OHIO RIVER COOLING WATER STUDY

by

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ABSTRACT

This study presents a review and critique of existing technical information relevant to the environmental effects of the use of the Ohio River main stem for cooling. In order to evaluate the effect of heat discharges on the indigenous aquatic life of the Ohio River, an extensive review and critique of past and existing studies dealing with the biological aspects of cooling water was undertaken. In order to judge the effect of heat discharges on the thermal regime of the river, three one-dimensional river temperature prediction models — COLHEAT, STREAM and Edinger-Geyer were evaluated, and the most appropriate model was selected to analyze changes in temperature distribution along the river. The effects of heat discharges on the thermal regime of the river near the points of discharge were evaluated by analyzing and critiquing available thermal plume study results.

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PREFACE

This report represents the results of a six month study undertaken by staff members of the Energy and Environmental Systems Division and the Environmental Statement Project of the Argonne National Laboratory.

Dr. Barbara-Ann Lewis conducted the review of previous and existing biological studies which are pertinent to the determination of the biological aspects of Ohio River cooling water use, and is the author of all the biological portions of the report with the exception of Section 4.2. That section, which deals with entrainment and condenser passage effects, was written by Dr. James J. Reisa, formerly of Argonne and now a staff member of the President's Council for Environmental Quality.

Mr. Donald R. Schregardus was responsible for the implementation of the study models on the Argonne computer as well as their operation throughout the study. He was responsible for assembling the Ohio River data base that was used throughout the project and assisted in interpretation of the simulation results.

A brief survey of the thermal plume studies that have taken place on the Ohio River was performed by Dr. Anthony J. Policastro. The results of the survey are reported by Dr. Policastro in Section 8 and in Section 1 where he makes conclusions and recommendations.

Dr. Brian P. Butz was the director of the Ohio River Cooling Water Study, was responsible for project co-ordination, and is the author of the remaining sections of the report.

The three computer models described in this report are available from either the United States Environmental Protection Agency Region V or the Argonne National Laboratory.

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Special thanks are given Dennis E. Peterson of the Hanford Engineering Development Laboratory for providing us with data previously collected on the Ohio River.

We thank those power companies who assisted us in this study: The Ohio Edison Company, The Cincinnati Gas and Electric Company, The Owensboro Municipal Utilities, The Indiana-Kentucky Electric Corporation and Electric Energy, Inc. We acknowledge the special efforts of Mr. James H. Carson of Ohio Edison and Mr. Edward E. Galloway of Cincinnati Gas and Electric, both of whom helped us acquire additional information about the power industry along the Ohio River. The efforts of Ronald Yates of the United States Corps of Engineers, David Calloway of the National Weather Record Center, William L. Klein and David A. Dunsmore of the Ohio River Valley Water

Sanitation Commission, and H. W. Defibaugh of the City of Wheeling are acknowledged.

Also, we sincerely appreciate the assistance rendered by fellow members of Argonne National Laboratory: Ernest Levinson for assistance in the preparation of Section 8, Robert Neisius and Walter Clapper for the report's graphics, Allen Kennedy and Donald McGregor for reviewing the draft and finally Jane Carey and Maria Pacholok for their patience and for their splendid job of editing and typing this report.

1. SUMMARY AND CONCLUSIONS

1.1 Thermal Models

Three far-field one-dimensional river temperature prediction models were chosen by the United States Environmental Protection Agency, Region V, for evaluation. The models—COLHEAT, STREAM, and Edinger-Geyer—were evaluated on a 300 mile reach of the Ohio River from Pittsburgh, Pennsylvania, to Huntington, West Virginia. The year 1964 was used as the data base year, and daily temperatures predicted by the model were compared with daily measured temperatures taken at four temperature measurement stations. The model most appropriate for use on the Ohio River for temperature prediction purposes was chosen by comparing the correlation between computed and measured temperatures as well as considering its theoretical completeness, data needs, and ease of use. Based on these evaluations (described extensively in Section 6), we conclude:

1. The COLHEAT Model is the most appropriate model of the three evaluated to use for river temperature prediction on the Ohio River at the present time.

2. The STREAM Model regularly predicts temperatures that are below measured temperatures.

3. The Edinger-Geyer Model tends to underpredict at the lower river temperatures and overpredict at the higher river temperatures.

4. The verification program used by the Ohio River Valley Water Sanitation Commission may have used temperature measurements too far from points of heat discharge to properly evaluate their exponential decay term.

We also conclude that:

5. Since three models evaluated in this study assume complete thermal mixing within the river at any given milepoint, it is improper to apply any of these models to river reaches which possess thermal stratification characteristics.

6. The STREAM model does not automatically add tributary flows to the Ohio River mainstreams.

7. The available river water temperature data is insufficient to allow model evaluation with a high confidence level.

8. The available river water temperature data is insufficient to allow proper model validation.

We recommend that efforts be undertaken to secure a significant Ohio River temperature data base such that models can be validated and evaluated on the Ohio River with a high degree of confidence. Special emphasis should be placed on measuring temperature close enough to heat sources and at such intervals so that the exponential decay of the river temperature is observed. We also recommend that thermal plume models be evaluated and used to determine any mixing zone violations by heat discharges.

Strategies, using the COLHEAT Model, were applied to the Ohio River and the resulting temperature distributions were analyzed. Conclusions drawn from these analyses are:

1. The natural temperature of the Ohio River can be determined by using COLHEAT.

2. There are both allowable maximum monthly temperature violations and temperature increment (ΔT) violations in the first two hundred miles of the Ohio River under low flow conditions.

3. The COLHEAT model predicts that advected heat discharged from large power plants under low flow conditions raises the river temperature. The new river temperature decays slowly in the downstream direction forming an ambient temperature which differs from the natural river temperature for distances of twenty miles or more.

4. The COLHEAT Model is amenable to strategy application on the Ohio River.

1.2 Biological Effects

Water quality and aquatic life of the Ohio River mainstream and major tributaries have been considerably degraded by the construction of navigational pools, heavy siltation, effluent from coal mines, and the discharge of industrial and municipal wastes. Efforts by federal and state agencies to prevent further deterioration of the river have stimulated research into the effects of cooling water use on the biota of this river. Results of these studies may be summarized as follows:

1. Phytoplankton abundance in the Ohio River varies markedly with flow rate, season, and river mile, usually reaching population peaks in the late summer or early fall. Diatoms generally predominate in the spring and fall, although green algae are always present and sometimes predominate at certain locations. Occasionally, blue-green algal blooms occur. The studies to date are inconclusive and generally inadequate to determine the effects of heated discharges on phytoplankton abundances.

