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Wet/Dry Cooling Tower Test Module

Interagency Energy/Environment R&D Program Report

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EPA REVIEW NOTICE

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Wet/Dry Cooling Tower Test Module

by

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ABSTRACT

In February 1978, a ten-member group of utilities, public agencies, and private concerns, with Southern California Edison Company acting as Project Manager, began the field testing of a single cell wet/dry cooling tower (capable of cooling the waste heat from a nominal 15 MW_e of generation) at a generating station located in San Bernardino, California. The objectives of the test program were to:

1. Determine the water conservation aspects of a wet/dry cooling tower in an arid climate.

2. Determine the operational characteristics of a wet/dry cooling tower.

3. Develop and verify a mathematical model of the wet/dry cooling tower.

The test program was successful in achieving the stated goals of determining the water conservation characteristics, determining the operational characteristics, and developing and verifying a mathematical model of a wet/dry cooling tower.

Reduction of the data revealed that the wet/dry tower could save approximately 19% of the water normally evaporated by an evaporative cooling tower at the San Bernardino Generating Station without significantly affecting the normal plant performance. This degree of water conservation must be considered to be very good given the conditions of operation. It is also indicative of the great potential of wet/dry cooling for achieving signficiant water conservation when the system is optimized with that goal in mind.

During the testing period of eighteen months there were several operational problems, the most notable being sticking wet and dry section dampers, which resulted in design modifications and revised maintenance and operational procedures.

The mathematical model was developed under EPRI contract by PFR Engineering Systems, Inc., and was verified by field test data obtained from the project.

TABLE OF CONTENTS

		Page
	Abstract	ii
	List of Figures	iv
	List of Tables	v
	Acknowledgements	vi
1.	Introduction	1
2.	Conclusions and Recommendations	7
3.	Operating History	8
4.	Test Results	9
5.	Mathematical Model	18
Appendices		
A.	Operational Characteristics	20
B.	Method of Determination of Heat Rejection Rate and Evaporation Rate	35
C.	Uncertainty Analysis	37
D.	Test Instrumentation	39
E.	Description of Damper Control System	47
F.	Test Plan	49
G.	Table of Conversion Factors	51

LIST OF FIGURES

Number		Page
1	San Bernardino Generating Station Plot Plan	2
2	Operational Schematic of Ecodyne Wet/Dry Cooling Tower	4
3	Dry Section Performance	10
4	Wet Section Performance, Hot Water Temp. = 96°F	11
5	Wet Section Performance, Hot Water Temp. = 94°F	12
6	Wet Section Performance, Hot Water Temp. = 92°F	13
7	Wet Section Performance, Hot Water Temp. = 90°F	14
8	Wet Section Performance, Hot Water Temp. = 88°F	15
9	Evaporation Rate	16
A-1	Damper Linkage (photograph)	21
A-2	Structural Support Member (photograph)	22
A-3	Damper Blades (photograph)	24
A-4	Biological Growth in Hot Water Basins (photograph)	26
A-5	Floating Scum in Hot Water Basins (photograph)	27
A-6	Top View of Hot Water Basin	29
A-7	Example of Finned-tube Fouling (photograph)	30
A-8	Workman Cleaning Finned Tubes (photograph)	32
A-9	Results of Finned-Tube Cleaning (photograph)	33
A-10	Effect of Finned-Tube Cleaning (photograph)	34
D-1	Wet/Dry Cooling Tower Anemometer Locations	40
D-2	Wet Bulb Temperature and Velocity Map of Stack, "All Wet"	42
D-3	Wet Bulb Temperature and Velocity Map of Stack, 50% Wet/50% Dry	43
D-4	View of Top of Stack showing Psychrometer Location	44
D-5	Wet/Dry Cooling Tower Instrumentation Schematic	46
E-1	Damper Control as a Function of Demand	48

LIST OF TABLES

Number		Page
1	Average Site Meteorological Conditions	3
A-1	Typical Wet/Dry Cooling Tower Circulating Water Quality	25

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Finally, a word of gratitude is given to Bill Vanderford who worked long, hard, and often alone to keep the project progressing.

1. INTRODUCTION

FORMATION OF THE WET/DRY COOLING TOWER TEST MODULE PROGRAM

During 1976, a ten member co-operative was formed for the purpose of constructing and testing a wet/dry cooling tower. The membership of this group is as follows:

Southern California Edison Company
Tucson Electric Power Company
Department of Water and Power of the City of Los Angeles
Ecodyne Corporation
Electric Power Research Institute (EPRI)
Western Energy Supply and Transmission Associates (WEST)
United States Department of Energy
United States Environmental Protection Agency
State of California Department of Water Resources
State of California Energy Commission

Southern California Edison Company was designated as Project Manager of the Wet/Dry Cooling Tower Test Module (Wet/Dry Tower). Onsite construction commenced in April 1977 and was completed in December 1977. The test program commenced in February 1978 and was completed in July 1979.

PROGRAM OBJECTIVES

The objectives of the test program were as follows:

1. Determine the operational characteristics of a wet/dry cooling tower in an actual generating station environment.

2. Develop a mathematical model of the wet/dry cooling tower and verify it with actual data.

3. Determine the water conservation aspects of a wet/dry cooling tower operating in an arid climate.

TEST LOCATION AND AVERAGE METEOROLOGICAL DATA

The Wet/Dry Tower was sited at the Southern California Edison Company's San Bernardino Generating Station located in San Bernardino, California. The generating station consists of two 60 MW oil/ gas fired units cooled by two 10-cell evaporative cooling towers. The layout of the station is shown in Figure 1. The Wet/Dry Tower is situated near the north station cooling tower with a portion of the plant circulating water being bypassed from that tower to the Wet/Dry Tower by a small circulating pump. The water is returned to the north tower basin by gravity flow from the Wet/Dry Tower basin.

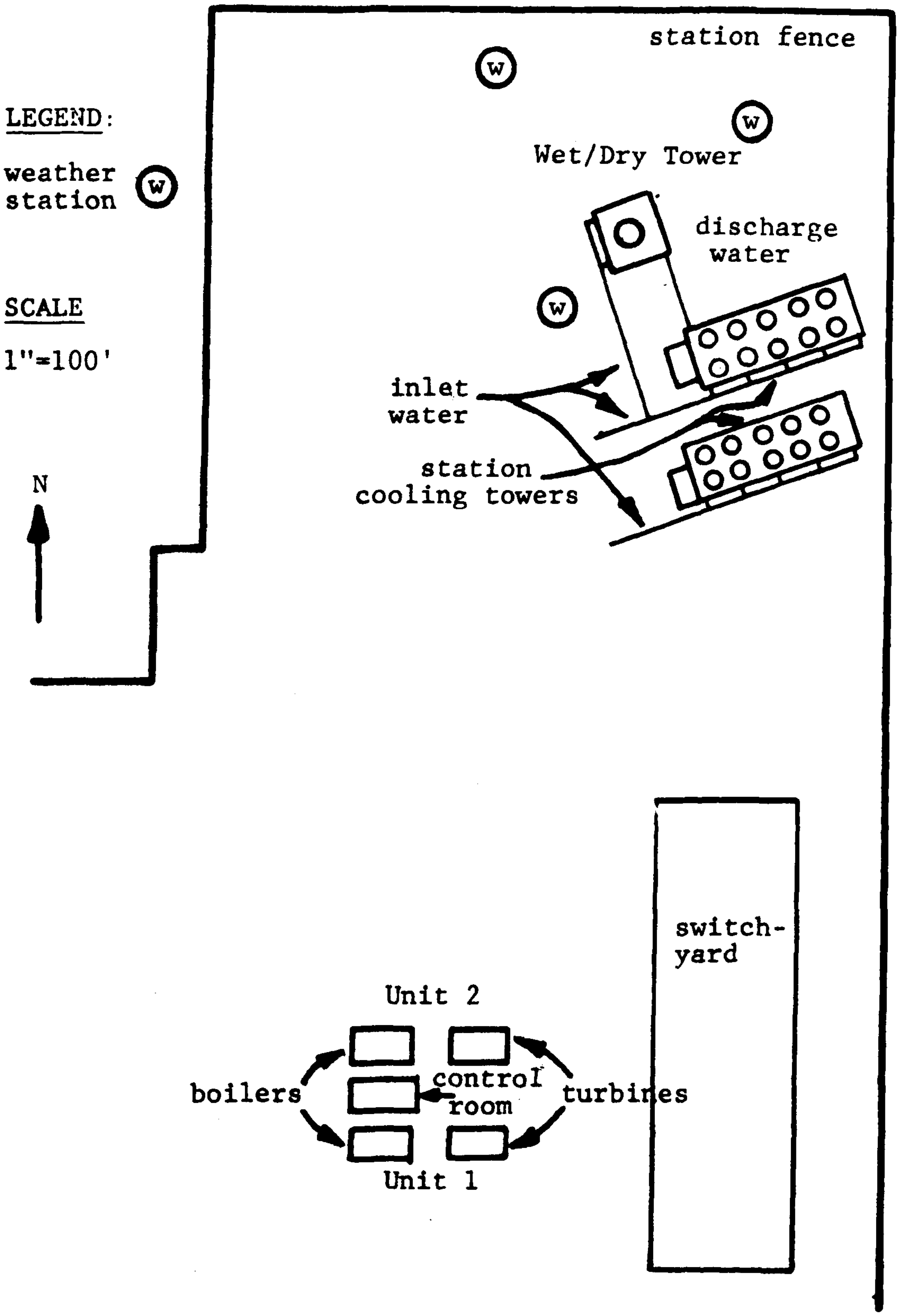


Figure 1. San Bernardino Generating Station Plot Plan

The average meteorological conditions recorded at the site during the test period are as follows:

TABLE 1. AVERAGE SITE METEOROLOGICAL CONDITIONS

		Jan	Feb	Mar	Apr	May	Jun
Mean High Temperature	Dry Bulb(°F)*	63	66	68	73	78	85
	Wet Bulb(°F)	52	53	53	56	59	61
Mean Low Temperature	Dry Bulb(°F)	38	40	43	47	51	55
	Wet Bulb(°F)	35	36	38	40	42	45
		Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Mean High Temperature	Dry Bulb(°F)	95	94	91	81	71	64
	Wet Bulb(°F)	64	64	63	59	55	54
Mean Low Temperature	Dry Bulb(°F)	60	61	58	51	43	39
	Wet Bulb(°F)	49	50	49	45	40	36

DESCRIPTION OF WET/DRY COOLING TOWER

As seen in Figure 2, the Wet/Dry Tower (manufactured by Ecodyne Corporation) is essentially a crossflow evaporative cooling tower below with a crossflow water-to-air surface heat exchanger on top. The water flow path is from the hot water basin atop the tower down through the finned-tube dry section directly onto the splash-fill wet section. The air flow path is parallel through both the wet and dry sections with air flow being controlled independently to each section by dampers. The amount of heat rejected by either the wet or dry sections is controlled by these dampers. It is possible to operate the tower in the all-wet or all-dry modes, or any combination of the two, by opening or closing the dampers.

The dry section tubes are 1 inch O.D., constructed of copper-nickel with aluminum fins rolled on the tubes. The overall diameter of the finned tubes is 2.25 inches; there are 11 fin spirals per inch, and the total length of the tubes is 19 feet, 3 inches. There is a total bare tube surface area of approximately 20,000 square feet. Operationally, water flows into the tubes from the hot water basins through flow control nozzles. The flow control nozzles are of a unique design which causes the water to spiral down the interior wall of the tube,

* English system units rather than metric have been used through this report because the English system remains the standard in the utility industry for which this report is intended. A conversion table is included as Appendix G.

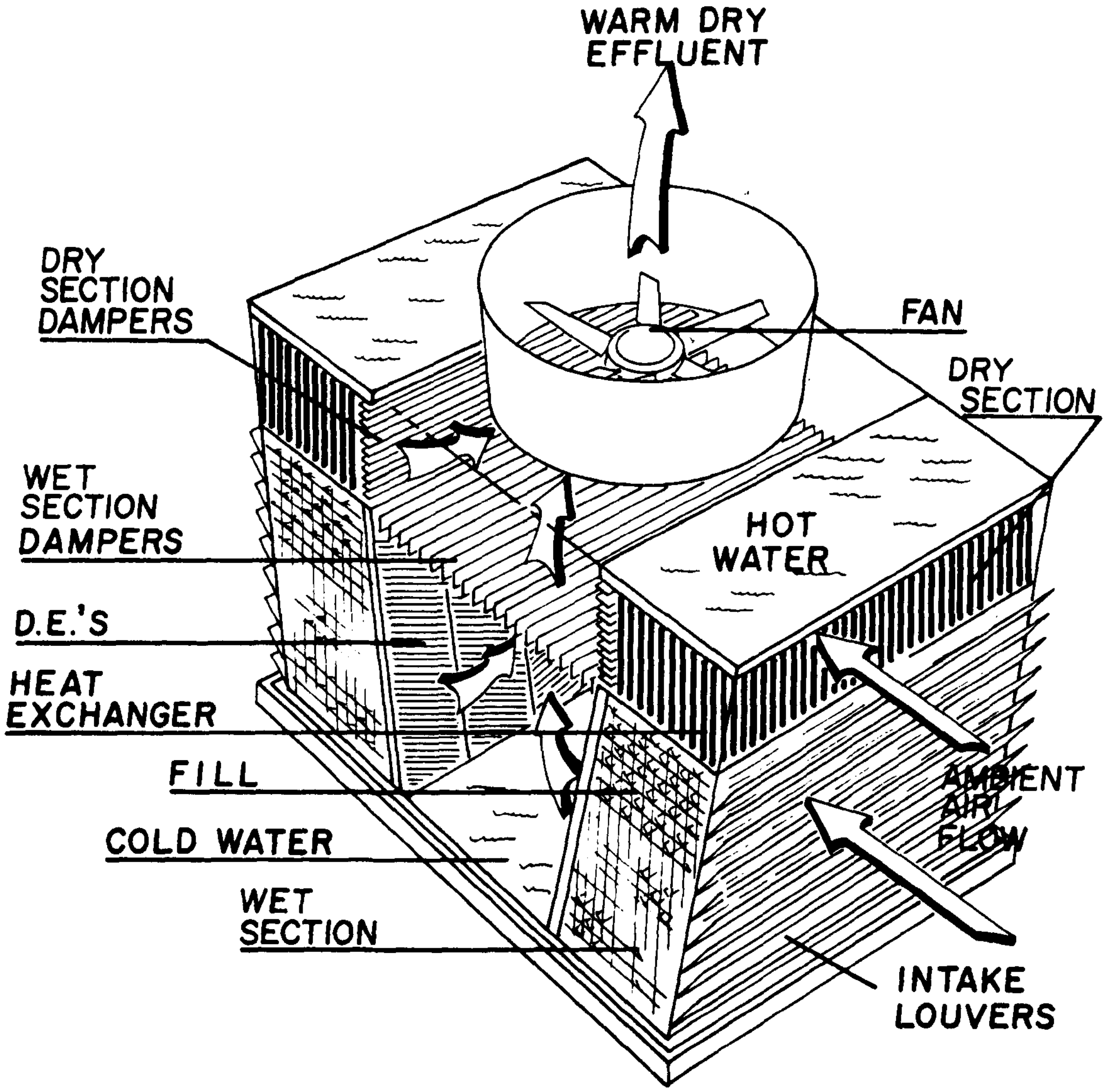


Figure 2

Operational Schematic of Ecodyne
Wet/Dry Cooling Tower

creating a film flow condition which significantly increases the heat transfer coefficient over conventional axial flow. There are 7 basins per side (14 in total) with 273 finned tubes per basin. The flow to each basin is individually controlled by butterfly valves.

The water exits the tubes through nozzles which spray the water directly onto the splash fill in the wet section. Fixed positon air intake louvers are provided to prevent splash leakage out of the wet section. The wet section is 29 feet high.

The dampers are actuated by motor drives which are located on the fan deck at the top of the tower. The drive elements pass through the deck to torque tubes which connect to the dampers. The damper positioning is accomplished by a unique damper control system which automatically controls the distribution of air flow between the wet and dry sections based on the exiting cold water temperature. A complete description of the damper control system is found in Appendix E.

Air flow is provided by a 28 foot diameter fan which has 8 blades. The fan is powered by a 250 horsepower motor and runs at a constant 135 RPM. The blades are manually adjustable for pitch angle.

LIMITATIONS OF TEST FACILITY

As can be seen from Figure 1, the Wet/Dry Tower is situated as a side-stream process to the station's main cooling towers. During normal testing, the Wet/Dry Tower has a water flow of approximately 20% of the total circulating water flow. Combined with the fact that the main towers have a larger cooling range and a lower approach than the Wet/Dry Tower, this results in the Wet/Dry Tower having little effect on the condenser circulating water exit temperature (cooling tower inlet water temperature). During the summer months this causes no difficulty as the cooling tower inlet temperature is sufficiently high enough to allow the tower to develop a full range of cooling, but in the winter a problem does exist. Because of the lower approach and larger range of the main towers, the cooling tower inlet temperature is too low to allow the Wet/Dry Tower to develop a full range in the all-dry cooling mode. During the winter the station condensers typically operated with a backpressure in the range of 1.1 to 1.4 inches HgA (mercury, absolute). A backpressure of 4 to 4.5 inches HgA would have been required in order to allow a normal cooling range in the all-dry cooling mode. Operating at such high backpressures solely for the purposes of this test could not be economically justified.

