

The results presented in Figures 4 and 5 show gross benefits as a function of the discount rate from 20 GWe by the year 2000. These results represent the means of the benefit distributions at each discount rate.

CASE I: SOA VERSUS NH₃ WITH INSTANTANEOUS LEARNING

Case I, Figure 4 and 5, is underlain with four assumptions:

- Without demonstrating ammonia cooling, the average cost differential using state-of-the-art technology over zero-cost cooling will forever be constant at 1.86 mills/kWh for 20 percent wet and 1.52 mills/kWh for 50 percent wet.
- With the demonstration, the average cost differential instantaneously drops to 1.49 mills/kWh for 20 percent wet and 1.27 mills/kWh for 50 percent wet, and remains forever constant.
- The demonstration has no effect on the growth rate of dry cooling.
- Ammonia cooling will never occur without the demonstration.

The probability analysis indicates that the best estimate of the gross benefits from this scenario is \$155 million for 20 percent wet and \$120 million for 50 percent wet.

CASE II: SOA VERSUS NH₃ WITH LEARNING

In this case, the assumption of instantaneous learning is relaxed. Costs using SOA are assumed to decrease asymptotically as capacity is increased. The probability analysis suggests that the best estimate of the gross benefits from this scenario is \$98 million for 20 percent wet and \$71 million for 50 percent wet. These represent minimum values of expected benefits for the SOA versus NH₃ scenario because, if the rate of commercialization increased due to demonstration, the benefits would increase.

FIGURE 4. Benefits if 20 GWe by Year 2000, 20 Percent Wet

FIGURE 5. Benefits if 20 GWe by Year 2000, 50 Percent Wet

CASE III: NH₃ WITH DIFFERENT GROWTH

Two crucial assumptions of the above scenarios were that 1) ammonia cooling will never be commercialized without the demonstration and 2) the demonstration would have no effect on the market penetration rate of wet/dry cooling. The second assumption is believed to be naive: considerable theoretical rationale and empirical evidence in other similarly-structured markets warrant relaxation of this assumption.

The first assumption is not so easily handled. Although evidence in general supports relaxation of this assumption, it is not as overwhelming as in the case of the second assumption.

For this reason, several computer runs were made to investigate how changes in the market penetration rate of wet/dry cooling due to a demonstration of advanced technology would affect the gross benefits. The assumptions for these scenarios are:

- Ammonia cooling will be commercialized regardless of whether a public investment in demonstration occurs.
- Demonstration of ammonia cooling will cause an increase in the market penetration rate of ammonia cooling.

Four scenarios were investigated where the market penetration rate without demonstration was assumed to be 70, 85, 95 and 100 percent of the penetration rate with demonstration. It was found that the benefits are extremely sensitive to changes in the market penetration rate. For example, assuming identical market penetration rates for ammonia cooling with and without the demonstration (the only difference in cumulative capacity being the demonstration plant), the gross benefits are estimated to be close to zero for both 20 percent and 50 percent wet. (This curve is not shown.) However, if the penetration rate without the demonstration were 95 percent of the growth rate after demonstration, the gross benefits estimated from the probability analysis are \$8 million for 20 percent wet and \$3 million for 50 percent wet. The gross benefits would increase to \$48 million and \$33 million, respectively, if the before-demonstration growth rates were 70 percent of the growth rate after demonstration.

MODEL SENSITIVITY

It was found that the expected benefits are sensitive not only to the relative growth rates for wet/dry cooling with and without demonstration, but also to the absolute growth rates with and without demonstration. For example, it was found that, over a wide range of capacity, a doubling of installed wet/dry cooling capacity between 1985 and 2000 would approximately double the expected benefits for each scenario investigated.

The analysis also indicated that the benefit estimates are extremely sensitive to the real rate of interest used. Rates of 4, 7 and 10 percent were used for each scenario. The estimated benefits at an interest rate of 4 percent were about twice those reported at an interest rate of 7 percent. Use of a 10-percent interest rate resulted in about half the benefits generated with a 7-percent interest rate.

PROBABILITY ANALYSIS

Cases I, II and III were run on the computer 50 times each for the fifteen different ultimate market equilibrium levels. The 50 values for each equilibrium level were then multiplied by the corresponding probability of attainment. The sum of these products yielded a distribution of benefits.