2. The zooplankton community consists primarily of rotifers. Species of cladocerans and copepods are also present, the former group predominating where water quality is poorer. Zooplankton mortality as a result of passage through the condensers of power plants was observed under certain conditions.

3. Benthic macroinvertebrates are scarce in the river due mainly to poor substrate conditions. Midges, caddisfly, mayfly, and damselfly larvae are ubiquitous. Oligochaetes and bloodworms are dominant at certain locations and in certain years. Thermal discharges appear to increase the abundance of caddisfly larvae.

4. About 50 species of fish are known to be present in the river and tributaries. Carp, gizzard shad, some shiners, channel catfish and buffalofish, which are more tolerant of turbidity and high temperatures, frequent the main stem. Species such as walleye, sauger, crappie, and sunfishes apparently prefer the cooler waters of the smaller streams and creeks. Little successful spawning has been observed in the main stem, and it is likely that spawning and nursery habitats occur in the cooler streams and quiet backwaters. Few incidents of thermal death have been reported but avoidance of heated discharges has reduced the fish species diversity at certain locations.

Studies on the biological effects of cooling water use on the Ohio River have provided good insight into some aspects of the problem, but suffer from one or more deficiencies, including:

1. Neglect of other factors besides discharge of heated water, such as the intake, condenser passage, and presence of chemicals in the discharge.

2. Lack of systematic, frequent, or extensive plume temperature measurements with which to relate responses of river biota.

3. Lack of statistical treatment of phytoplankton and zooplankton data to determine significance of observed effects.

4. Lack of water quality considerations in plume effects.

5. Little characterization and measurement of natural seasonal variations in populations of river biota.

6. Little information on migration habits, movements, and spawning of river fish.

Despite difficulties inherent in the study of complex life systems such as the Ohio River and its biota, several effects of cooling water use have been well established. It is thus no longer excusable to cite the lack of information as a basis for inaction. Measures that can be taken to prevent or minimize adverse effects of cooling water use include:

1. Siting and design of intake structures primarily on the basis of biological effects, and only secondarily on economic factors.

2. Minimization of entrainment effects by shortening exposure times to elevated temperatures and reducing intake volumes.

3. Design of discharge structures such that fish do not have access to the discharge canals and cannot be trapped in small bays.

4. Avoidance of spawning and nursery areas in siting intakes and discharges.

5. Providing a zone of passage that takes into consideration the habits of the fish.

6. Careful control of chlorination, if such is used to control condenser sliming. A total residual chlorine concentration of 0.2 mg/l (not to exceed 2 hours/day) as measured in the effluent before discharge to the river would protect Ohio River fish.

7. Design and location of intake and discharge structures that avoid the necessity of extensive and repeated dredging.

1.3 Thermal Plume Analysis

All available nonproprietary data on Ohio River thermal plumes either from infrared surveys or boat measurements are of a quality too poor to permit meaningful quantitative evaluations of plume characteristics. Only the general size of the plumes could be determined from the two aerial infrared surveys. Moreover, the temperatures measured were not of sufficient detail to be useful for mixing zone analyses, much less model verifications. Finally, water temperature measurements taken from a boat were not sufficient to provide any kind of plume detail.

We conclude that more detailed temperature measurements should be made along the river so that accurate plume characteristics may be delineated. The data required consist of temperature measurements sufficient to yield a three dimensional temperature map of the plume as well as velocity measurements sufficient to yield a velocity profile at a short distance upstream of the plant discharge. We feel that these measurements will serve to verify and improve existing and future thermal models as well as assisting EPA enforcement personnel in determining plant violations.

2. INTRODUCTION

The thermal capacity of the Ohio River has been a subject of much discussion and considerable controversy during the past several years. Presently, about thirty-five electric generating stations use the Ohio River for cooling purposes and the majority of these stations use once-through cooling. In addition, several other major industries such as steel mills, chemical companies, smelters, etc., discharge heat into the river. What is the effect of this heat on the indigenous aquatic life of the Ohio River? What is the effect of this heat on the natural thermal regime of the river? Several studies have been made to determine the effect of this heat on the indigenous aquatic life of the Ohio River, but the results have varied substantially. At least three agencies, the Atomic Energy Commission, the Ohio River Valley Water Sanitation Commission, and the U.S. Environmental Protection Agency have modeled the impact of heat discharges on the thermal regime of the river. Again, the results of the studies have varied substantially. This study originated because of the conflicting results of previous inquiries.

Purpose

The purpose of this study is to review and critique existing technical information relevant to the environmental effects of the use of the Ohio River main stem for cooling. In order to evaluate the effect of heat discharges on the indigenous aquatic life of the Ohio River, an extensive review and critique of past and existing studies dealing with the biological aspects of cooling water was undertaken. In order to judge the effect of heat discharges on the thermal regime of the river, three one-dimensional river temperature prediction models - COLHEAT, STREAM and Edinger-Geyer were evaluated and the most appropriate model was selected to analyze changes in temperature distribution along the river. The effects of heat discharges on the thermal regime of the river near the points of discharge were evaluated by analyzing and critiquing available thermal plume study results.

Organization of the Report

Section 3 is an introduction to the Ohio River and the Ohio River basin area. A brief description of the river, its use, its quality and its biota is given, together with a description of power industry growth along the river.

The biological aspects of water cooling use are discussed in Section 4. Nationwide studies as well as those particular to the Ohio River are evaluated and critiqued. Recommendations for the Ohio River conclude this section.

Sections 5 and 6 deal with the three river temperature prediction models analyzed in this study. The theoretical foundations of the models - COLHEAT, STREAM, and Edinger-Geyer - are presented in Section 5, while each model is evaluted in Section 6. Section 7 uses the model selected in Section 6 to predict river temperature distributions under various conditions.

Thermal plume studies which have been performed on the Ohio River are examined and discussed in Section 8.

3. THE OHIO RIVER REGION

Section 3 presents a brief overview of the Ohio River region. The description of the Ohio River basin contained in Section 3.1 includes a discussion of the area's notable physical features as well as a climatological profile. The use of Ohio River water for cooling purposes, especially by the power industry, is the theme of Section 3.2. Past, present and future uses of cooling water are discussed.