This limitation did not present serious difficulties in defining the dry section parameters, but did limit the simulation of normal winter operation.

2. CONCLUSIONS AND RECOMMENDATIONS

Possibly the most important result of the test program was the development and verification of the mathematical model. This will be very valuable in future site selection and preliminary engineering. Unfortunately, the model at this time is limited to this particular design of wet/dry cooling tower, which somewhat limits its usefulness. It is anticipated that additional improvements will be made to the model a result of the data taken during the test program, resulting in a more flexible predictive tool.

The major goals of the program were achieved and wet/dry cooling has been shown to be an effective and viable method of achieving water conservation at an inland generating station (approximately 19% during the test program). However, during the test period several areas of investigation, the most notable being the measurement of the individual wet and dry section air flow rates, had to be abandoned as unproductive.

The eighteen month period of field operation revealed two deficiencies which will require further rectification before this design of wet/dry cooling could be recommended without reservation for commercial operation. The major concern lies with the sticking air control dampers; this problem renders automatic control of the tower impossible. As discussed in this report, it is recommended that several improvements be made in order to assure reliable operation:

1. Redesign of the damper drive linkages. Although this is already being done by the manufacturer, it will be necessary to field test in order to prove the design.

2. New motor drives should be selected to provide more starting torque.

3. The drive linkages for the damper blades should be positioned on both ends of the blades rather than on one end only as is presently done.

The other deficiency lies with the fouling of the dry section finned tubes. Ecodyne has presented and proved one method of cleaning which is labor intensive and expensive. Some type of permanently mounted cleaning system which would provide the option for reduced manpower must now be developed. This would allow an evaluation of the site to be made, taking into account such factors as expected cleaning frequency, site remoteness, cost of labor, and capital expense of the permanent system, yielding the most economical method of cleaning.

3. OPERATING HISTORY

On February 6, 1978, testing was initiated and on July 23, 1979, the test program was completed. During the 532 day test period, the Wet/Dry Tower was available for testing 80.3% of the period. Additionally, due to a labor strike which required the reassignment of some SCE technical and managerial personnel, the Wet/Dry Tower was unmanned a major portion of the period from May 1, 1978, through July 30, 1978. During this period no testing was performed although data was collected automatically on an hourly basis.

The unavailability of the Wet/Dry Tower can be broken down into the following categories:

Sticking Dampers	10%
Biological Growth in Hot Water Basins	1%
Instrumentation Failures	5%
Fan Drive Shaft Bearing Failure	8%
Recalibration and Relocation of Instrumentation	76%

The problems encountered with sticking dampers and biological growth in the hot water basins are discussed in detail in Appendix A. The fan drive shaft bearing failure was due to faulty maintenance. The instrumention failures occurred solely with the data acquisition and storage systems. The recalibration is discussed in Appendix D.

Because of these problems, most notably the sticking dampers and instrumentation failures, the test plan was not followed in its entirety as is detailed in Appendix F. However, the primary objectives of the test plan were met.

4. TEST RESULTS

TOWER PERFORMANCE

Figure 3 shows the dry section performance in degrees Fahrenheit of water cooling (dry section range of cooling) as a function of the temperature difference between the inlet hot water temperature and the inlet air dry-bulb temperature at a constant water-air mass flow ratio. Two distinct sets of data are plotted, data taken with the finned tubes heavily fouled and data taken after cleaning of the tubes (see Appendix A). A marked difference between the two is obvious. The data taken with the finned tubes heavily fouled were all taken within a two month period and, therefore, do not reflect any function of fouling with relation to time. By calculation, the air-side heat transfer coefficient was found to be 45% higher for the clean tubes over the fouled tubes. The data taken with the clean tubes were taken during a short period of time and cannot be considered complete. However, the greatly improved agreement between this data and the performance predicted by the mathematical model is very encouraging.

Figures 4, 5, 6, 7 and 8 show the wet section performance in degrees Fahrenheit of water cooling (wet section range of cooling) as a function of the temperature difference between the inlet hot water temperature and the inlet air wet bulb temperature at a constant inlet hot water temperature and constant water-air mass flow ratio. Both the performance predicted by the mathematical model and the measured performance are shown. The predicted performance is very close to the measured, never varying more than +3% or -7%. For the mathematical model, water flow rate and inlet hot water temperature are input values, which means that the calculated cold water temperatures never varied from these measured by more than + 3% or -7%.

Figure 9 shows the evaporation rate of the Wet/Dry Tower as a percentage of the inlet water flow rate per degree Fahrenheit of the wet section range of cooling. The evaporation rate is a function of the difference between the wet section inlet water temperature and inlet wet bulb temperature at a constant wet bulb depression. Both the predicted evaporation rates and the measured evaporation rates are shown. Correlation is acceptable with the predicted ranging from -4% to -19% of the measured rate.

The data used in preparing these curves were obtained from carefully controlled tests in order to minimize error. Data were taken both at constant air flow rates with varying water flow rates and at constant water flow rates with varying air flow rates.

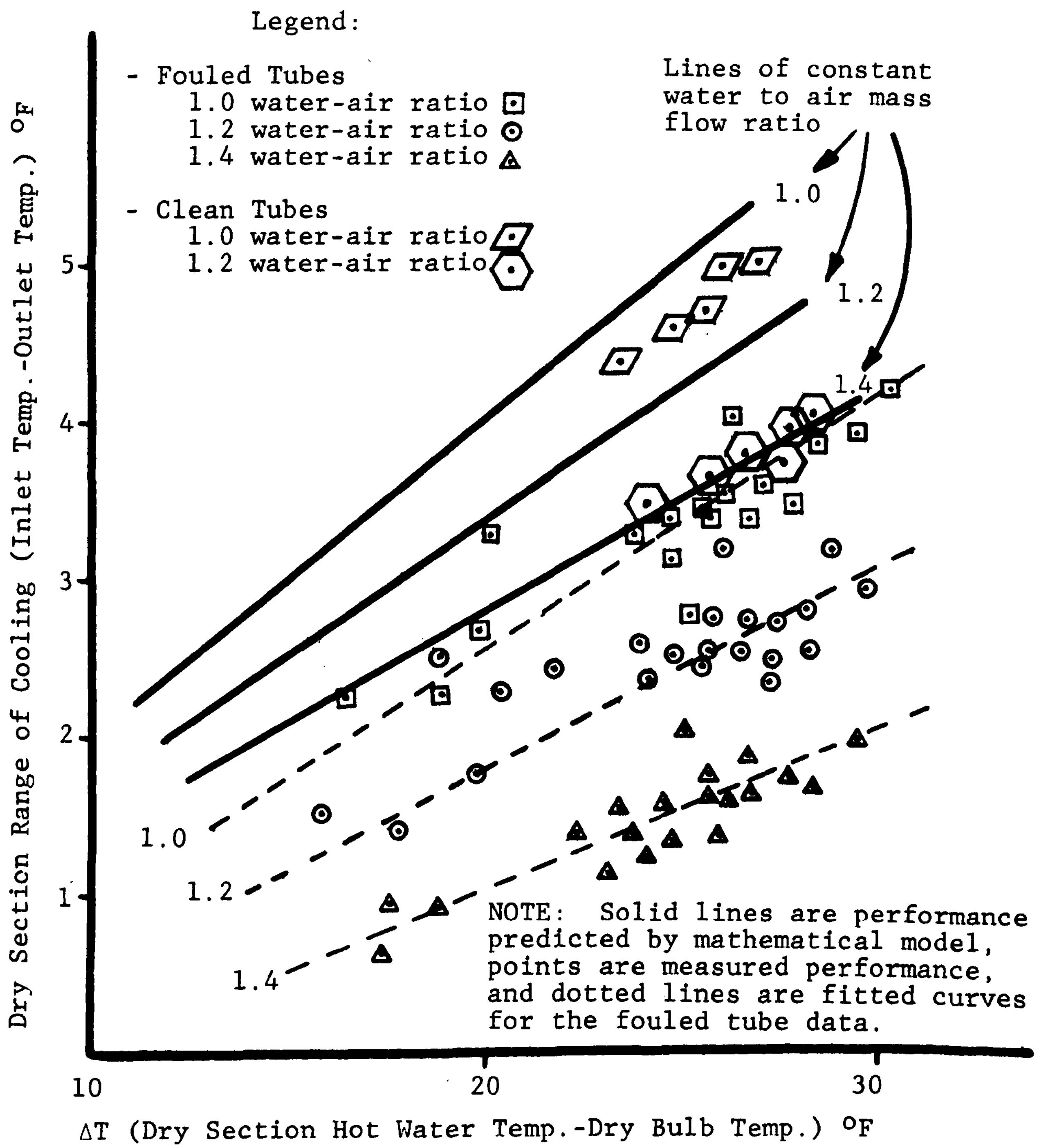


Figure 3. Dry Section Performance

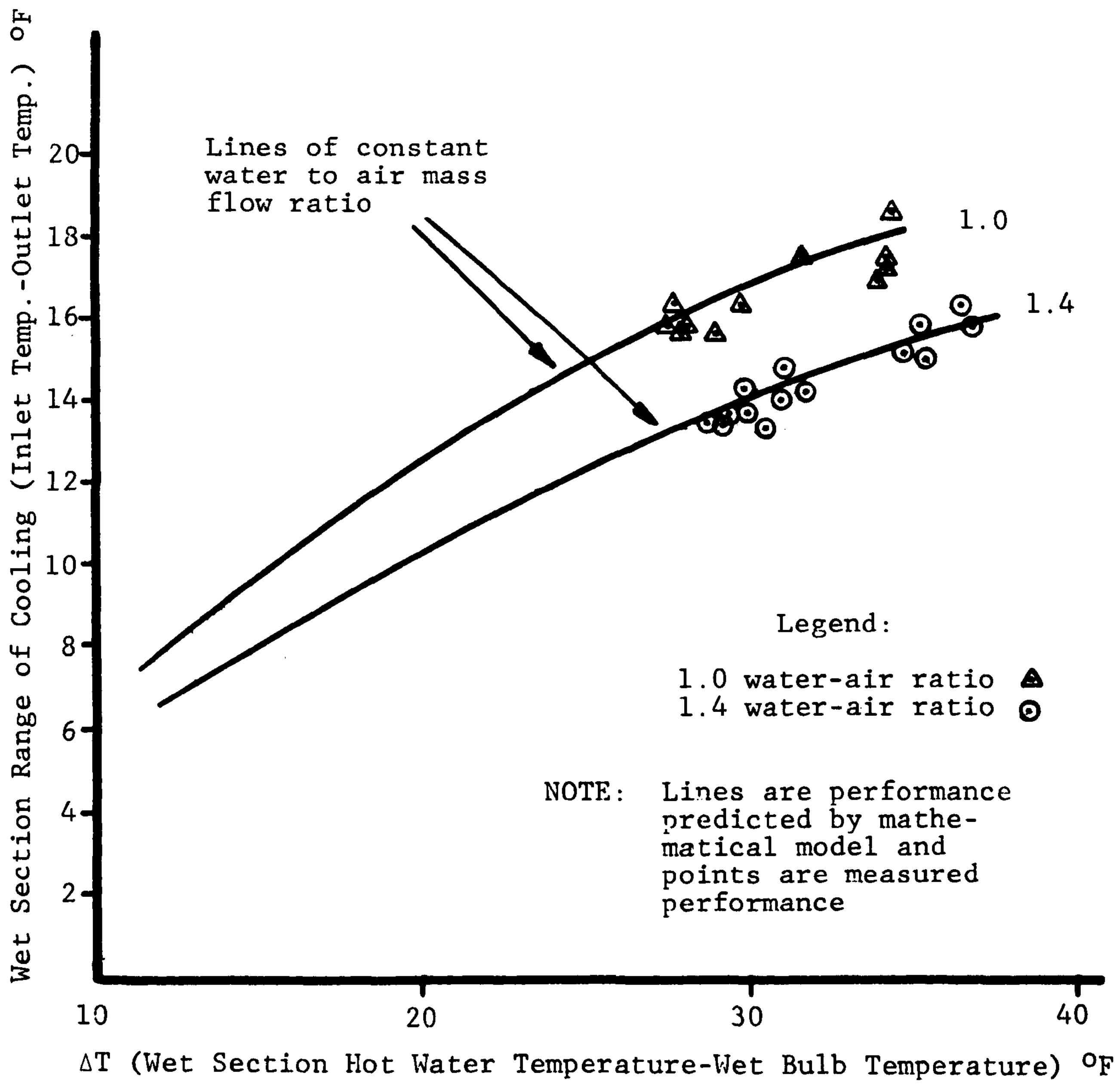


Figure 4. Wet Section Performance, Wet Section Hot (Inlet) Water Temperature = 96°F