This analysis indicated the degree of uncertainty surrounding the estimated benefits when explicitly treating the learning function parameters and the maximum market penetration rates as having a considerable degree of uncertainty. The results of this analysis provide the "best" estimates, statistically speaking, for the most realistic scenarios and are shown in Table 2.

There are at least two very important results in Table 2. First, if NH_3 cooling were to occur without a public investment in demonstration but penetrate the market at a rate of 15 percent less than had a demonstration occurred, there is an approximately 80 percent chance that gross benefits (\$8 to \$13 million) from a demonstration would exceed the demonstration

TABLE 2. Expected Values and Standard Deviations
of Gross Benefits for Cases II and III

	Expected Value		Standard Deviation		80% Chance That Gross Benefits	
	\$10 ⁶		\$10 ⁶		>\$10 ⁶	
	20% Wet	50% Wet	20% Wet	50% Wet	20% Wet	50% Wet
<u>Case III</u>						
<u>NH₃ vs. NH₃</u>						
W/D growth w/o demo = 0.95 x growth with demo	8	3	4	2	4	1
<u>NH₃ vs. NH₃</u>						
W/D growth w/o demo = 0.85 x growth with demo	24	16	11	8	13	8
<u>NH₃ vs. NH₃</u>						
W/D growth w/o demo = 0.7 x growth with demo	48	33	23	16	25	17
<u>Case II</u>						
<u>NH₃ vs. SOA</u>						
learning as a function of capacity	98	71	71	48	27	23

cost. Second, if commercialization of NH₃ cooling would occur only with a publicly-funded demonstration, there is an 80 percent chance that gross benefits from demonstration would exceed \$23 million. These numbers again point out the sensitivity of the estimates to

- the assumptions inherent in Cases II and III; and
- the market penetration rates with and without the demonstration.

Additional curves showing results of the analysis are presented in Appendix B.

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APPENDIX A
THERMAL ELECTRIC AND DRY COOLING
ADDITIONS TO THE YEAR 2000

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TABLE A-1. Thermal Electric Additions, 1981-2000^(1,2)

Year	Low Growth			High Growth		
	GWe Additions	Cumulative GWe	10 ⁶ kWh ^(a)	GWe Additions	Cumulative GWe	10 ⁶ kWh ^(a)
1981	14	14	73,584	14	14	73,584
1982	15	29	78,840	15	29	78,840
1983	16	45	84,096	16	45	84,096
1984	17	62	89,352	17	62	89,352
1985	18	80	94,608	20	82	105,120
1986	18	98	94,608	30	112	157,680
1987	18	116	94,608	30	142	157,680
1988	18	134	94,608	30	172	157,680
1989	18	152	94,608	30	202	157,680
1990	18	170	94,608	30	232	157,680
1991	26	196	136,656	34	266	178,704
1992	26	222	136,656	34	300	178,704
1993	26	248	136,656	34	334	178,704
1994	26	274	136,656	34	368	178,704
1995	26	300	136,656	34	402	178,704
1996	36	336	189,216	52	454	273,312
1997	36	372	189,216	52	506	273,312
1998	36	408	189,216	52	558	273,312
1999	36	442	189,216	52	610	273,312
2000	36	480	189,216	52	662	273,312

(a) Assumes capacity factor = 0.6.

TABLE A-2. Projected Additions to Dry-Cooled Electric
Generation (Percent of New Thermal Additions)