A biologist's view of the Ohio River region is given in Sections 3.3 and 3.4. Section 3.3 describes the history and present status of the water quality in the region, while Section 3.4 is concerned with the effect of water quality change on the region's biota.

Section 3.5 concludes Section 3 with a discussion of past, present and future electric power generating capacity on the Ohio River.

3.1 Description of the Ohio River Basin

The Ohio River basin, an area of 203,910 square miles, lies in the middle eastern portion of the United States. The Ohio River is formed by the confluence of the Monongahela and Allegheny Rivers at Pittsburgh, Pennsylvania, the point usually designated as river mile zero on Ohio River mainstream navigation charts. From Pittsburgh (see Fig. 3.1) the river flows in a northwesterly direction for about 25 miles and then turns westward where it becomes the Ohio-West Virginia boundary. From this point the river continues in a southwesterly direction progressively forming the northern boundaries of Kentucky-West Virginia and the southern boundaries of Ohio, Indiana and Illinois.[1] The Ohio River joins the Mississippi River at Cairo, Illinois, 981 miles downstream from its origin at Pittsburgh.

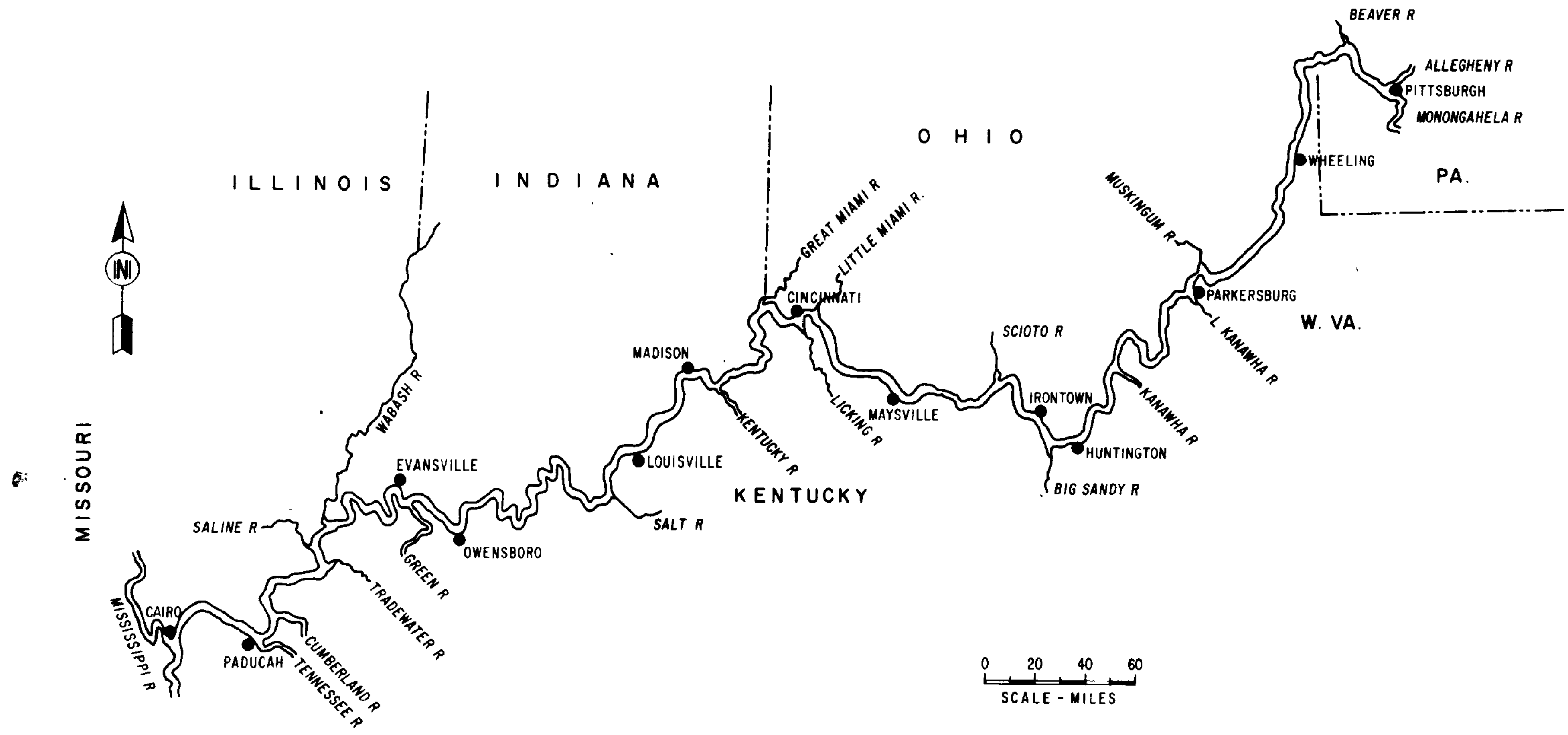

Figure 3.1
The Ohio River

The Ohio River is the eleventh largest river (by length) in the United States and it supplies the largest volume of flow of the six Mississippi natural tributary drainage patterns, and, of these, the Ohio basin is exceeded in land area only by the Missouri River basin.

Physical Features[1]

The area comprising the Ohio River basin includes several distinctive physiographic regions. The eastern portion of the basin lies mainly within the Appalachian Plateau, although portions of the drainage areas of the Monongahela and Kanawha Rivers are in the Blue Ridge provinces. The western portion of the basin is located within the interior low plateau and Central Lowland provinces, except for a small area at the mouth of the Ohio River where it drains into the lower Mississippi River at the northern tip of the Gulf Coastal Plain.

Ancient buried river valleys that are deeply entrenched in the bedrock and subsequently have been filed with glacial debris are widespread subsurface formations of the basin in Indiana, Ohio, northwestern Pennsylvania and New York. The material filling many of the valleys is of a highly permeable composition and because of its present and future use, may be considered one of the water assets of the basin. Throughout the basin, the bedrock is principally of sedimentary origin and varies from dense impermeable siltstones and shales to open textured limestone and sandstone. The degree to which the bedrock is water bearing and forms, or might form, a significant source of ground water varies with location.

The Appalachian coal fields are found beneath the basin in eastern Ohio, western Pennsylvania, southeastern West Virginia, and eastern Kentucky, while in the western part of the basin, parts of the mid-continental fields are found in western Kentucky and southern Illinois and Indiana. Generally, petroleum deposits can be found associated with the coal fields as fringe areas along the basin interior. Extraction of these materials is an important industrial activity in the locations of occurrence, and the coal reserves seem sufficient to sustain the area's coal industry for quite some time. However, the extraction and subsequent processing of coal has given rise to acid mine and silt contamination of the local surface drainage while the oil wells have frequently been a source of brine discharge to local surface streams and underground aquifiers.