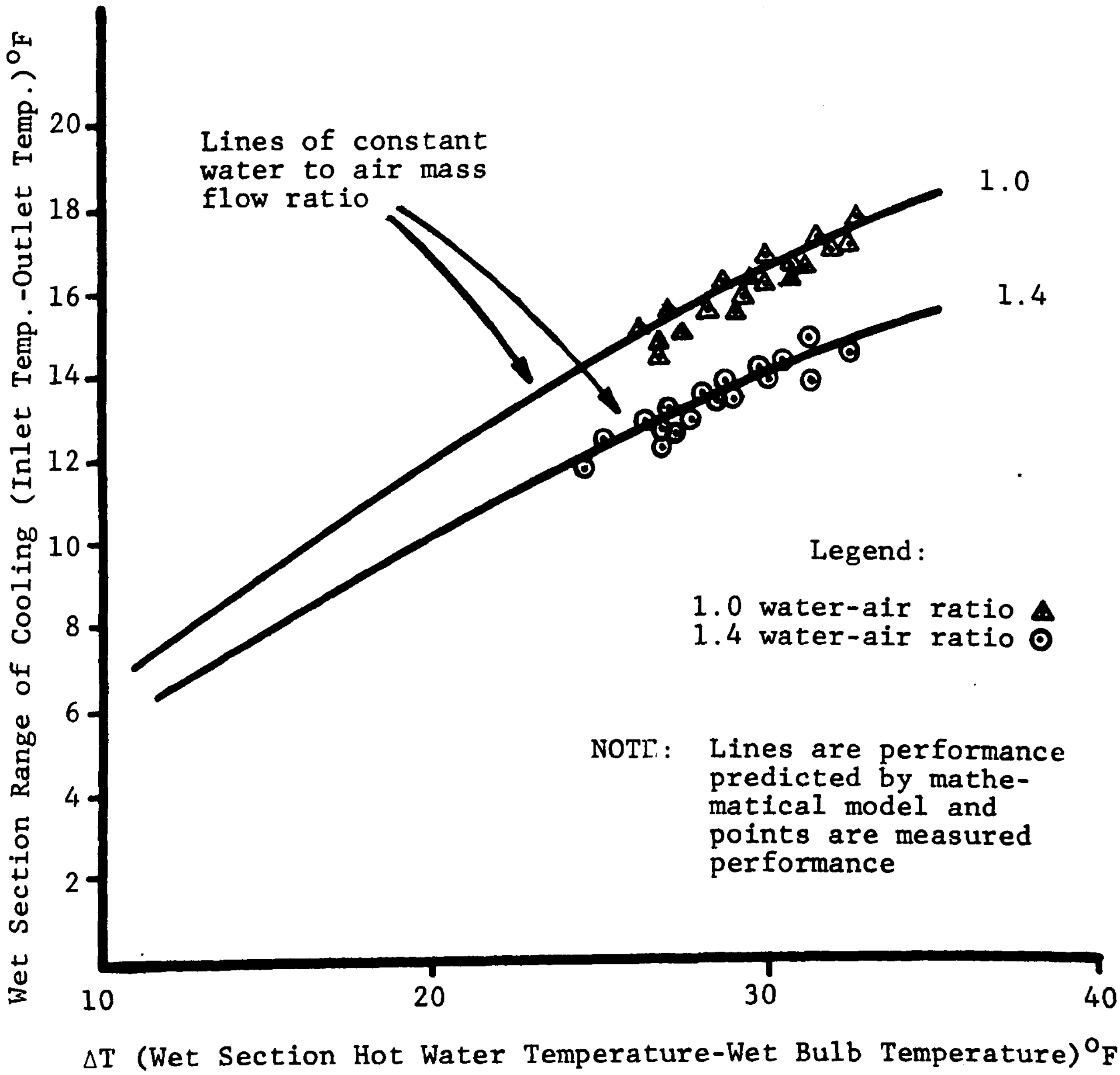


Figure 5. Wet Section Performance. Wet Section Hot Water Temperature = 94°F

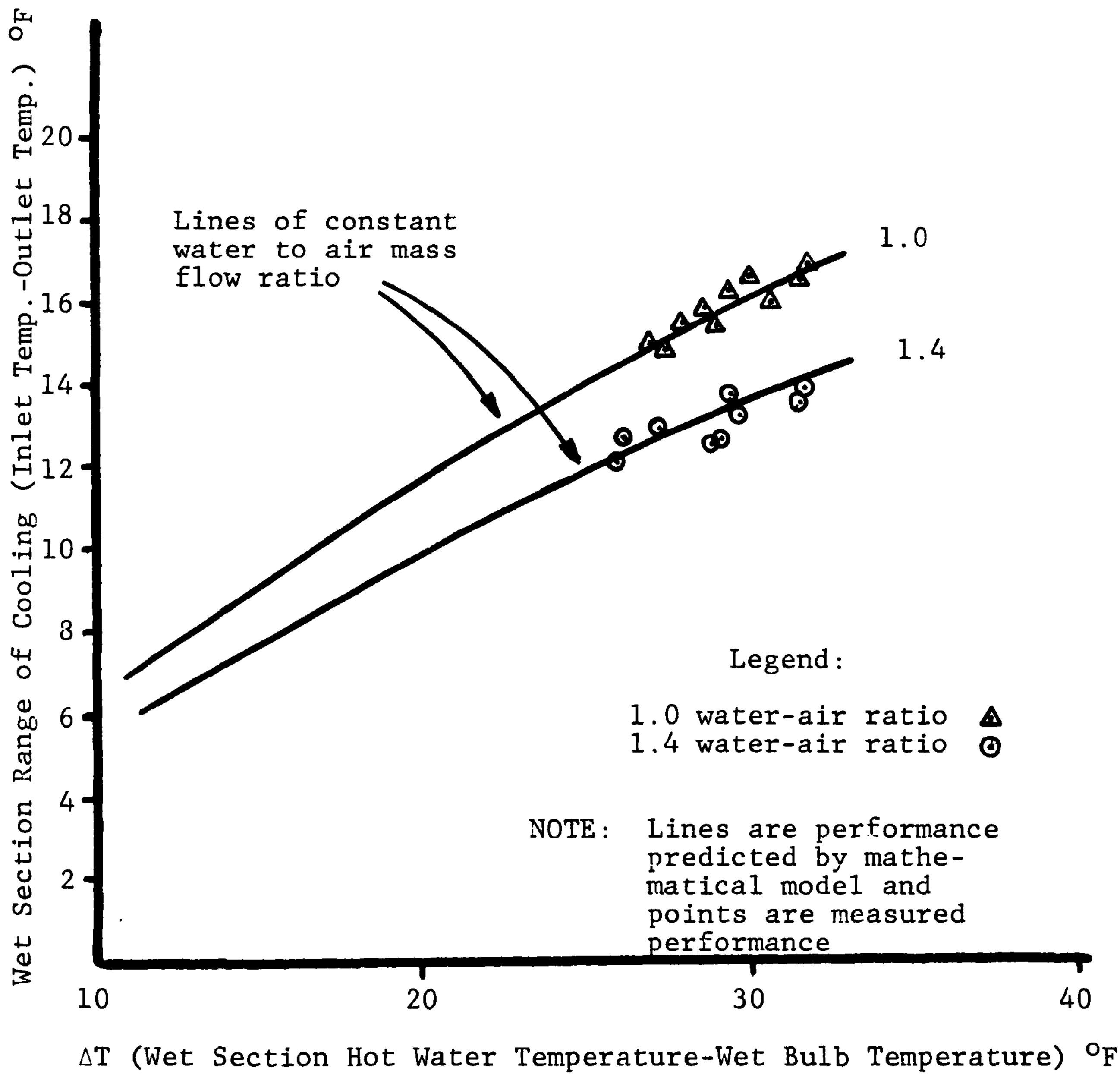


Figure 6. Wet Section Performance, Wet Section Hot Water Temperature = 92°F

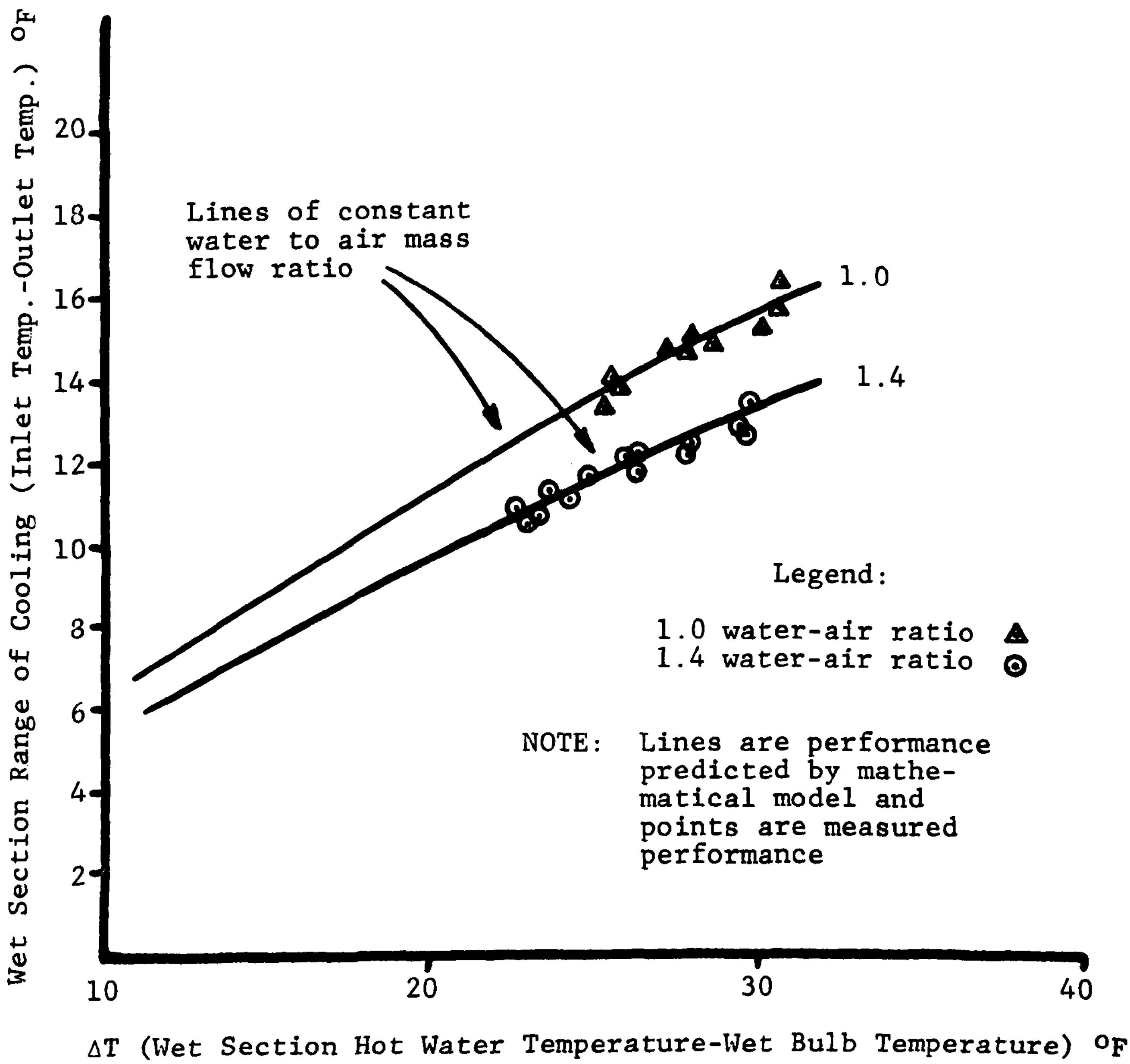


Figure 7. Wet Section Performance, Wet Section Hot Water Temperature = 90°F

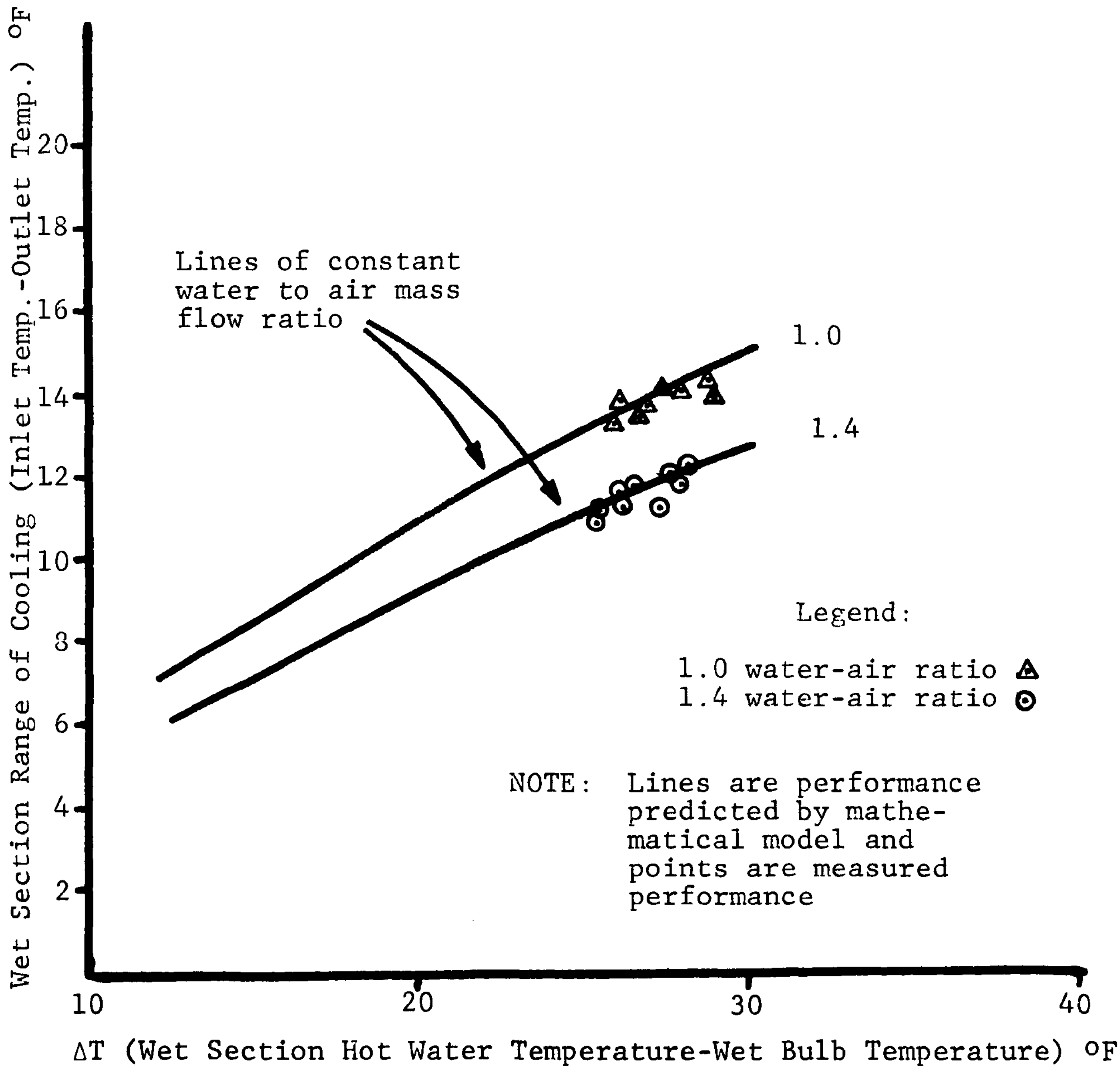


Figure 8. Wet Section Performance, Wet Section Hot Water Temperature = 88°F

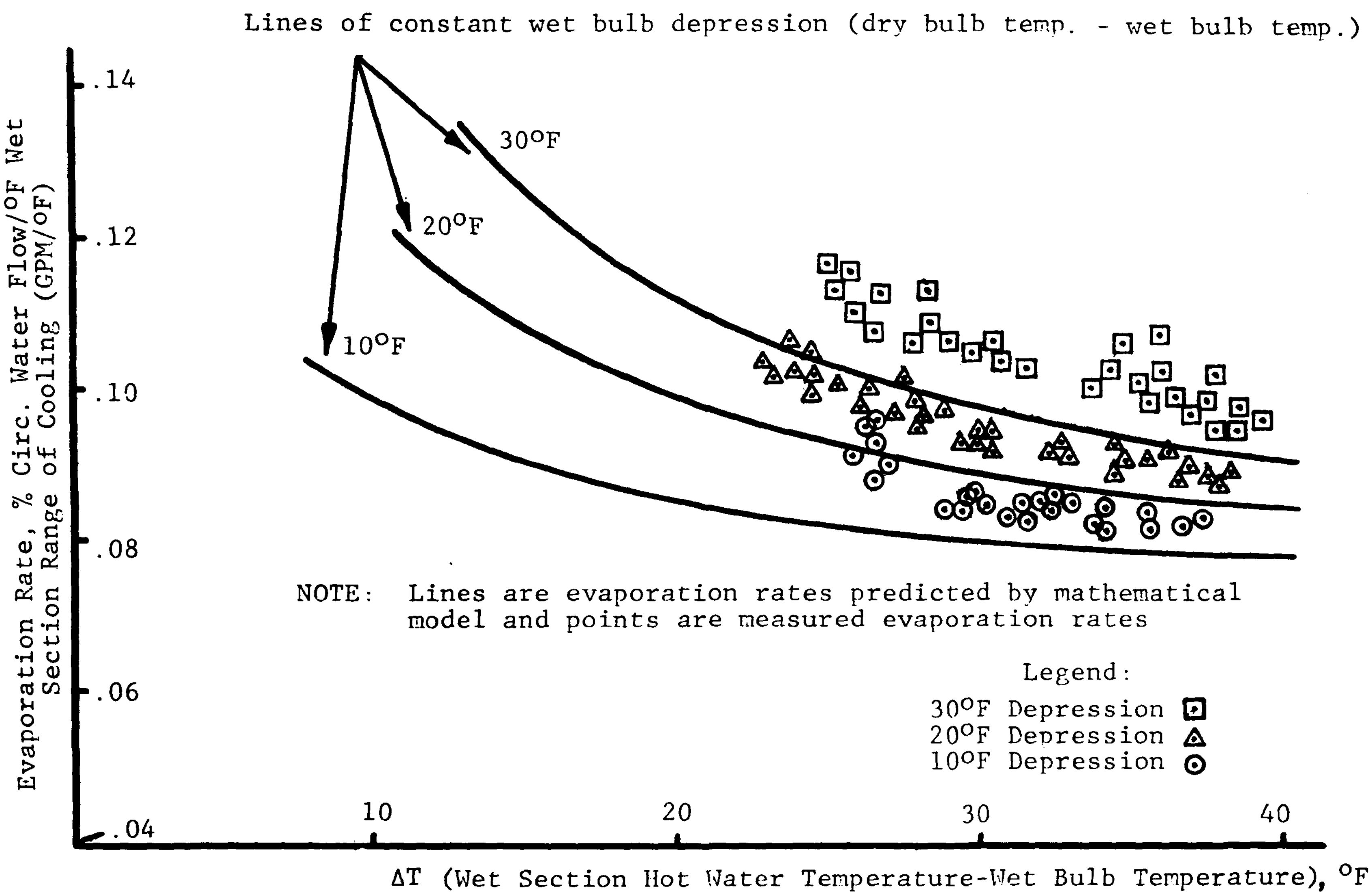


Figure 9. Evaporation Rate

Data collected hourly by the data acquisition system were used to analyze the Wet/Dry Tower operational modes during varying atmospheric conditions. During the one-year period of operation from July 1, 1978, to June 30, 1979, the dry section dampers were open 41% of the time, creating a water savings of 13%. Because of the fact that the Wet/Dry Tower was down for repairs and relocation of instrumentation during a large period extending from October to December 1978, this is not a true measure of the potential water savings. Based on the performance of the Wet/Dry Tower and the atmospheric conditions during that period, it is estimated that the potential water savings during that period would be approximately 19%. An even more significant water savings could have been achieved had it been possible to develop a full range of cooling in the all-dry cooling mode during the winter months (see Limitations of Test Facility for a full discussion).

MEASUREMENT OF DAMPER AIR LEAKAGE

One of the unknowns when this program began was the amount of air leakage which could be anticipated through the dampers. One method which was tried to measure the leakage was holding a totalizing anemometer in various locations near the closed dampers for a specific period of time. The repeatability of data using this method was very poor. After several other trials, it was concluded that the air flow rate due to leakage was too low to be measured by direct means.

The entering and exiting water temperatures of both the wet and dry sections were then examined. In the case of the all dry cooling mode with the wet dampers closed, it was found that a large, easily measured differential existed between the entering and exiting water temperatures in the wet section. This temperature differential indicated a significant air leakage. By calculation, it was determined that the air leakage through the wet dampers must have been approximately 8 to 9% of the total measured air flow through the tower in order to cool the water by that amount. In all, 15 different cases were examined with a low leakage rate of 8.3% and a high of 9.1%.