Max. Penet. %	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
2	.0	.1	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0	1.1	1.2	1.3	1.4
4	.1	.1	.2	.4	.5	.7	.9	1.1	1.4	1.6	1.9	2.1	2.3	2.5	2.7	2.8
6	.1	.2	.4	.5	.8	1.1	1.4	1.7	2.1	2.4	2.8	3.1	3.4	3.7	4.0	4.3
8	.2	.3	.5	.7	1.0	1.4	1.8	2.3	2.8	3.2	3.7	4.2	4.6	5.0	5.4	5.7
10	.2	.4	.6	.9	1.3	1.8	2.3	2.9	3.4	4.0	4.6	5.2	5.7	6.2	6.7	7.1
12	.2	.4	.7	1.1	1.6	2.1	2.7	3.4	4.1	4.8	5.6	6.2	6.9	7.5	8.0	8.5
14	.3	.5	.8	1.3	1.8	2.5	3.2	4.0	4.8	5.7	6.5	7.3	8.0	8.7	9.4	9.9
16	.3	.6	.9	1.4	2.1	2.8	3.7	4.6	5.5	6.5	7.4	8.3	9.2	10.0	10.7	11.4
18	.4	.6	1.1	1.6	2.3	3.2	4.1	5.1	6.2	7.3	8.3	9.3	10.3	11.2	12.0	12.8
20	.4	.7	1.2	1.8	2.6	3.5	4.6	5.7	6.9	8.1	9.3	10.4	11.5	12.5	13.4	14.2
22	.4	.8	1.3	2.0	2.9	3.9	5.0	6.3	7.6	8.9	10.2	11.4	12.6	13.7	14.7	15.6
24	.5	.9	1.4	2.2	3.1	4.2	5.5	6.8	8.3	9.7	11.1	12.5	13.8	15.0	16.1	17.0
26	.5	.9	1.5	2.3	3.4	4.6	5.9	7.4	8.9	10.5	12.0	13.5	14.9	16.2	17.4	18.5
28	.6	1.0	1.7	2.5	3.6	4.9	6.4	8.0	9.6	11.3	13.0	14.5	16.0	17.4	18.7	19.9
30	.6	1.1	1.8	2.7	3.9	5.3	6.9	8.6	10.3	12.1	13.9	15.6	17.2	18.7	20.1	21.3

TABLE A-3. Additions to Dry-Cooled Electric Generation, MWe

Max. Penet. %	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	Cum. Total 1985-2000
2	0	0	0	0	0	0	200	200	200	200	200	400	400	400	400	600	3,200
4	0	0	0	0	200	0	400	200	400	400	400	800	800	1000	800	1200	6,600
6	0	0	0	200	0	200	400	400	600	600	800	1000	1200	1400	1400	1600	9,800
8	0	0	0	200	200	200	600	400	800	800	1000	1400	1800	1800	1800	2200	13,200
10	0	0	200	0	400	200	600	800	800	1000	1200	2000	2000	2200	2400	2600	16,400
12	0	0	200	200	200	400	800	800	1000	1400	1400	2200	2400	2800	2800	3200	19,800
14	0	0	200	200	400	400	800	1000	1200	1600	1600	2600	3000	3000	3400	3600	23,000
16	0	0	200	200	400	600	800	800	1400	1800	1800	3000	3400	3600	3800	4200	26,000
18	0	0	200	400	400	600	1000	1400	1600	1800	2200	3400	3600	4000	4400	4600	29,600
20	0	200	200	200	600	600	1200	1400	1800	2000	2400	3800	4200	4400	4800	5200	33,000
22	0	200	200	400	400	800	1200	1600	2000	2200	2800	4000	4600	5000	5200	5600	36,200
24	0	200	200	400	600	800	1400	1600	2200	2600	2800	4400	5000	5400	5800	6200	39,600
26	0	200	200	400	600	800	1600	1800	2400	2800	3000	5000	5200	6000	6200	6600	42,800
28	0	200	200	600	600	800	1800	2000	2400	3000	3400	5200	5800	6200	6800	7200	46,200
30	0	200	400	400	800	800	1800	2000	2600	3200	3600	5600	6200	6800	7200	7600	49,400

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APPENDIX B
PROBABILITY ANALYSIS CURVES

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FIGURE B-1. Case I, 20 Percent Wet

FIGURE B-2. Case II, 20 Percent Wet

FIGURE B-3. Case III, 20 Percent Wet, $Z = 0.7$

FIGURE B-4. Case III, 20 Percent Wet, $Z = 0.85$

FIGURE B-5. Case III, 20 Percent Wet, $Z = 0.95$

FIGURE B-6. Benefits if 50 GWe by Year 2000, 20 Percent Wet

FIGURE B-7. Case I, 50 Percent Wet

FIGURE B-8. Case II, 50 Percent Wet

FIGURE B-9. Case III, 50 Percent Wet, $Z = 0.7$

FIGURE B-10. Case III, 50 Percent Wet, $Z = 0.85$

FIGURE B-11. Case III, 50 Percent Wet, $Z = 0.95$

FIGURE B-12. Benefits if 50 GWe by Year 2000, 50 Percent Wet

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