The Ohio River drainage system is almost completely devoid of natural lakes and swamps. The existing natural lake areas are found only in the upper headwaters of the Wabash River drainage and these are so limited in extent as to be of only local concern in respect to water supply sources and water disposal. Notable swamp areas had appeared contiguous to the Wabash lake area region, but the development of dikes, dredged ditches, and tilling systems have brought the lands to a well-drained condition. Water conservation reservoirs, which range in size from farm ponds to large government developments, and navigation dams, creating flow through impoundments and whose pools range in depth from 6 to 45 feet, are found throughout the basin. Many of the dams serve as diversion and temporary water storage facilities for community and industrial use and all of them modify the natural assimilative capacities of the impounded streams.

Climate[1,2]

The Ohio River basin's climate is temperate with marked seasons. The eastward passage of cyclonic storms cause changes in the weather, considerable rainfall, snowfall, humidity as well as moderate cloudiness and windiness. Several tornadoes occur each year within the basin, and hurricanes sometimes encroach on the southern and eastern portions of the basin before their energy is spent.

The average annual air temperature along the Ohio River varies from about 58°F near its end at Cairo, Illinois, to about 50°F at its origin at Pittsburgh, Pennsylvania. The average annual temperature is, in general, uniformly distributed from southwest to northeast between the aforementioned limits. Average January temperatures in the basin range from 25°F to 35°F, while those in July are from 70°F to 80°F. Summer maximums of 100°F to 111°F have been recorded throughout the basin, while winter temperature extremes are well below freezing and often of sufficient length to cause ice to form on the surface streams.

The average annual precipation varies from about 36 inches in the northern part of the basin to about 52 inches in the southern part and, except for local departures over the Highlands, is generally uniformly distributed from north to south. Usually the average precipitation is uniformly distributed throughout the year, but wide departures from the average have occurred. In severe drought years as little as 50 percent of the annual average occurred in various parts of the basin, and there have been instances when drought conditions have continued over several consecutive years. The effects of drought periods on streamflow and subsequent water availability are of particular interest. For example, the years 1930 and 1934 witnessed a severe drought throughout the western-central portion of the basin. With an average annual runoff of 10.85 inches, the Little Wabash fell to 2.36 inches in 1930 and fell to 2.40 inches in 1934.

The average monthly air temperature and average monthly precipitation figures for various stations along the Ohio River are given in Table 3.1 below.

Table 3.1

Average Monthly Air Temperatures and Precipitation Amounts for Selected Stations on the Ohio River*

MONTH	Pittsburgh, Pa.		Cincinnati, Ohio		Louisville, Ky.	
	Air Temp (°F)	Precip. (in.)	Air Temp (°F)	Precip. (in.)	Air Temp (°F)	Precip. (in.)
January	28.9	2.97	33.7	3.67	35.0	4.10
February	29.2	2.19	35.1	2.80	35.8	3.29
March	36.8	3.32	42.7	3.89	43.3	4.59
April	49.0	3.08	54.2	3.63	54.8	3.82
May	59.8	3.91	64.2	3.80	64.4	3.90
June	68.4	3.78	73.4	4.18	73.4	3.99
July	72.1	3.88	76.9	3.59	77.6	3.36
August	70.8	3.31	75.7	3.28	76.2	2.97
September	64.2	2.54	69.0	2.71	69.5	2.63
October	53.1	2.52	57.9	2.24	57.9	2.25
November	40.8	2.24	44.6	2.95	44.7	3.20
December	30.7	2.40	35.3	2.77	36.3	3.22

*All data based on standard 30-year period 1931 to 1960.

3.2 Ohio River Cooling Water Use

The earliest known use of water in the Ohio River basin was primarily for domestic purposes. Water needs were quite simple by today's standards and were served by withdrawals of a few gallons per day per person or per household. The water itself was carried in buckets or by some other simple means from the source of supply to the point of use.[2] However, as the elements of society became more interdependent resulting in an industrialized economy, water use rapidly increased. For example, by 1963 there were 1,908 municipal water supply systems in the Ohio River basin, and 1,595 of these had water treatment facilities furnishing water to approximately 13 million people.[2]

Industrialization created a large demand for water as a cooling agent. In both the Ohio River basin and the Ohio River the electric power industry asserts the largest demand on the available water resources and nearly all of the water used by the power industry is for cooling and condensing the steam used to produce electric energy. In 1965 an estimated 31 billion gallons per day were drawn from the Ohio River basin for man's use, and about one billion gallons of this total were used consumptively. The electric power industry withdrew 19 billion gallons per day (61% of the total water withdrawn) for cooling purposes. About 8.5 billion gallons per day of the power industry's 19 billion gallons per day withdrawal were taken from the Ohio River and the lower reaches of its principal tributaries.

The fact that the electric power industry uses much more water for cooling purposes than other industries is not unique to the Ohio River basin. In 1964 the cooling water-use distribution on a nationwide basis was[3]

Electric power	81.3%
Primary metals	6.8%
Chemical and allied products	6.2%
Petroleum and coal products	2.4%
Paper and allied products	1.2%
Food and allied products	0.8%
Machinery	0.3%
Rubber and plastics	0.3%
Transportation equipment	0.2%
Other	0.5%

As stated earlier, the electric industry requires cooling water in order to efficiently generate electricity. The water withdrawn by a power company circulates through the power plant condensors and absorbs most of the heat retained by the steam after it leaves the turbine and before the condensate is returned to the feedwater heaters and boilers (see Fig. 3.2). The quantity of water required for this purpose varies depending upon plant size, plant heat rate, and the acceptable temperature rise of the cooling water. Returning the now-heated water directly to the stream from which it was withdrawn may contribute to stream pollution by reducing the water's capacity to hold dissolved oxygen. A reduction in stream dissolved oxygen content adversely affects aquatic life, waste elimination, and the use of the water for other purposes.