The consistency of these results allow a comfortable prediction of the leakage in the wet dampers, but unfortunately this is not the case for the dry dampers. The temperature differential that exists in the dry section with the dry dampers closed was quite small, in most cases being less than the accuracy of the instrumentation. However, since the design of the wet and dry dampers is identical, it should be reasonable to assume that the leakage per unit area of damper would be nearly the same. The area of the wet dampers is 2474 ft^2 and of the dry dampers 1622 ft^2. This then would correspond to a dry damper leakage rate of approximately 5 to 6% of the total air flow through the tower.

5. MATHEMATICAL MODEL

As previously stated, one of the three objectives of the test program was the development and verification of a mathematical model of the Wet/Dry Tower. PFR Engineering Systems, Inc., of Marina del Rey, California, was selected to provide the analysis in the form of a computer program.* The analysis was performed separately for the wet and dry sections with the water condition at the exit of the dry section used as input to the wet section. Each section is treated as a crossflow tower which is divided into a grid of small increments in both the water flow direction and air flow direction.

As the wet and dry sections are both served by a common fan system, neither the total air flow through the system nor the distribution of air between the wet and dry sections is known. The program incorporates several convergence calculation loops, enmeshed in each other, which determine the above unknowns. The total air flow and its distribution between the wet and dry sections are initially assumed to allow a first set of calculations to be made.

The calculation procedure determines the amount of heat and mass transferred and the pressure drop in each section for the assumed flows. The pressure drop over each major element in the flow path is determined including the tube bundle, the fill, dampers, louvers and any turns encountered by the air. The heat transfer in the dry section and the heat and mass transfer in the wet section are calculated on the basis of the physical principles of the transfer process combined with empirical data for the properties of the fill.

The first convergence loop checks whether the air side pressure drop from the inlet to the tower to the exit of the fan is identical for both the wet and dry sections. If the pressure drop comparison is not within 1% convergence tolerance, a new split of the flow distribution is assumed, and the calculation is repeated until convergence. An outer convergence loop determines the total air flow rate that corresponds to tower air pressure and the fan characteristics.

Verification of the mathematical model was done with two fan pitch angles, 13° and 17°, at various damper settings, including all-wet, all-dry, and 50%-wet/50%-dry. Because of the difficulties experienced with sticking dampers (see Appendix A), less useful data were obtained at the intermediate damper setting

* PFR Engineering Systems, Inc. A Computer Program for the Performance Simulation of Wet/Dry Cooling Towers. Marina del Ray, CA. 1977. 48pp.

complete discussion of the correlation of predicted and actual performance is found in Test Results. Briefly, however, with the exception of the dry section, correlation of actual data with predicted results fell within acceptable limits. Additional testing showed the extreme fouling of the finned tubes to be the chief contributing factor to the poor correlation of the dry section data, and also pointed out a weakness of the mathematical model, the need to provide a dry section fouling factor. PFR has agreed to make the necessary modifications to the program to provide this factor.

APPENDIX A
OPERATIONAL CHARACTERISTICS

The number of operational problems encountered was small; however, correction of the problems proved to be quite difficult. Three specific problems (sticking dampers, biological fouling, and finned tube fouling) accounted for all abnormal maintenance activities.

STICKING DAMPERS

The most significant problem was that of sticking dampers, which rendered automatic control of the Wet/Dry Tower impossible. Sticking was first noted in the wet section dampers in May 1978, less than 5 months after the Wet/Dry Tower commenced operation and only 3 months after the tower began continuous operation. At that time a design deficiency was noted in the linkages that connect the damper panels to the torque tubes (see Figure A-1). The O.D. of the shoulder bolt and the I.D. of the metal linkage bushing were nearly identical and did not allow room for the fiber bushing which was to fit between them. This resulted in galling which appeared to be causing the sticking. New linkages were supplied by the manufacturer and installed, but within a short period the sticking resumed in the wet section dampers.

After a careful review, it was concluded by the manufacturer that the sticking was due to a misalignment of the damper panels. Additionally, it was found that the torque tube universal joints contained hollow pins which were falling out, causing a situation where the dampers were being partially opened by the torque being transmitted through the U-joint dust cover. Following these repairs, the Wet/Dry Tower operated for a short period without sticking before the tower was shut down for recalibration of the instrumentation.

When the Wet/Dry Tower resumed operation, the south dry section dampers jammed in the mid-range position. Individual damper blades were impacting both structural support members and structural bolts. The solution was providing additional clearances between the dampers and the structural support members, and removal of some bolts (see Figure A-2).

Immediately after the tower was returned to service, the wet section dampers began sticking again. At this point, a panel was loosened from the torque tube and an attempt was made to actuate it manually. It took two men to move the damper through its complete range of motion. Penetrating oil was then applied to the 38 pivot points in the panel with the result that the damper could be moved easily with one hand. With this knowledge, several linkage arms were removed and sent to the manufacturer for analysis. Extensive corrosion between the brass bushing and the stain-

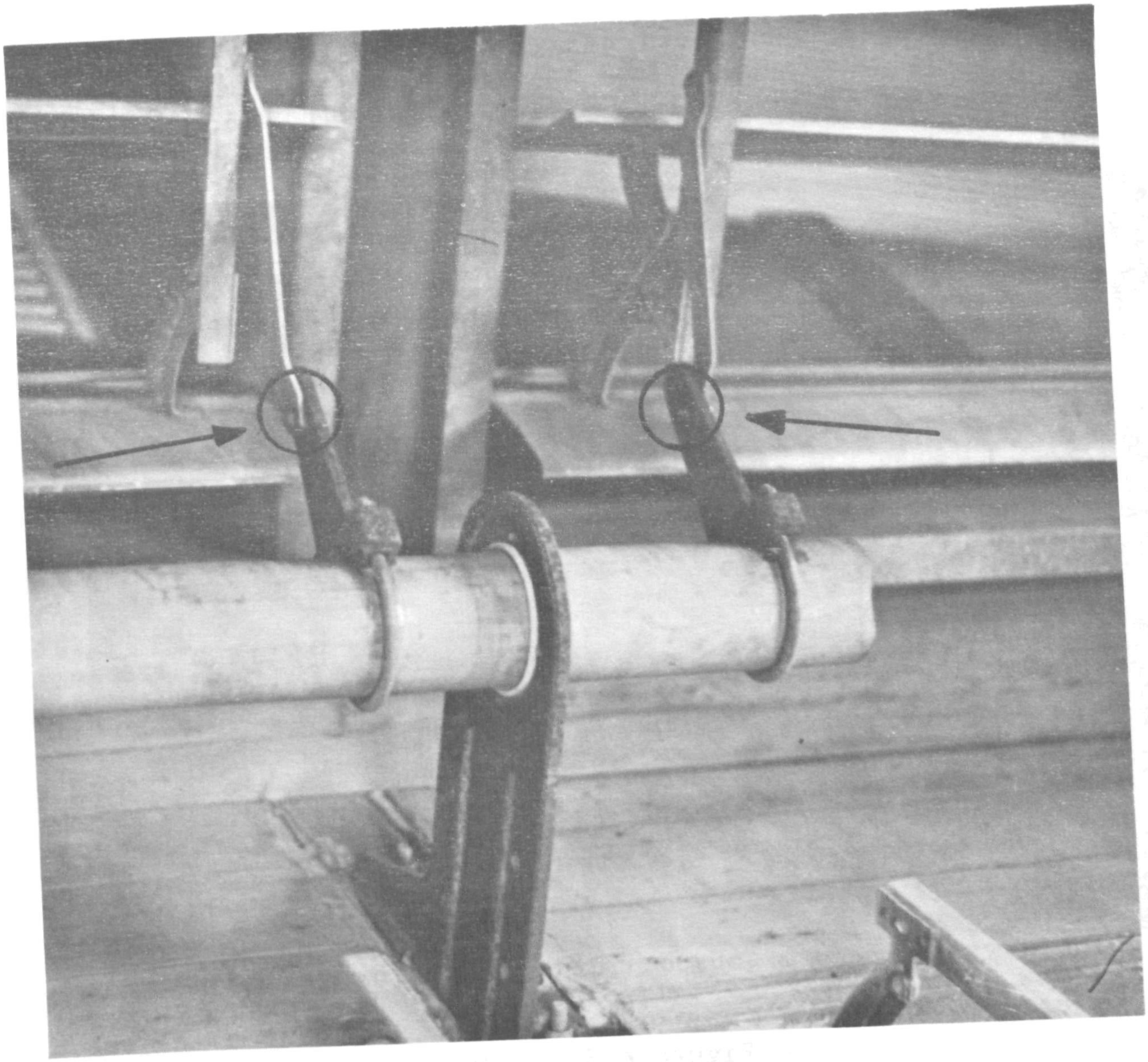


Figure A-1

Damper Linkage with Linkage
Shoulder Bolt and
Bushing Shown Circled

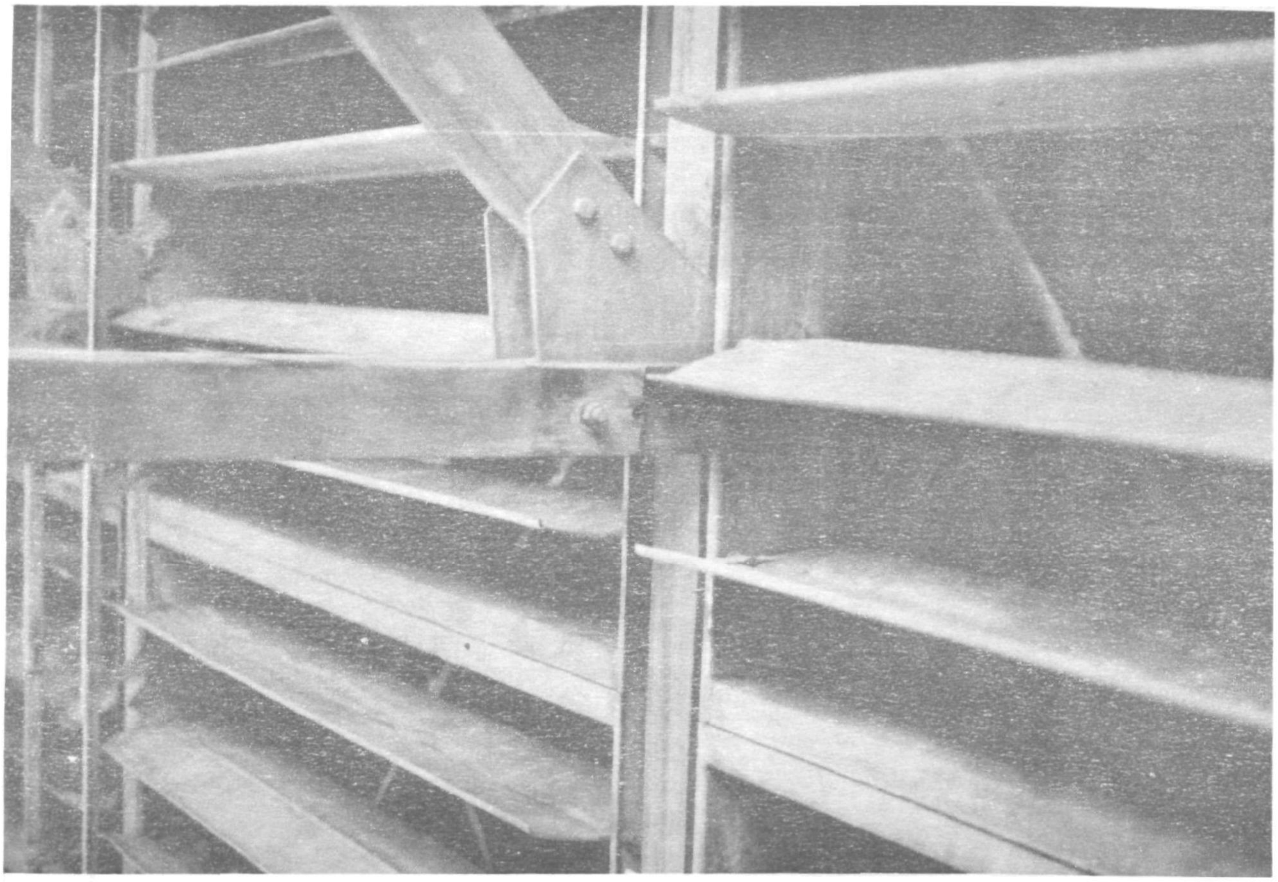


Figure A-2

Structural Support Member
with Bolt Removed
and Clearances
"Chipped" Away

less steel linkage pin was discovered. The solution to this will, at a minimum, require the complete redesign of the linkages.

Currently, redesigned linkages have been installed in the Wet/Dry Tower, and an operational test of approximately 3 months is underway. Results of that test will be issued as an addendum to this test report.

It is important to note, however, that unless the new linkages are completely successful, additional redesign of the dampers will be required in order to make them suitable for a commercial utility application. As can be seen in Figure A-3, a heavy deposit of scale has already built up on the damper blades after only 18 months of operation. Considering the good quality of the circulating water at the Wet/Dry Tower (Table A-1), the reliability of the linkage pivot points with the poorer quality water typical of the Southwest is questionable. The use of some form of either sealed or pressure-lubricated joints may ultimately be required. Additionally, the present method of driving the dampers from only one side only appears inadequate; an arrangement of driving from each side of the dampers would be much more suitable for reliable operation. This would result in the torque being transmitted directly through the area where the sticking occurs, rather than being reduced by the twisting of the flexible blades as the torque is transmitted along the length of the blade. Finally, the size of the motor drives, which is presently 1/4 horsepower, should be significiantly increased to provide more starting torque.

BIOLOGICAL FOULING

In mid-summer of 1978, after approximately six months of operation, a heavy build-up of biological growth was observed in the hot water basins (Figure A-4). The majority of the growth occurred at the end opposite the hot water distribution piping where the lowest water velocities occur. A secondary problem, the buildup of a foamy scum floating on the surface, was also observed in the same area (see Figure A-5). The growth is primarily algae, not tenacious in its adherence, and easily removed with a garden hose stream of water. In fact, it is this quality which created the worst problem; the algae would break off in chunks and block the flow control nozzles.

In investigating this problem, a large quantity of sawdust was discovered to be layered in with the algae. The presence of the sawdust is due to standard operating procedure at the San Bernardino Generating Station; sawdust is added to the circulating water to stop small condenser leaks temporarily. It is probable that the presence of the sawdust acts to accelerate biological growth by supplying nutrients, but the growth would most likely still be present and result in operational problems

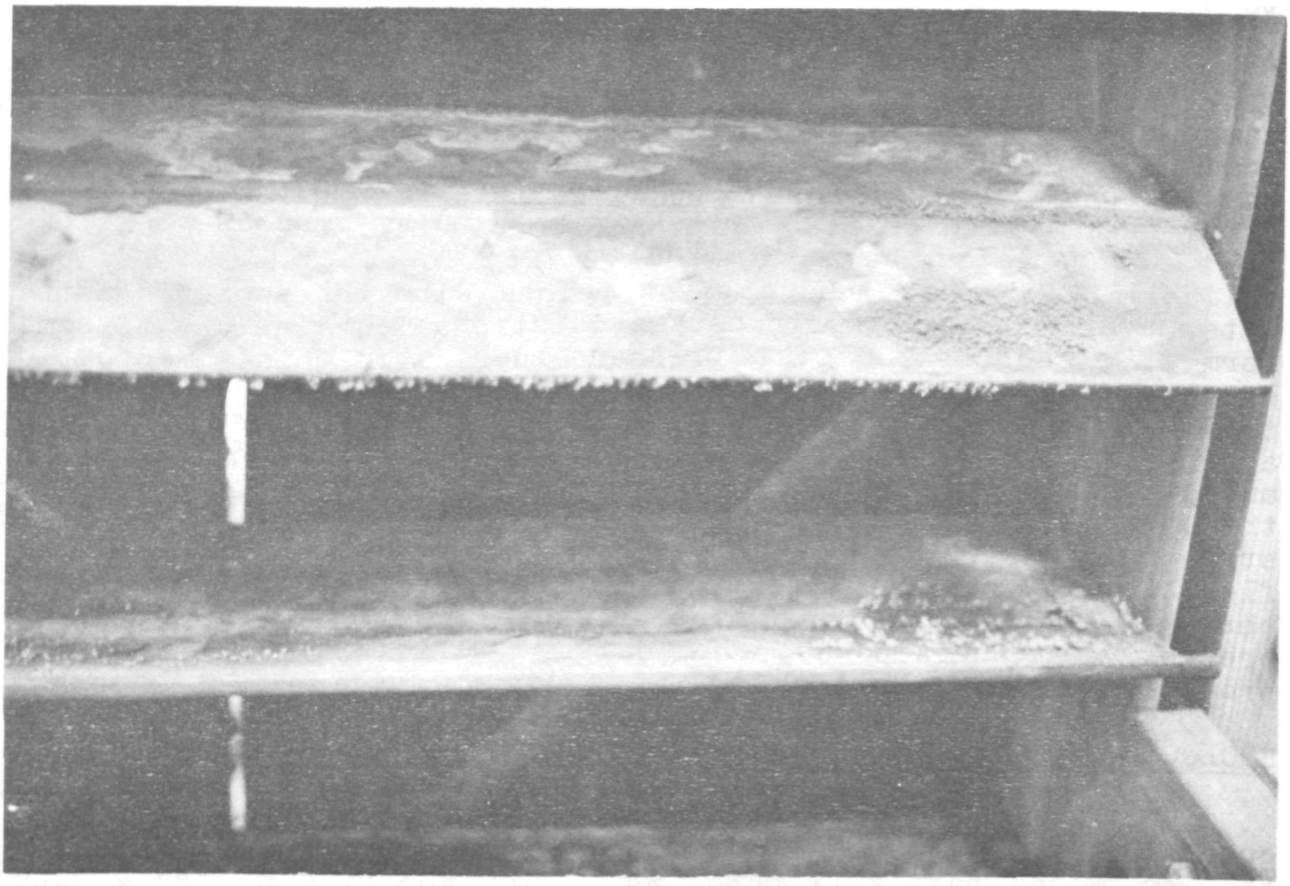


Figure A-3

Damper Blades Showing Heavy Deposition of Scale

TABLE A-1

TYPICAL WET/DRY COOLING TOWER

CIRCULATING WATER QUALITY

Total Hardness as $CaCO_2$	100-150 mg/1
Total Alkalinity as $CaCO_2$	200-300 mg/1
Total Dissolved Solids	300-400 mg/1
Electrical Conductivity	500-700 $\frac{umhos}{cm}$
pH	8.2 - 8.7
Calcium	35 - 55 mg/1
Magnesium	4 - 8 mg/1
Sodium	50 - 120 mg/1
Potassium	4 - 6 mg/1
Sulfate	30 - 70 mg/1
Chloride	10 - 50 mg/1
Nitrate	5 - 15 mg/1