Historically, the cooling water needed by power plants was withdrawn from nearby lakes or rivers, circulated through the plant, and discharged into the same water body. This process, called once-through cooling, enabled the power industry to produce electricity efficiently with relatively low capital and operating costs for the cooling system. However, the increasing capacity of the newer power plants along with the increasing number of power plants have created thermal problems on many waterways. Increased social awareness of the environment in which we live and of the

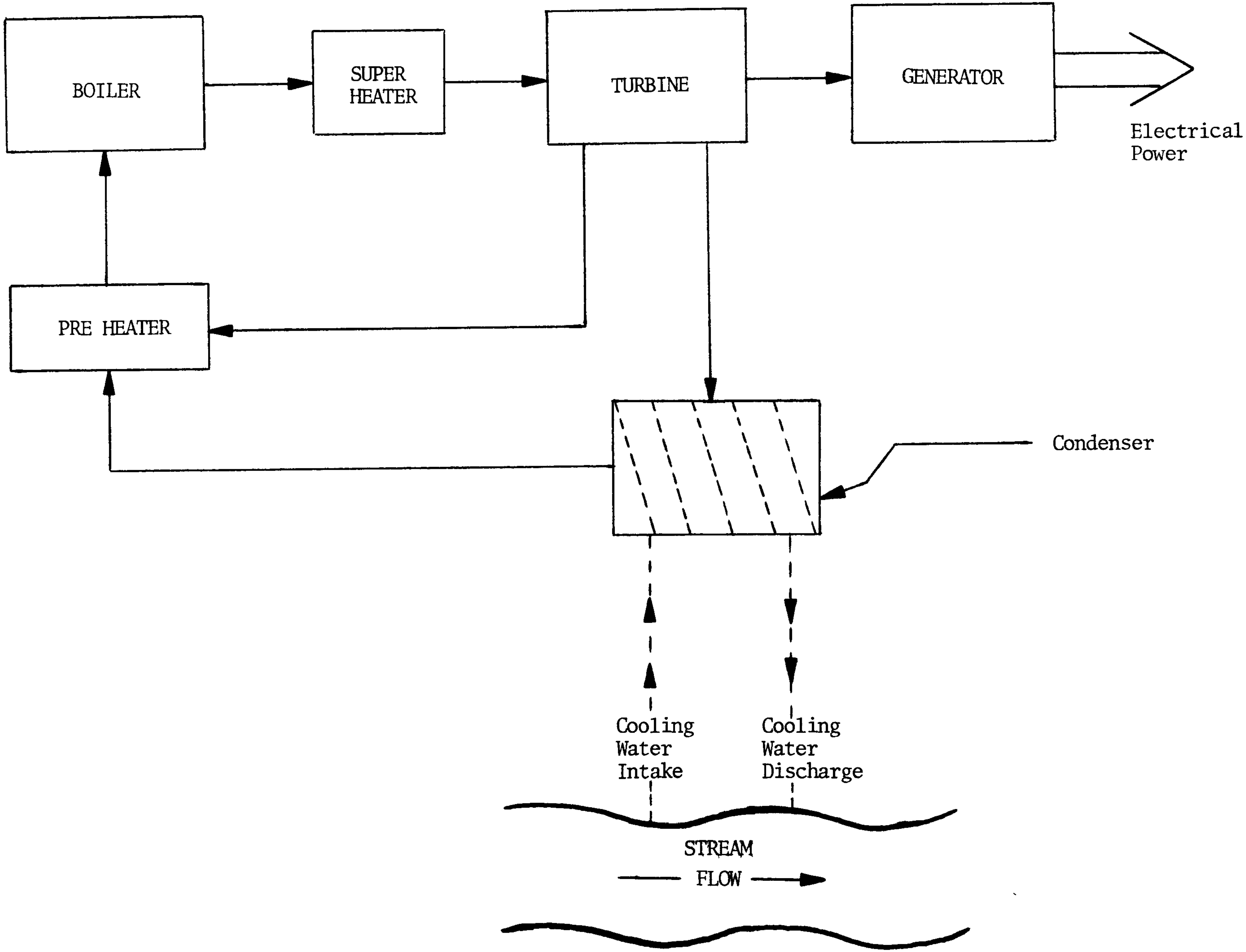

Figure 3.2
Steam-Electric Power Station Cooling System

need for its preservation have resulted in statutes which require the electric power industry to turn to alternative cooling techniques such as cooling ponds and towers.

Present Cooling Water Usage

In 1969 the total water withdrawal from the Ohio River for cooling purposes by the electric power industry amounted to over 13 billion gallons per day, an increase of over 60% of the water withdrawn in 1964. A detailed breakdown of cooling water use by individual plants with a capacity greater than 50MW is given in Table 3.2. The amount of water used for cooling by other industries can be estimated to be between 10-20% of the power industry total.

Future Cooling Water Usage

Predictions of the cooling water requirements for steam electric generation 10 to 15 years hence is difficult and uncertain, and the figures generated may prove to be inadequate in most cases.[4] This difficulty is compounded by the unknown effect that the present "energy crisis" will exert on the demand curve facing the power industry. Although confronted with the problems mentioned above, some statements about future cooling water use can and should be made.

Peterson and Jaske[3] and then later Peterson, et al.,[5] have estimated the total potential low flow direct cooling capacity of the Ohio River

Table 3.2

Electric Power Industry Cooling Water Use - 1969

River Mile Point	Station	Water Withdrawn (MGD)
2.3	J. H. Reed	315.6
15.6	F. Phillips	399.9
33.8	Shippingport	128.6
55.0	W. H. Sammis	1054.4
59.1	Toronto	181.2
74.5	Tidd	259.0
75.0	Cardinal	1151.2
79.5	Windsor	662.2
102.5	R. E. Burger	370.3
101.9	Mitchell	*
111.1	Kammer	646.0
160.5	Willow Island	145.4
241.0	Philip Sporn	969.0
260.2	Kyger Creek	1124.0
405.7	J. M. Stuart	N.A.
453.3	W. C. Beckjord	475.5
471.4	West End	211.2
490.3	Miami Fort	295.9
494.5	Tanners Creek	917.3
558.5	Clifty Creek	1376.0
604.0	Paddy's Run	91.6
607.0	Canal	0.6
616.6	Cane Run	575.5
618.0	Gallager	453.9
728.2	Coleman	151.2
752.8	Owensboro Municipal #1	61.2
755.3	Elmer Smith	105.2
773.0	Warrick 1,2,3	N.A.
773.0	Warrick 4	N.A.
773.8	Culley	135.8
793.5	Ohio River	129.2
803.6	Henderson	40.0
946	Shawnee	129.2
958	Joppa	566.5
		13,122.7

N.A. - Data not available

*Cooling tower

and have concluded:

> "Under the maximum condition of development and with some partial supplementary cooling, the entire needs of the (Ohio River basin) area could be accommodated through the foreseeable future. Without supplementary cooling, the available siting opportunities would be totally committed by 1984."

Care should be taken when interpreting the results of the Peterson-Jaske report. Too often that report is interpreted to mean that there is an enormous untapped capability for once-through cooling remaining in the Ohio River basin. Peterson, et al., point out:

> "As natural river temperatures approach the maximum allowable under state standards, the capacity calculations based on incremental temperature rise may not be indicative of the river's actual capacity, since the capacity could be reduced occasionally by the maximum temperature constraint."[5]

Also, neither report mentioned above takes into consideration state statutes regarding mixing zones which may further reduce the total low flow direct cooling capacity of the river in question.

The preceding discussion should not be construed to indicate that the Ohio River does not have the cooling capacity necessary to accommodate additional once-through cooling power plants. The question, which is yet unresolved, is just how many once-through cooling power plants can be sited at which locations on the Ohio River without violating state standards.

In 1969 the Power Industry Advisory Committee to the Ohio River Valley Water Sanitation Commission (ORSANCO)[6] reported that all future power plants would be closed cycle. Since the power plants planned for the Ohio River in the 1975-1981 time span are all closed cycle, cooling water use by the power industry during this period should remain constant or rise slightly.

3.3 Water Quality -- History and Present Status

Before the 19th Century, little was known about the water quality of the Ohio River, but there is information which indicates that the river at that time was clear throughout most of its length; the bottom was gravelly, rocky, or sandy, and aquatic plants abounded. The shading effect of trees along the banks may have helped keep the water cooler in the summer than it is now.[7] In the early 1800's steamboats began to use the Ohio, coalpits appeared around Pittsburgh, and the Ohio River Valley became an industrial center. In 1824, the U. S. Army began its modification of the river starting with the removal of rocks and the construction of dikes. Eventually, a system of 46 locks and dams changed the free-flowing Ohio to a series of slow-moving impoundments. Today, the lock and dam system is being replaced by a new system of 19 high level dams to improve navigation, reduce the number of lockages, and accommodate the increased sizes of tow boats. As with many of man's well-intentioned but shortsighted endeavors, little consideration was likely given to the ramifications of these actions, particularly to the effects on the river's biotic community.

Concurrent with the river modification; removal of forests, agriculture, and construction throughout the river valley have caused tremendous silt loads to build up in the river, so that a once transparent river has become a turbid one. The gravelly or sandy bottom, so essential as spawning substrate for many fish species, is now covered in many places with layers of silt and finer sediments.

In 1948 the Ohio River Valley Water Sanitation Commission (ORSANCO) was established to conduct a regional program of water pollution control. From 1959 to 1970, some improvement in dissolved oxygen levels, pH, dissolved solids, and chlorides were observed at some monitoring sites. ORSANCO maintains water quality monitoring stations as indicated in Table 3.3.

In addition to silt carried into the river by runoff, about 1648 industries and 130 sewage treatment plants are discharging organic compounds, heavy metals, high BOD wastes, and fecal organisms into the main stem and tributaries, leading to unsightly oil and scum on the water surface, toxic levels of certain compounds such as cyanide and lead, low dissolved oxygen concentrations, occasions for dead or unpalatable fish, and unsanitary water conditions due to the presence of fecal bacteria including, in some areas, salmonella species.[9]

3.4 Biota - History and Present Status

Before the impoundment of the Ohio River into a series of pools, it is likely that there was little true plankton in the river except as was

Table 3.3

ORSANCO Water Quality Monitor Stations[a]

Ohio River Stations

	Mile Point	Type*		Mile Point	Type*
Pittsburgh (Reed) Pa.	2.3	B	South Point, Ohio	318.0	B
South Heights, Pa.	15.8	A, B, C	Portsmouth, Ohio	350.7	B
Stratton, Ohio	55.0	A, C	Meldahl Dam	436.2	A, C
Toronto, Ohio	59.1	B	New Richmond (Beckjord) Ohio	452.8	A
Weirton, W. Va.	62.2	B	Cincinnati (Waterworks) Ohio	462.8	A, B
Steubenville, Ohio	65.3	B	Cincinnati (West End) Ohio	471.3	A
Power, W. Va.	79.3	B	Cincinnati (Anderson Ferry) Ohio	479.1	A
Yorkville, Ohio	83.6	B	North Bend (Miami Fort) Ohio	490.0	A, B
Wheeling, W. Va.	86.8	B	Aurora, Ind.	496.7	A
Moundsville, W. Va.	111.0	B	Markland Dam	531.5	A, C
Natrium, W. Va.	119.4	B	Madison (Clifty Creek) Ind.	559.5	A, B
Willow Island, W. Va.	161.0	A, B	Louisville (Waterworks) Ky.	600.6	A, B
Parkersburg, W. Va.	183.7	B	Louisville (Cane Run) Ky.	616.8	A, C
New Haven, W. Va.	241.6	A, B, C	Evansville, Ind.	791.5	A, B
Addison, Ohio	260.7	B	Dam 53	962.7	C
Huntington, W. Va.	304.2	A, B			

Tributary Stations

	Mile at which tributary enters Ohio River	Miles from sampling station to confluence of tributary with Ohio River	Type*
Allegheny River near Kinzua, Pa.	0.0	198.0	C
Allegheny River at Oakmont, Pa.	0.0	13.3	A, B, C
Allegheny River at Wilkinsburg, Pa.	0.0	8.9	B
Monongahela River at Point Marion, Pa.	0.0	90.8	C
Monongahela River at Charleroi, Pa.	0.0	42.6	A, B
Monongahela River at South Pittsburgh, Pa.	0.0	4.5	B, C
Beaver River at Beaver Falls, Pa.	25.4	5.3	A, B
Muskingum River at Philo, Ohio	172.2	66.8	B
Muskingum River near Beverly, Ohio	172.2	28.0	A, B, C
New River at Glen Lyn, W. Va.		193.9	B
Kanawha River at Cabin Creek, W. Va.	265.7	74.3	B
Kanawha River at Winfield, W. Va.	265.7	31.1	A, C
Big Sandy River near Louisa, Ky.	317.1	20.3	A, B
Little Miami River at Cincinnati, Ohio	463.5	3.4	A
Licking River at Kenton County, Ky.	470.3	4.5	A
Great Miami River near Cleves, Ohio	491.1	5.5	A
Wabash River near Hutsonville, Ill.	848.0	174.0	A, C

* A -- Electronic Monitors

B -- Water Users Committee Stations

C -- U.S. Geological Survey Stations

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[a] ORSANCO, Twenty-third yearbook, 1971.

supplied from slow-flowing tributaries, quiet backwaters, and detached benthos. Construction of the navigation pools essentially changed a lotic environment into lake-like ecosystems where plankton are able to accumulate.