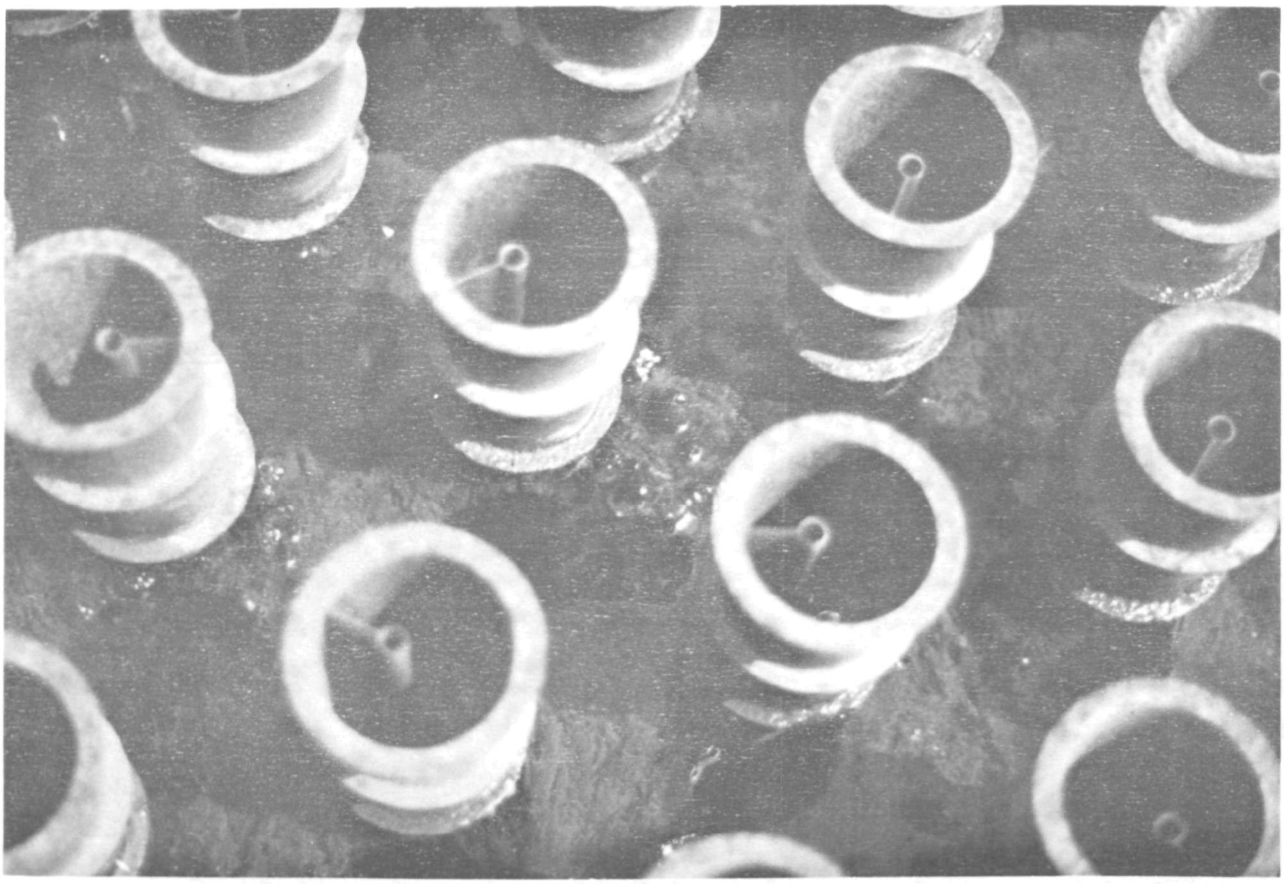


Figure A-4

Build-up of Biological
Growth in Hot Water
Basins

Figure A-5

Floating Scum in
Hot Water Basins

without the sawdust.

A review of the station's water quality control revealed that chlorine is used as the only form of biological control. The injection of chlorine is made near the inlet of the condenser for a period of 30 minutes per eight-hour shift, and the level of residual chlorine is maintained below 0.5 ppm at the condenser outlet. By the time the chlorine travels nearly 1000 feet to the tower, its concentration level is far too low to be effective for biological control.

By trial and error the following steps were discovered to be effective in controlling the problem. Removal of three flow control nozzles in the outboard row, one from each corner and one from the middle (Figure A-6), significantly increases the water flow rate in the otherwise stagnant outboard area. The benefits from this are threefold: (1) slower build-up of growth, (2) lessening of flow control nozzle pluggage, and (3) elimination of the build-up of floating scum. Additionally, the individual basins are shock treated with sodium hypochlorite on a quarterly basis by isolating the basin from hot water flow, adding two gallons of the sodium hypochlorite, and "soaking" for a period of one hour. The basin is drained and then thoroughly rinsed before returning to service. This process is performed one basin at a time with the tower in operation.

FOULING OF FINNED TUBES

Fouling of the finned tubes in the dry section became obvious after a few months of operation and grew steadily worse throughout the test program. In discussions with the manufacturer, it became apparent that although a fouling factor was used in determining the heat transfer area required, no one had anticipated the degree of fouling which occurred (see Figure A-7). In fairness, the San Bernardino site is possibly a little unusual in that besides being situated on a dirt and loose gravel field, the Wet/Dry Tower is also located near the northern and eastern fence of the station. The land on the other side of these fences is agricultural and is disked and plowed several times a year, which puts a considerable amount of dust into the air. Also, a high degree of pollen and insects exist in the area. However, dust, pollen and insects are factors which will exist to some degree at most sites located in the Southwest and as such must be accounted for in future design.

Another point of consideration is that although no documentation could be located as to the condition of the tubes either when they arrived at the site or when they were installed, a small sample section which was cut for demonstration purposes does exist. Examination of that section yielded a light machine oil coating on the fins, most likely left there from the rolling

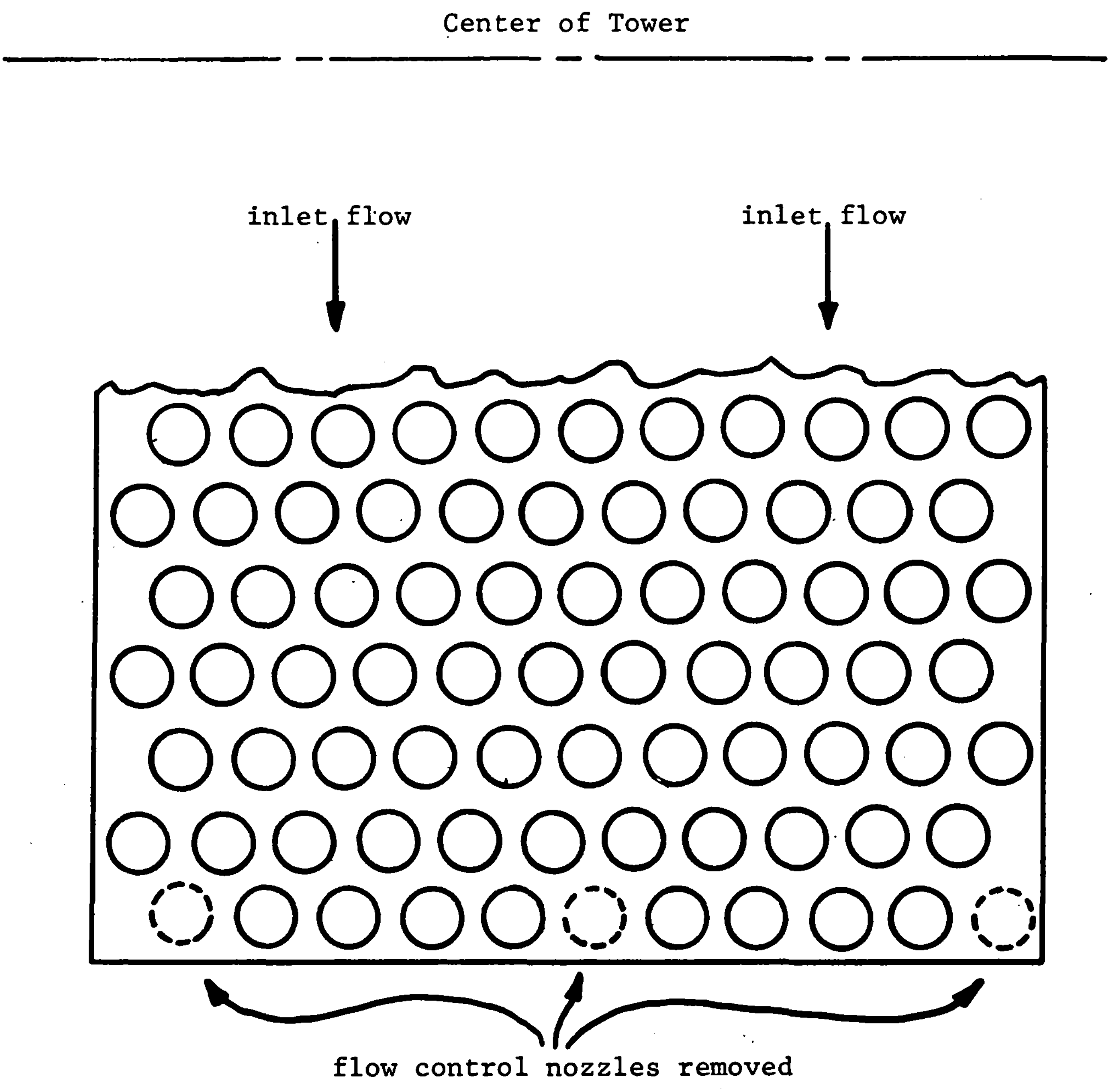


Figure A-6. View from top of a hot water basin showing location of flow control nozzles removed to aid in control of biological growth

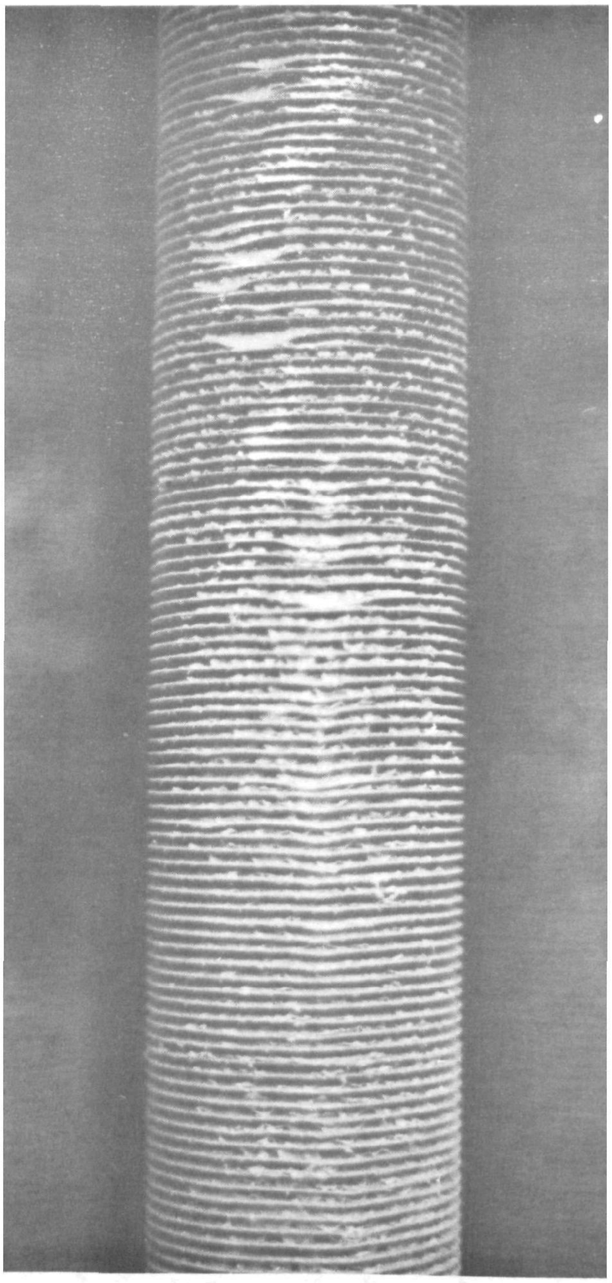


Figure A-7. Example of Finned Tube Fouling. The Tube Shown is in the Outermost Row (Row 1).

process which attached the fin to the tube. The presence of this oil on the fins would very likely result in a faster initial build-up of fouling and possibly a thicker deposit.

Following the completion of the test program and the shutting down of the Wet/Dry Tower, a demonstration cleaning of the south dry section tubes was performed in order to ascertain the cost of periodically cleaning the tubes. The cleaning was performed by SERMAC Industrial Cleaning, Inc., with an eight-foot long "lance" which allowed the operator to reach in approximately five feet into the dry section (see Figure A-8). A 45° angle spray nozzle was used with a flow rate of 8 gpm, a water temperature of approximately 140°F, and a water pressure of 300 psi eight inches from the tip. Initially a degreasing agent was used, but examination revealed that hot water alone was nearly as efficient in cleaning and greatly reduced the time required. Results of the cleaning are shown in Figure A-9. By visual examination, it appears that in excess of 90% of the fouling was removed.

Figure A-10 shows the effects of the cleaning to a depth of 15 rows of tubes. The number attached to each tube is its row number counting from the outside in, and there are a total of 25 rows in each basin. Because this was a demonstration cleaning, it was decided to clean only the exterior half of the south dry section to limit cost. As can be seen in Figure A-10, good cleaning was achieved through Row 9, but slight fouling is observed in Row 12, which is almost the mid-way point of the dry section. By row 15 the effects of cleaning are not observable. It is estimated that the cost to perform the entire cleaning job from both the outside and inside of the two dry sections would be approximately $3600.

Based upon this experience, it would seem that some form of in-place cleaning system should be explored for commercial applications of the tower.