A study of the distribution of stream plankton in the Ohio River main stem and tributaries was made in 1939 and 1940.[10] Although sampling was not very systematic (e.g., tributaries were not all sampled in the same year or in the same month; at some locations, samples were collected for a large part of the year, while at other locations less frequently; more samples were taken during the summer than during other months of the year), the results from over 1400 samples gave some idea of the general plankton populations of the river system at that time. It was concluded that, in general, the numbers of individuals and species in the tributaries increased with the onset of warm weather, reaching a peak in August and September although there was no marked seasonal variation for most of the plankton. In the Ohio River main stem, the reverse change occurred, i.e., numbers and species decreased during the warm months. This was attributed to change in stream size and to water quality factors. Diatoms were the predominant group of phytoplankton in the main stem, occurring in larger number than in the tributaries.

In 1960-1961, a study on the upper Ohio River indicated that the phytoplankton community in January through May was dominated by diatoms, mainly the genera Synedra, Navicula, Asterionella, Cyclotella, Stephanodiscus, Fragillaria, Meridion, and Melosira.[11] From June through December, green algae predominated, mainly Chlamydomonas, Ankistrodesmus, Scenedesmus, Pediastrum, Micratinium, Crucigenenia, and Dictyosphaerium. Euglenoids, chiefly Trachelomonas, occurred during the spring and fall but were scarce in the summer. Blue-green algae were present in February and September, mainly Oscillatoria. Numbers of individuals collected appeared to be influenced by the flow rate,[11] and it has been suggested that plankton population studies in rivers may be more meaningful during periods of low flow when populations can develop without the influence of high velocity.[12] There are periods in the year when water in the pools can reach flood stage in the Ohio River, and coupled with the opening and closing of the locks makes flow rates in the river extremely variable, even on a day-to-day basis. These factors should be considered in the evaluation of plankton populations in the main stem of the river.

A study in the Louisville area (on the middle portion of the river) indicated that the diatoms Asterionella, Melosira, and Synedra were abundant in the fall. About 28 species of green algae of the order Chlorococcales were also present. In October 1959, a heavy algal bloom of Anacystis (a blue-green alga) occurred, and probably contributed to the taste of the water during that period.[7]

Other studies on phytoplankton distribution in the Ohio River[13,14,15] substantiate some present conclusions concerning the phytoplankton in the main stem of the river, i.e., abundance varies markedly with flow rate, season, and river mile (location); diatoms usually predominate in the spring and fall, although green algae are always present and sometimes predominate at certain locations; occasionally, blue-green algal blooms occur, as well as blooms of the "sewage fungus" *Sphaerotilus natans* in some areas close to sewage discharges.

Zooplankton

A survey of zooplankton in seven selected regions along the length of the Ohio River was made in 1959.[7] The dominant members of this community were rotifers, mainly *Keratella* and *Brachionus*. The cladocerans, *Bosmina* and *Chydoras*, and the copepod, *Cyclops*, also occurred in nearly all the samples taken.

In 1970 and 1971, rotifers were dominant at three sampling locations on the river; i.e., River Mile (RM) 54.4, 260, and 452. At RM 616.7, where water quality was poorer than at the abovementioned stations due to heavy use by industry and municipalities, cladocerans were dominant. At all four stations, populations were near zero during the winter until late March, became evident in April, and reached population peaks coincident with phytoplankton peaks in the summer.[16]

Macroinvertebrates

Bottom-dwelling macroinvertebrates of the Ohio River and tributaries were sampled over a five-year period (1963 to 1967). Taxa found to be ubiquitous in the Ohio River and tributaries were midges, *Dicrotendipes*, Procladium, Coelotanypus, Cricotopus; the caddisfly Cyrnellus fraternus; the damselfly Argia; the mayfly Stenonema; and the coelenterate Cordylophora lacustris. The midges Glyptotendipes and Chironomus attenuatus were common in organically enriched water; Chironomus riparius, Cricotopus, and Procladius were commonly found in water receiving toxic pollutants and low pH.[17] Populations downstream from Pittsburgh, Pennsylvania, principally bloodworms and oligochaetes, were limited by pollution from the lower Allegheny and Monongahela Rivers. A marked change in macroinvertebrate populations occurred in the Wabash River at New Harmony, Indiana, during the five-year study period. The large and diverse fauna, consisting of midges, caddisflies, odonates, and mollusks, existing in 1963 and 1965, were markedly reduced in 1966 when bloodworms were predominant. This change occurred during a period of low flow in the summer. In 1967, the fauna returned to its former composition. Other taxa of the river basin found during the five-year study were:

> "The midge Chironomus riparius (upper Ohio River) C. attenuatus and Xenochironomus xenolabis (middle Ohio River) and Tanypus (lower Ohio River); the crayfish Orconectes obscurus (Allegheny River and upper Ohio), O. rusticus (Wabash River and middle Ohio); the caddisflies Potamyia flava and Hydropsyche orris, stoneflies Isoperla bilineata and Acroneuria spp., mayflies Hexagenia and Caenidae and the dragonfly Neurocordulia sp. (middle and lower Ohio River). The asiatic clam Corbicula was found from Marietta to Cairo. The stoneflies Acroneuria occurred in the spring and summer and Taeniopteryx nivalis was collected in the late fall. Peak periods of hydropsychid caddisflies were observed from mid-August to late September in the middle and lower Ohio River basin."[8]

In 1972, results from benthic sampling using the Ponar dredge at RM 54.4, 260, 452.9, and 494 indicated very low numbers of benthos at all areas. Oligochaeta were the most abundant group. The asiatic clam Corbicula manilensis was also found at all sampling sites.[8]

The paucity of benthos in the Ohio River is very likely the result of poor substrate conditions, low dissolved oxygen levels at lower depths, and possibly toxic materials adsorbed onto sediment particles. Since benthic organisms serve as food for many species of fish, including game and sport fish, the adverse effects of the loads of silt and industrial pollutants are eventually manifested by the populations of fish in the river.