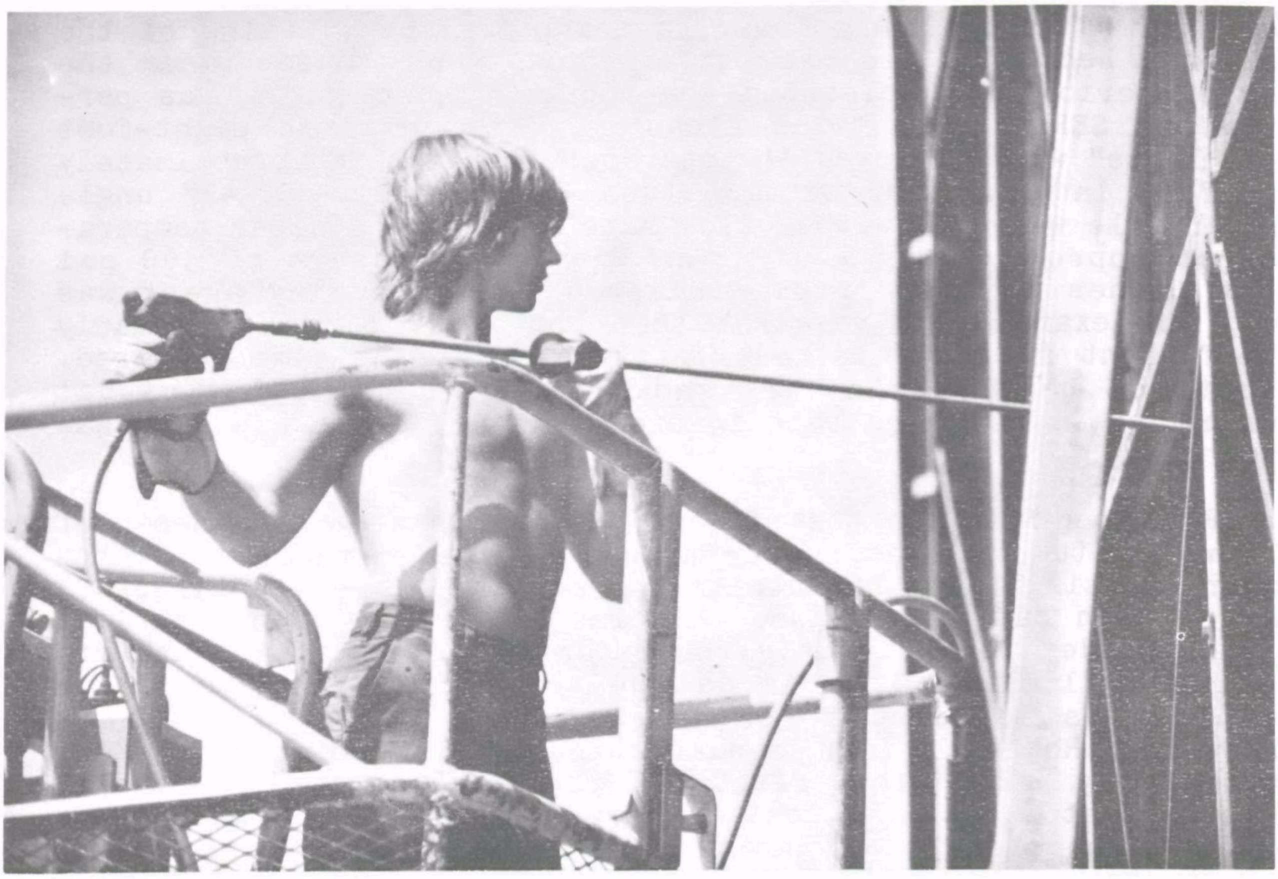


Figure A-8

Workman using eight foot "lance" to clean finned-tubes.

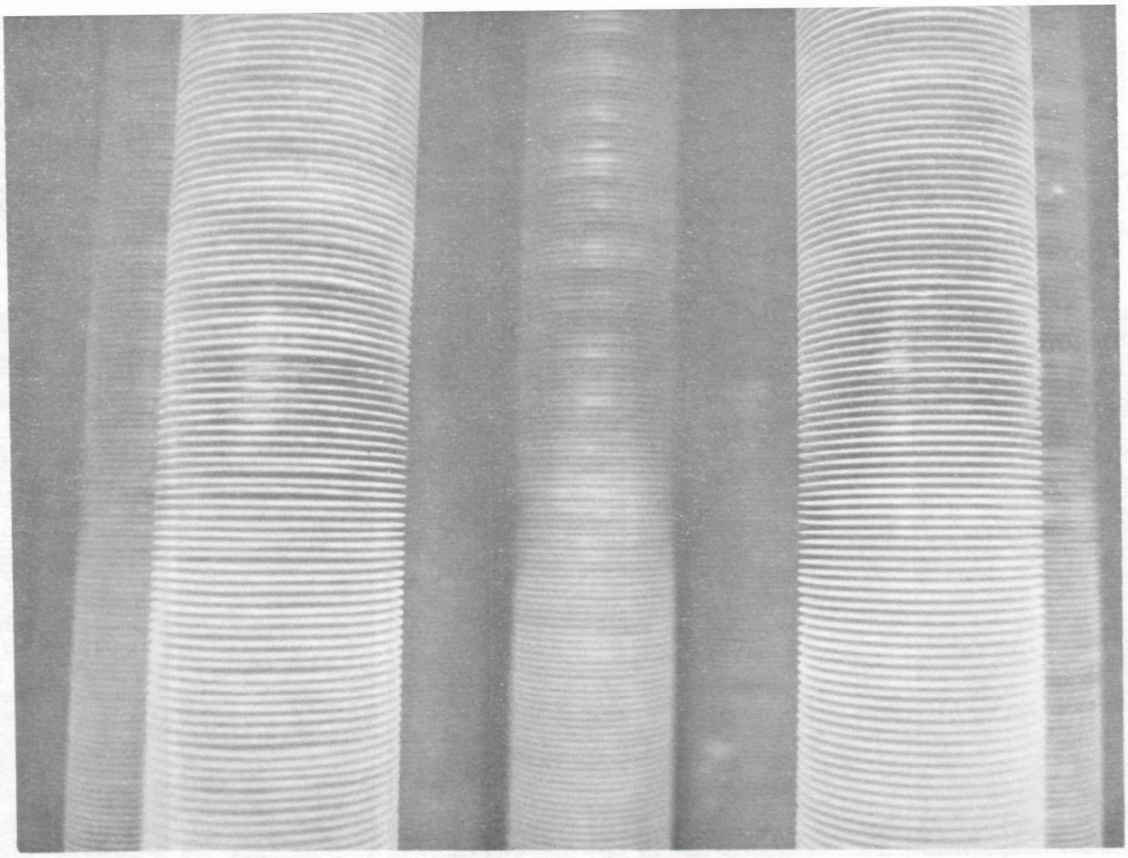


Figure A-9

Results of finned-tube cleaning. View is from outermost row (Row 1) inward.

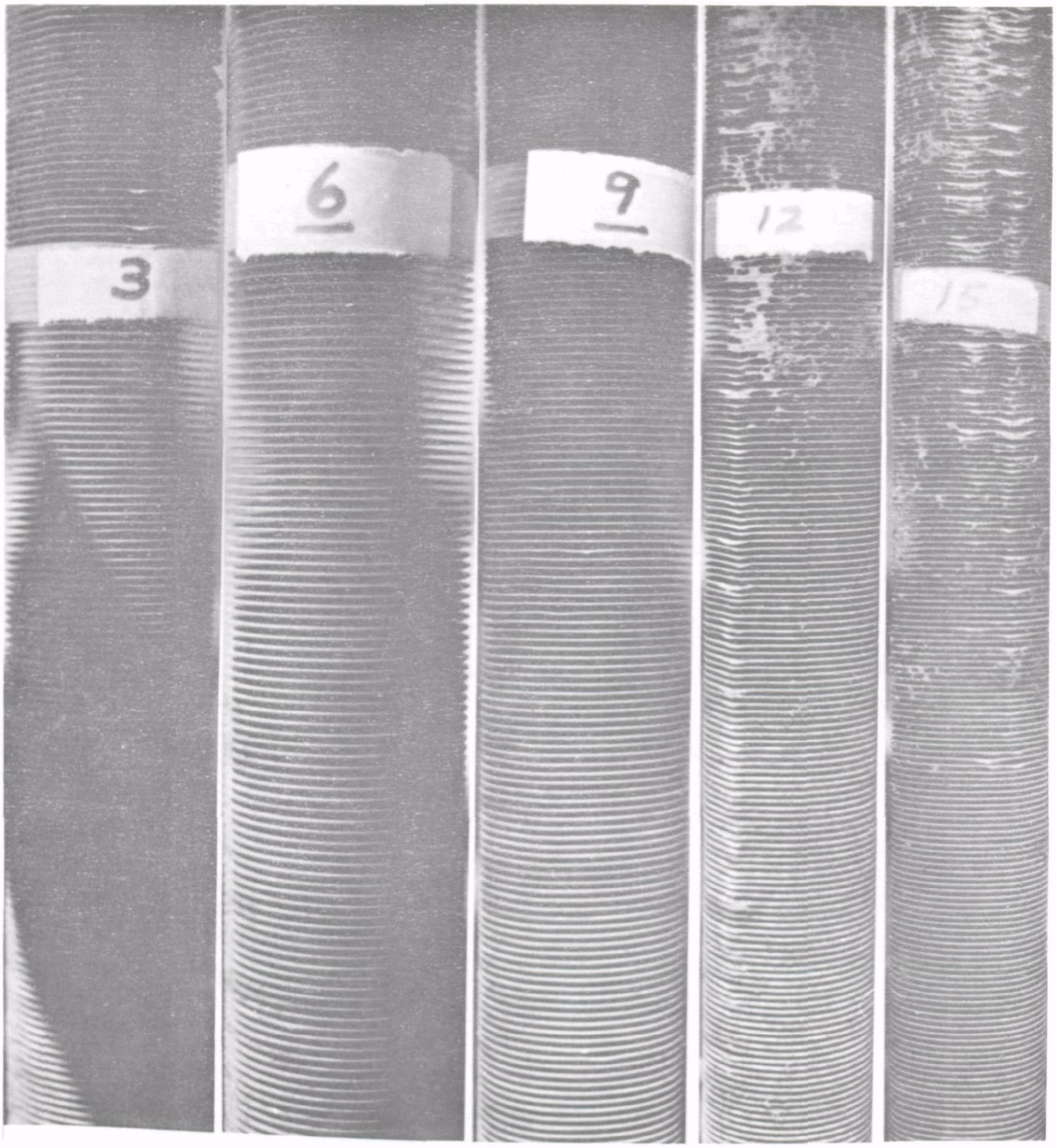


Figure A-10

Effects of finned-tube cleaning progressing toward center of tower. Number on tube is the row number, with row 1 (not shown) being the outmost row away from center of tower.

APPENDIX B
METHOD OF DETERMINATION OF HEAT REJECTION RATE AND EVAPORATION RATE

The method used to calculate the actual heat rejection rate and evaporation rate of the Wet/Dry Tower is relatively simple. Based on the data taken, a total tower heat rejection rate can be calculated for both the water-side (which loses the heat) and the air-side (which gains the heat). As is shown in Appendix 7.3, the water-side calculation is the more accurate and is used to confirm the air-side data for calculation of the evaporation rate.

$$Q_w = M_w C_p (T_2 - T_1)^* \qquad (1)$$

Where

Q_w = water-side heat rejection rate (Btu/hr)

M_w = circulating water mass flow rate (lbs/hr)

C_p = constant pressure specific heat of water (Btu/lb-°F)

T_2 = inlet (hot) water temperature (°F)

T_1 = outlet (cold) water temperature (°F)

The air-side heat rejection rate is calculated as follows:

$$Q_a = M_a (h_2 - h_1)^* \qquad (2)$$

Where

Q_a = air-side heat rejection rate (Btu/hr)

M_a = dry air mass flow rate (lbs/hr)

h_2 = enthalpy of air exiting the cooling tower (Btu/lb of dry air)

h_1 = enthalpy of air entering the cooling tower (Btu/lb of dry air)

For these two calculations, T_2 and T_1 are measured directly and M_a, M_w C_p, h_2, and h_1 are determined from tables.

* Kreith, Frank. Principles of Heat Transfer, International Textbook Company, Scranton, PA, 2nd edition, 1967. 620 pp.

The evaporation rate can be determined using the equation:

$$E = M_a (W_{m_2} - W_{m_1}) \qquad (3)$$

Where

E = evaporation rate (lbs./hr.)

W_{m_2} = weight of moisture per pound of dry air at tower outlet

W_{m_1} = weight of moisture per pound of dry air at tower inlet

In this equation W_{m_1} and W_{m_2} are determined by the respective wet and dry bulb temperatures and are available in psychrometric tables.

In expressing the water savings of a wet/dry cooling tower, the evaporation rate of the wet section is the critical parameter. If all of the heat rejection from the water to the air is assumed to be by release of the latent heat of vaporization (evaporation), then it can be said that the evaporation rate varies directly with the wet section range of cooling (hot water temperature minus cold water temperature) for any particular set of conditons (tower air flow, tower water flow, ambient air conditions, and tower inlet water temperature). This is true because the latent heat of vaporization of water is nearly constant for small changes of temperature such as is experienced in a cooling tower. From equation (1) it can be seen that the wet section heat rejection rate must vary directly with the wet section range of cooling, and since all heat is rejected by evaporation, then the rate of evaporation must vary directly with the wet section range of cooling.

Therefore, since the dry section (when in operation) displaces a portion of the wet section range of cooling, the water savings may be expressed as the ratio of dry section range of cooling to the total tower range of cooling.

$$\text{Water Savings} = \frac{T_2 - T_{dc}}{T_2 - T_1} \times 100 \qquad (4)$$

Where T_{dc} = dry section exit water temperature (°F)

and T_2 and T_1 are defined above

APPENDIX C
UNCERTAINTY ANALYSIS

The uncertainty in the calculated parameters may be determined by replacing the measured values with the measured values plus the instrument errors and solving for the total error. In the cases where multiple measurements are made, the probable error of the instruments is determined by the method of least squares and substituted for the instrument error. Data taken from the Wet/Dry Tower consisted of two types: (1) data taken during controlled testing and (2) data taken hourly by the automatic data acquisition system. Data taken during controlled testing are as accurate as possible, with all sources of error minimized. The data were taken at steady-state conditions, and several runs of data were taken within a short time of each other and averaged in order to minimize transients due to changing barometric conditions, wind, contact resistances, etc. These data were used for the verification of the mathematical model. The hourly data describe the operational modes of the Wet/Dry Tower and were useful in estimating water savings, although the errors associated with these data must be significantly higher. The accuracy of the instrumentation used at the Wet/Dry Tower is as follows:

Hot and Cold Water Temperature, measured by Resistance Temperature Detectors (RTD)	± 0.2°F
Stack Psychrometers	
- Wet Bulb Temperature (RTD)	± 0.8°F
- Dry Bulb Temperature (RTD)	± 0.8°F
All Other Psychrometers	
- Wet Bulb Temperature (RTD)	- 0.2°F, + 0.7°F
- Dry Bulb Temperature (RTD)	± 0.2°F
Water Flow Meter	± 1%
Air Flow Rate (Fan Curve from measured Fan KW)	± 5% estimated
Data Acquisition System	+ 0.1%

The uncertainty expected for the calculated parameters are as follows:

Waterside Heat Rejection Rate	± 4 to 6%
Airside Heat Rejection Rate	± 6 to 10%
Evaporation Rate	± 6 to 10%
Wet Section Range of Cooling	± 3 to 5%
Dry Section Range of Cooling	± 10 to 20%

Where the probable error of each measured value was determined by Peter's Formula.

$$r_o = \frac{0.8453}{n \quad n-1} |v_1| + |v_2| + \ldots\ldots + |v_n|)^*$$

Where

r_o = probable error of the mean

n = number of measurements

v = residual of the observed value in relation to the mean (i.e., $v_n = x_o - x_n$)

* Franklin, Phillip. Mathematics. In: Standard Handbook for Mechanical Engineers, T. Baumeister and L. F. Marks, eds. McGraw-Hill Book Company, New York, NY, 6th edition, 1967. pp. 2-32 to 2-34.

APPENDIX D
TEST INSTRUMENTATION

AIR FLOW MEASUREMENTS

During the early stages of the testing program, extensive instrumentation was in place on the exterior of the tower for the determination of individual air flows through the wet and dry sections. The instrumentation consisted of eight anemometers per section (See Figure D-1). The anemometers were propeller-type, designed to null in a crosswind.

Attempts to calibrate the anemometers were unsuccessful, due to the prevailing west winds which caused erratic readings. Several types of shielding were tried with some improvement, but the readings remained too erratic to be of value. Trials were made at other locations, including inside the tower, but these were also unsuccessful. Inside the tower, the problem was the dampers. Each change in damper angle altered the air currents and affected the anemometer readings.

Total tower air flow was obtained indirectly from the fan motor horsepower using a calibrated air flow - fan horsepower curve for each fan blade pitch angle. The curves were plotted from equal area traverses which were performed with the dampers in the all-wet mode, the all-dry mode, and the 50% wet/50% dry mode. It is estimated that the curve data are accurate to ± 5%.

STACK PSYCROMETRIC MEASUREMENT

Initial efforts to calibrate the instrumentation monitoring the stack exit air temperatures (wet-bulb and dry-bulb) were unsuccessful, as demonstrated by an inability to balance the air-side and water-side heat rejection rates. It is essential that the heat rejection rates balance within the error of the instrumentation as a check of the validity of the measured exit air conditions. From these conditions the evaporation rate of the wet section is calculated.

The difficulty lies in correctly determining the location of the instrumentation under a 28-foot diameter fan with various structural crossbeams creating eddys and localized high velocity areas. It was finally determined that it would be necessary to "map" the stack on a one foot grid for both wet-bulb temperature and air velocity.

In mapping the stack, it was first determined by measurement that the north and south halves of the stack were symmetrical. This allowed the mapping of only one-half of the stack to gain the required results. The instrumentation, a wet-bulb psychrometer and an anemometer, were located on a moveable trolley 1.5

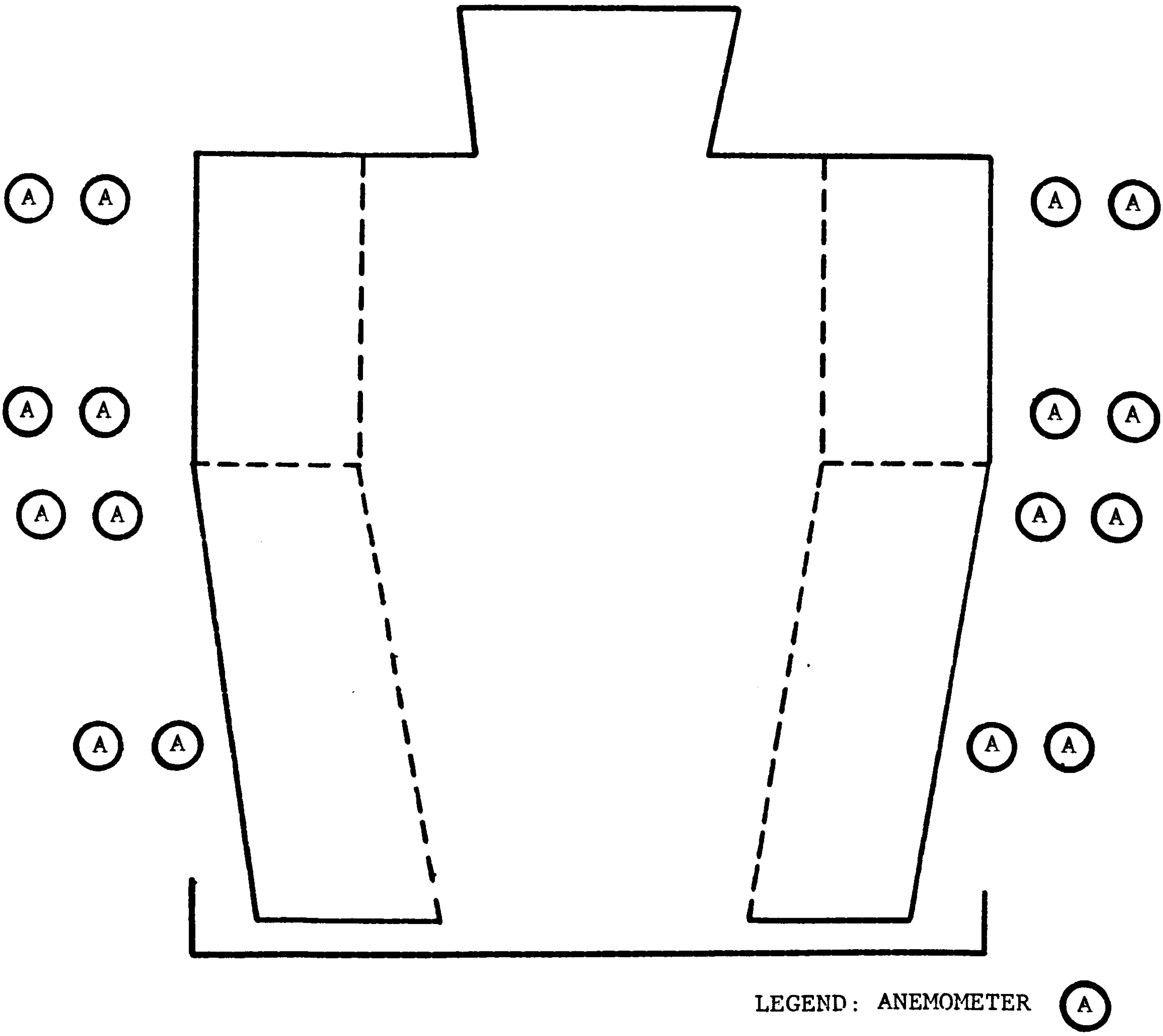


Figure D-1. Wet/Dry Cooling Tower
Anemometer Locations

feet below the fan. The results of the mappings are shown in Figures D-2 and Figures D-3.

As a result of the mapping exercise, it was learned that placing fixed location instrumentation in the stack for measuring exit air conditions does not provide optimum results. Due to the shifting of the air currents that occur with changes in the damper settings, the placement of the instrumentation (Figure D-4) was a compromise. The locations were selected to take advantage of the symmetry of the stack while still allowing for effects such as fouling, wind, etc. which might affect one side of the tower more severely than another.

Because of schedule and budget restraints, a more ideal system for this test facility could not be installed. Such a system would consist of a minimum of four packages, each containing a psychrometric station and an anemometer, running on tracks in the fan stack. Positioning of each package would be controlled by a mini-processor. Such a system would be capable of performing an equal area traverse of the stack (based on 10 areas) every half-hour. However, observations indicated a repeatable error of approximately $\pm$ 0.8°F for the fixed location instrumentation in both the wet bulb and dry bulb temperatures of the exiting air, which was considered acceptable.

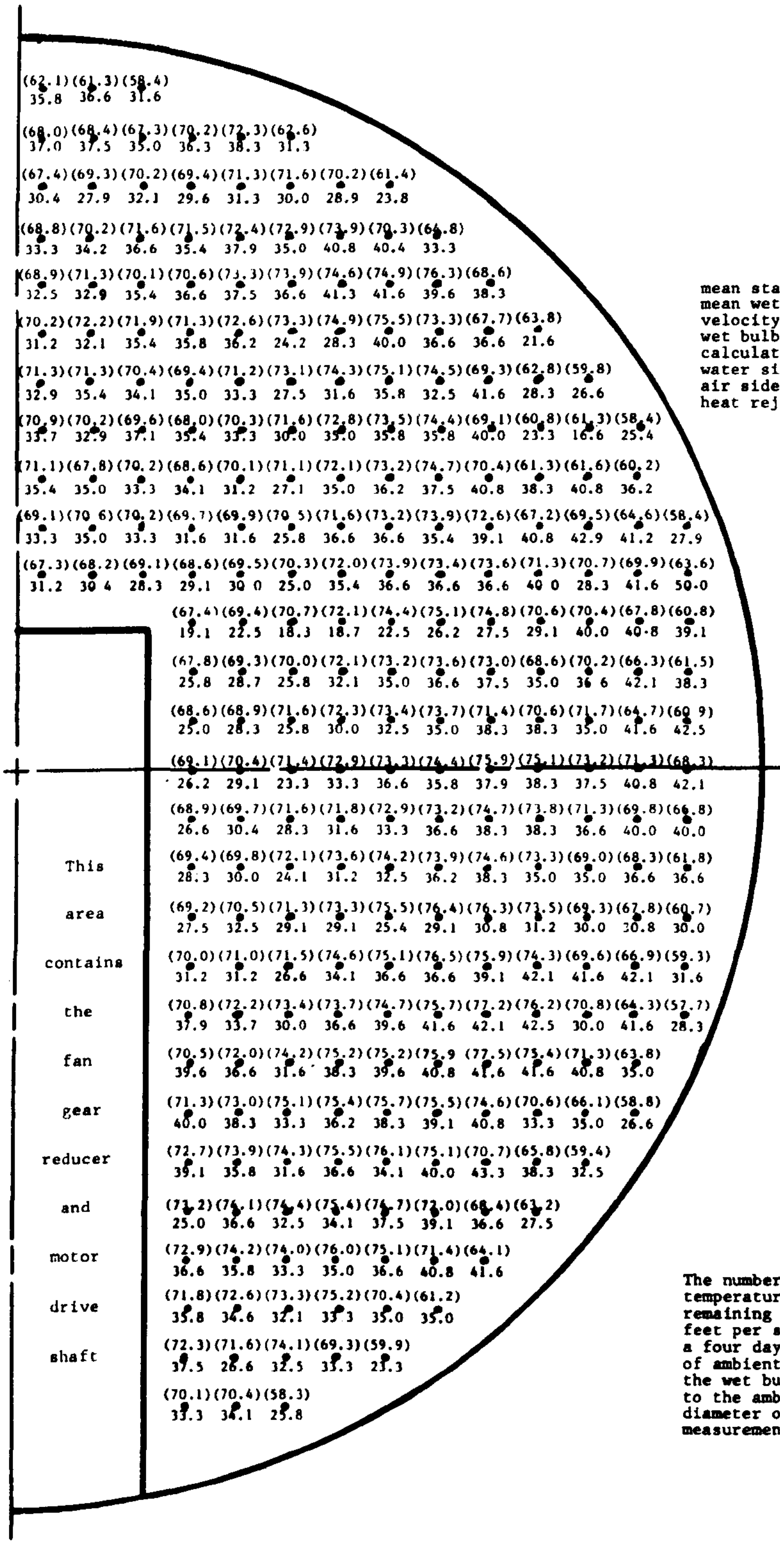
RECALIBRATION AND RELOCATION OF TEST INSTRUMENTATION

All resistance temperature detectors (RTD) were calibrated to $\pm$ 0.2°F against an NBS calibrated thermometer. The data acquisition system was calibrated to $\pm$ 0.1°F. Both air flow and water flow were recalibrated by equal area traverses with calibrated Pitot tubes.

During this same time period, it was determined that some relocation of instrumentation would be undertaken to increase data accuracy. Specifically, two more ambient weather psychrometric stations were established in addition to the one existing, ten RTDs were placed beneath the dry section water discharge to monitor dry section cold water temperature, and two additional psychrometric stations were placed in the stack (see STACK PSYCHROMETRIC MEASUREMENTS in this Appendix) for the measurement of stack exit air temperatures. Eight of the sixteen psychrometric stations on the exterior faces of the tower were removed to supply the needed instrumentation, with four stations being relocated and four stations being pirated to supply eight of the ten required RTDs. The remaining two RTDs were purchased.

LOCATION OF TEST INSTRUMENTATION

As mentioned earlier, some improvements in type and location of instrumentation were accomplished in order to increase sensi-



<u>Ambient Conditions</u>

wet bulb temperature = 46.5°F

<u>Tower Conditions</u>

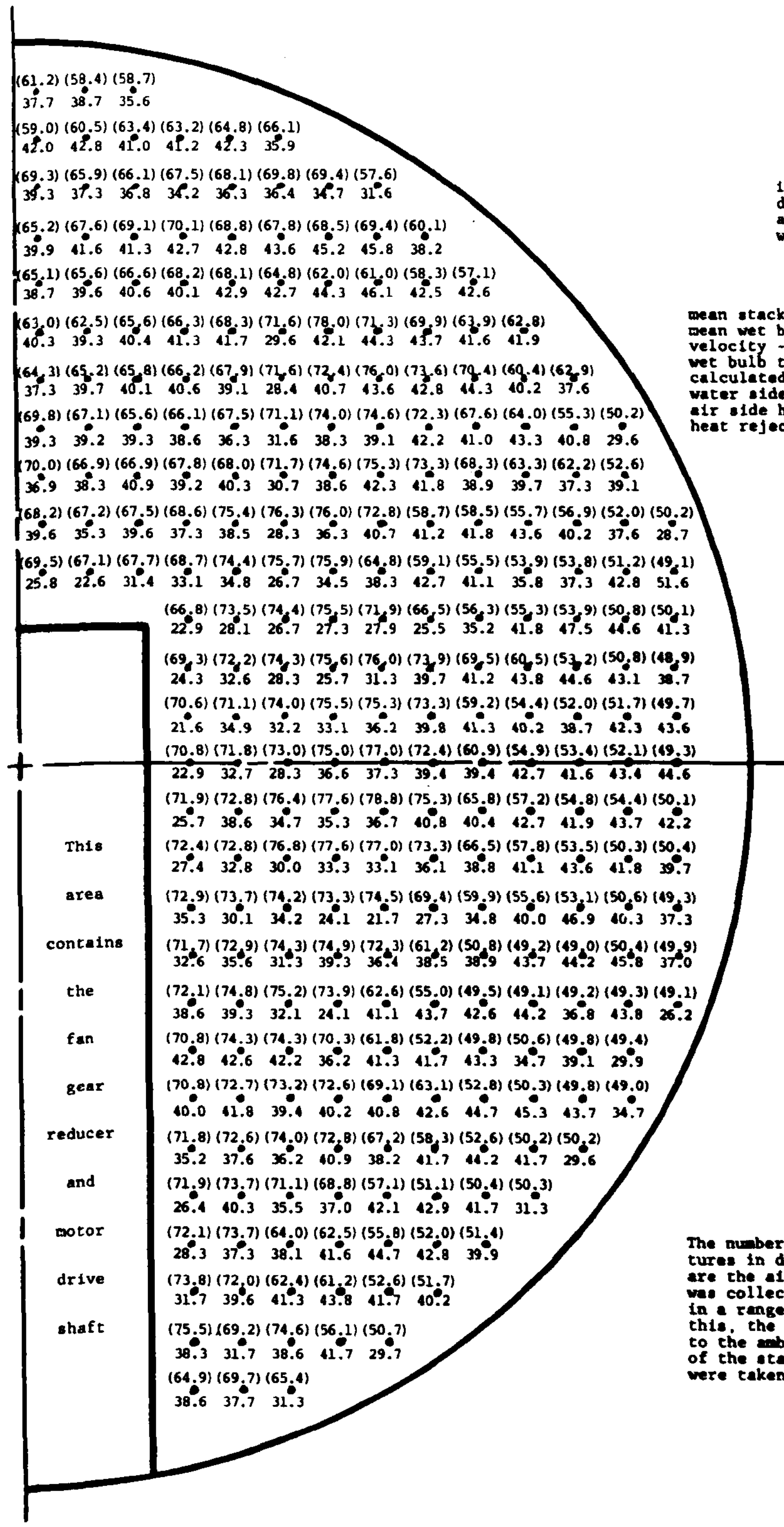
inlet water temperature = 79.0°F
discharge temperature = 66.3°F
air flow rate = 1,240,000 CFM
water flow rate = 13800 GPM

<u>Calculated Results</u>

mean stack velocity	= 34 ft/sec.
mean wet bulb temperature	= 70.5°F
velocity - weighted mean wet bulb temperature	= 73.1°F
calculated air flow rate	= 1,320,400 CFM
water side heat rejection rate	= 1,459,900 BTU/min.
air side heat rejection rate	= 1,647,700 BTU/min.
heat rejection rate deviation	= 12.9% (within error of instruments)

The numbers in parentheses are the wet bulb temperatures in degrees Fahrenheit. The remaining numbers are the air velocities in feet per second. The data was collected over a four day period which resulted in a range of ambient conditions. To account for this, the wet bulb temperatures have been normalized to the ambient conditions indicated. The diameter of the stack is 28.7 feet where the measurements were taken.

Figure D-2. Wet Bulb Temperature and Velocity Map of Stack During "All Wet" Mode of Operation



<u>Ambient Conditions</u>

wet bulb temperature = 42°F

<u>Tower Conditions</u>

inlet water temperature = 78.6°F
discharge temperature = 67.9°F
air flow rate = 1,390,000 CFM
water flow rate = 13800 GPM

<u>Calculated Results</u>

mean stack velocity	= 38 ft/sec.
mean wet bulb temperature	= 64.4°F
velocity - weighted mean wet bulb temperature	= 63.7°F
calculated air flow rate	= 1,475,700 CFM
water side heat rejection rate	= 1,230,000 BTU/min.
air side heat rejection rate	= 1,312,000 BTU/min.
heat rejection rate deviation	= 6.7% (within error of instruments)

The numbers in parentheses are the wet bulb temperatures in degrees Farenheit. The remaining numbers are the air velocities in feet per second. The data was collected over a three day period which resulted in a range of ambient conditions. To account for this, the wet bulb temperatures have been normalized to the ambient conditions indicated. The diameter of the stack is 28.7 feet where the measurements were taken.

Figure D-3. Wet Bulb Temperature and Velocity Map of Stack During 50% Wet/50% Dry Mode of Operation

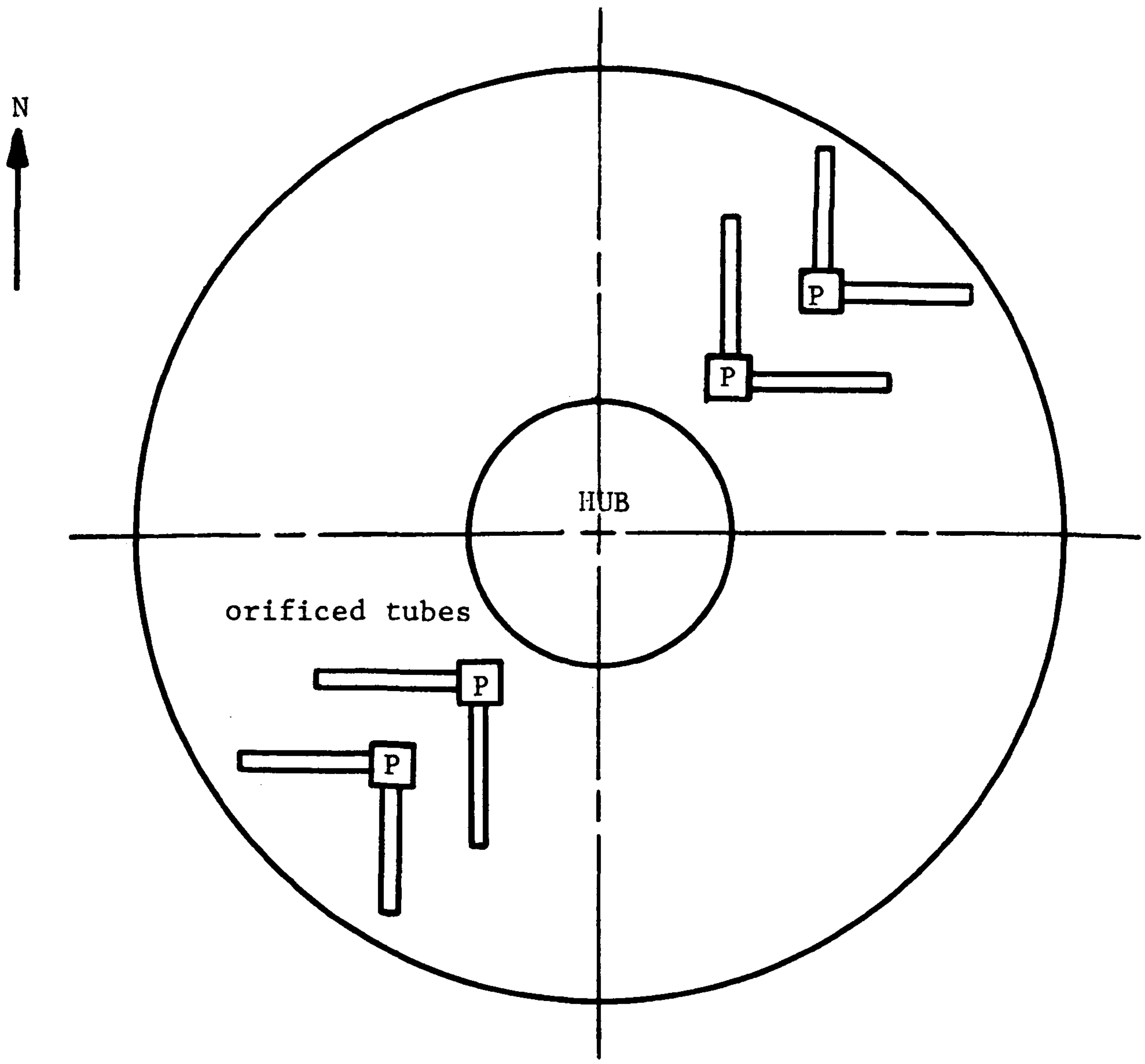


Figure D-4. View from top of stack showing location of stack psychrometers. The two tubes shown with each psychrometer are orificed to provide a weighted air sample.

tivity or improve data accuracy. The discussion below reflects the final instrumentation used for the test results.

Figure D-5 depicts the location of the psychrometric stations, hot and cold water temperature detectors, and other instrumentation situated on the tower. The location of the ambient weather stations is shown on Figure 1. In all cases, 100 ohm platinum resistance temperature detectors (RTD) were used.

Water flow measurement created some difficulties which should be noted. Initially, both inlet and outlet flow was measured by turbo-probe flowmeters. However, it was discovered that the sawdust which the station personnel routinely add to the circulating system to plug small condenser leaks, also worked well for plugging the flowmeters. After some trials, it was determined that the flowmeters were inoperable. A differential pressure cell was then installed to monitor the total developed head of the circulating pump and a calibrated head - flow curve was developed from a series of equal area traverses performed with a Pitot tube at varying flows.

While this method of flow measurement proved adequate, it was not totally satisfactory, particularly when it was discovered that the differential pressure cell had to be recalibrated every time the pump was shut down. Finally, with the cooperation of EPRI an "Annubar" flow measuring device was installed which has performed flawlessly and maintains an error of ±1%.

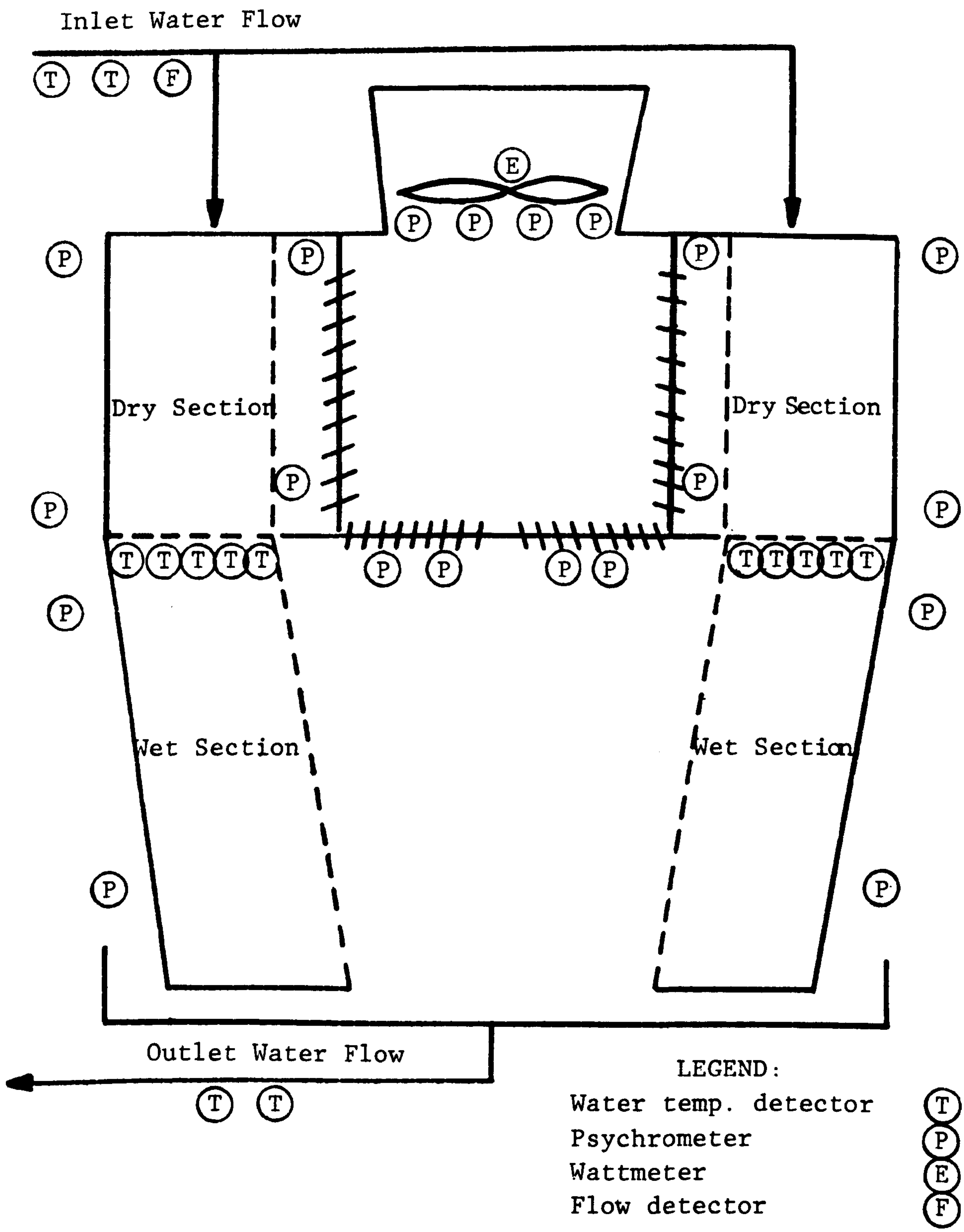


Figure D-5. Wet/Dry Cooling Tower Instrumentation Schematic

APPENDIX E
DESCRIPTION OF DAMPER CONTROL SYSTEM

The damper control system of the Wet/Dry Tower controls the distribution of air flow between the wet and dry sections. The temperature of the cold water exiting the tower serves as the control element. When the cold water temperature is at setpoint (which in this case was 78°F) or within the deadband (1.5°F above or below the setpoint), no demand signal is issued to the control system and the dampers remain in their current positions. In order to provide stability and prevent "hunting" of the system, a thermal time delay relay (agastat) is located between the demand signal and the control system. It was discovered that a 5-minute setting on this agastat was sufficient to allow the cold water temperature to stabilize after a change in damper settings. Additionally, another agastat is provided to limit the period of time the control system may actuate the dampers after each 5-minute time delay. A 3-second setting provided 11 degrees of damper movement, which gave sufficient change without encountering "over-shooting." Figure E-1 shows the basic damper operation as a function of demand. A key to understanding the operation is the fact that interlocks are provided to prevent the operation of either the wet or dry section dampers unless the other section dampers are either fully open or fully closed. On a typical cool day, the operation of the dampers might be as depicted in Table E-1.

TABLE E-1

(A)	12 Midnight to 8:00 AM	- Dry Dampers 100% Open	- Wet Dampers Fully Closed
(B)	8:00 AM	- Dry Dampers 100% Open	- Wet Dampers Begin to Open
(C)	10:00 AM	- Dry Dampers 100% Open	- Wet Dampers Complete Opening
(D)	10:30 AM	- Dry Dampers Begin to Close	- Wet Dampers 100% Open
(E)	12 Noon	- Dry Dampers Complete Closing	- Wet Dampers 100% Open
(F)	6:00 PM	- Dry Dampers Begin Opening	- Wet Dampers 100% Open
(G)	7:30 PM	- Dry Dampers Complete Opening	- Wet Dampers 100% Open
(H)	8:00 PM	- Dry Dampers 100% Open	- Wet Dampers Begin Closing
(I)	11:00 PM	- Dry Dampers 100% Open	- Wet Dampers Complete Closing

Each of these modes are depicted on Figure E-1 by the corresponding circled letter found in the above left hand column.

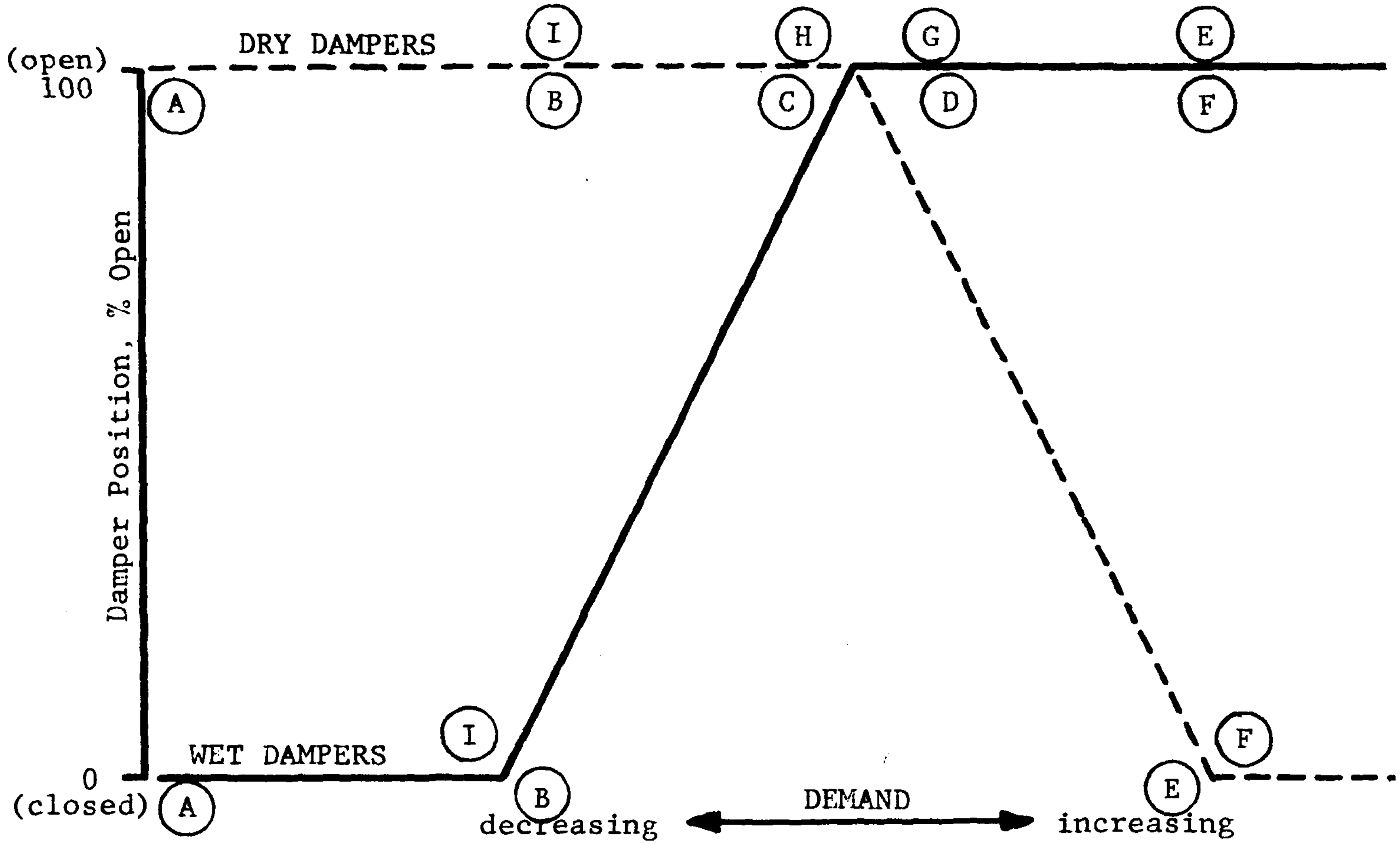


Figure E-1. Damper Control as a Function of Demand

APPENDIX F
TEST PLAN

The objectives of the test program, as stated earlier in this report, were as follows:

1. Determine the operational characteristics of a wet/dry cooling tower operating in an actual generating station environment.

2. Determine the water conservation aspects of a wet/dry cooling tower operating in an arid climate.

3. Develop a mathematical model of the wet/dry cooling tower and confirm it with actual test data.

The first objective was achieved merely by operating the Wet/Dry Tower, but the remaining two objectives required a test plan to follow in order to assure success of the program.

To simplify the plan it is broken into test blocks; however, because of the need to obtain data over a wide range of ambient conditions, the test blocks were repeated throughout the test period.

TEST BLOCK I - START-UP AND CALIBRATION

1. Confirm fan characteristics

2. Confirm pump characteristics

3. Determine velocity and temperature distribution of stack exit air (see discussion in STACK PSYCHROMETRIC MEASUREMENTS in Appendix D)

4. Confirm uniform distribution of water to cooling tower (This was accomplished by balancing the flows in the two risers and then equalizing the levels of the hot water basins.)

5. Determine air velocity distribution entering the Wet/Dry Tower (see discussion in AIR FLOW MEASUREMENTS in Appendix D).

6. Calibrate instrumentation within limits (See Appendix C)

TEST BLOCK II - CONSTANT WATER FLOW RATE, VARIABLE AIR FLOW RATE

These tests were run at several constant water flow rates. Air flow was varied by changing the pitch angle of the fan and by varying the dampers.

TEST BLOCK III - CONSTANT AIR FLOW RATE, VARIABLE WATER FLOW RATE

These tests were run at two constant air flow rates corresponding to fan pitch angles of 13° and 17°. Water flow rate was varied by use of a valve at the discharge of the circulating water pump.

APPENDIX G

TABLE OF CONVERSION FACTORS

Length:	1 inch = 2.54 centimeters 1 foot (ft) = 0.305 meters (m)
Area:	1 ft^2 = 0.093 m^2
Energy:	1 horsepower = 1.341 kilowatt
Pressure:	1 inch Hg. = 0.013 atmospheres 1 psi = 0.068 atmospheres
Flow Rate:	1 CFM = 0.472 liters/sec 1 gpm = 0.063 liters/sec
Velocity:	1 ft/sec = 0.305 m/sec
Temperature	1 °F = 0.556 °C to convert from °F to °C use this formula

$$°C = \frac{5(°F - 32°)}{9}$$

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-80-078	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Wet/Dry Cooling Tower Test Module		5. REPORT DATE April 1980
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15. SUPPLEMENTARY NOTES IERL-RTP project officer is Theodore G. Brna, Mail Drop 61, 919/541-2683.

16. ABSTRACT The report gives results of an evaluation of the engineering performance of a single-cell wet/dry cooling tower (about 25 MW) in an 18-month field test at San Bernardino, CA. Test objectives included determination of the water conservation and operating characteristics, and verification of a mathematical model for the wet/dry cooling tower. The crossflow tower had parallel air flows through the wet and dry sections, and dampers which regulated air flow to allow cooling in either section, or any combination of the two. Without significantly affecting normal plant performance, the wet/dry cooling tower could save about 19% of the water normally evaporated annually by an all-wet tower at the test site. Greater savings could have been achieved by accepting some loss of plant efficiency during the winter months. The mathematical model developed for the tower was verified by test results. Although some operational problems developed during testing, the major goals of the test program were achieved.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Cooling Towers	Stationary Sources	13A,07A,13I
Testing	Wet/Dry Cooling	14B
Water Conservation	Operating Characteristics	
Characteristics		
Mathematical Models		12A

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