Fish

A collection of historical notes[7] on the species and abundance of fish in the Ohio River and tributaries indicates that before 1900, fish in the Ohio River included muskellunge, blue sucker, buffalo fishes, catfish, blue catfish, brown bullhead, channel catfish, flathead catfish, lake sturgeon, gar pike, spoon-bill cat, freshwater drum, walleye, mudpuppy, sauger, mooneye, and crappie (see Appendix B for the Latin names of species mentioned in this report).

After 1900, as silting of the river increased, fish which could tolerate muddy bottoms and turbid water increased in numbers. Such species were the black bullheads, goldeye, skipjack herring, gizzard shad, and spotted bass. A 1956 history of the fish populations in the Upper Ohio River Basin[18] describes the changes that have occurred in these populations, e.g., the extinction of certain species and the survival of more tolerant and hardy species, due largely to the work of man.

By 1968, many of the species mentioned as present around 1900 had disappeared or declined greatly in numbers. A study on the Ohio River main stem[19] indicated that carp (an introduced species) and bullheads were predominant in the middle and lower portions of the river. About 20 other species were also found, including channel catfish, sunfishes, freshwater drum (mostly in the middle and lower portions of the river), and shiners (mostly in the upper and middle portions). Walleye were scattered throughout the river, and a significant number of sauger were found in the Kentucky area above Cincinnati. The species composition of the commercial catch for selected years from 1894 to 1963 is listed,[20] and indicates that species such as black bass, mooneye, walleye, and drum have disappeared from the commercial catch or declined in numbers, while the proportions of carp and buffalofish in the commercial catch have increased.

Fish collections made at four areas on the river main stem and at several tributary creeks during April to August, 1971, indicated that at least 47 species were present.[16] These are listed in Table 3.4.

The existence and accessibility of suitable spawning habitats for fish is obviously essential to maintaining populations. Due largely to construction of the dams, spawning sites for many of the species in the Ohio River main stem have been eliminated. For example, migratory fish such as the paddlefish and walleye are prevented by the dams from reaching their spawning streams; reduction of the floodplain areas eliminated many backbays and sloughs which provided spawning habitat for nest-building species such as the blackbass and various sunfishes; natural cycles of high and low flow which are essential to the spawning success of many species have been altered.[16] It is likely that many species move into quiet, relatively clean creeks to spawn. During April and May of 1971,

Table 3.4

Fish Species Collected in the Ohio River and Tributaries, April - August, 1971[a]

SPECIES (Common Name)	SPECIES (Scientific Name)
Carp	Cyprinus carpio
Brown Bullhead	Ictalurus nebulosus
Bluegill	Lepomis macrochirus
Black Bullhead	Ictalurus melas
Yellow Bullhead	Ictalurus natalis
Silver Chub	Hybopsis storeriana
American Eel	Anguilla rostrata
Quillback Carpsucker	Carpiodes cyprinus
Sauger	Stizostedion canadense
Mooneye	Hiodon tergisus
Golden Redhorse	Moxostoma erythrurum
Channel Catfish	Ictalurus punctatus
Longnose Gar	Lepisosteus osseus
White Crappie	Pomoxis annularis
White Bass	Roccus chrysops
Gizzard Shad	Dorosoma cepedianum
Warmouth	Chaenobryttus gulosus
Rockbass	Ambloplites rupestris
Spotted Sucker	Minytrema melanops
Largemouth Bass	Micropterus salmoides
Spotted Bass	Micropterus punctulatus
Smallmouth Buffalofish	Ictiobus bubalus
Drum	Aplodinotus grunniens
Emerald Shiner	Notropis atherinoides
Bluntnose Minnow	Pimephales notatus
Striped Shiner	Notropis chrysocephalus
Sand Shiner	Notropis stramineus
Carpsucker	Carpiodes carpio
Smallmouth Bass	Micropterus dolomieui
Spotfin Shiner	Notropis spilopterus
Ghost Shiner	Notropis buchanani
White Sucker	Catostomus commersoni
Rainbow Darter	Etheostoma caeruleum
Blacknose Dace	Rhinichthyes atratulus
Mottled Sculpin	Cottus bairdi
Longnose Dace	Rhinichthyes cataractae
Fantail Darter	Etheostoma flabellare
Silverjaw Minnow	Ericymba buccata
Creek Chub	Semotilus atromaculatus
Stoneroller	Campostoma anomalum
Yellow Perch	Perca flavescens
Trout Perch	Percopsis omiscomaycus
Goldfish	Carassius auratus
White Catfish	Ictalurus catus
Redear Sunfish	Lepomis microlophus
Orangespotted Sunfish	Lepomis humilis
Golden Shiner	Notemigonus crysoleucas

[a]WAPORA, Inc. The effect of temperature on aquatic life in the Ohio River-Final Report. July 1970-September, 1971.

investigations into the spawning habits of fish in the Ohio River were undertaken in the vicinities of four power plants situated at RM 54.4, 260, 452, and 616 respectively. No successful spawning was observed in the river's main stem within several miles of the stations. It was suggested that sauger and walleye, which deposit their eggs at random in shallow water and therefore expected to spawn successfully in the Ohio, were prevented from spawning, or delayed in their spawning, by low water levels.[16] Numerous spawning populations of emerald shiners, bluntnose minnows, and sand shiners were observed in Island Creek below the Sammis Station (RM 54.4). Gravid white crappie were also observed at the mouth of Campaign Creek, two miles downstream from the Kyger Creek power plant (RM 260).[16]

The observations of fish spawning habits, which included those mentioned above, were limited but serve to point out the need for investigations into this major aspect of fish survival in the Ohio River. If it is found that spawning does not occur to any large extent in the river's main stem due to conditions brought about by the dams, siting of thermal and chemical discharges in tributary creeks or streams tributary to the Ohio River, may very well decimate present fish populations since it is likely that it is in these streams that much of the successful spawning occurs.

3.5 Electric Power Generation on the Ohio River

Low cost electric energy as a result of the abundance of coal in the region has been a major factor in industrial development throughout the Ohio River basin area. In the recent past, the demand for electric energy within the region has nearly doubled each decade.[2]

Trends indicate that nuclear power plants will furnish increasing shares of electrical energy in the future. Because of the lower efficiency inherent in nuclear power plants and the tendency to build larger plants than were built in the past, serious waste heat pollution problems are a potential threat to the Ohio River. However, if the power companies continue to build closed-cycle plants, the potential thermal load may be reduced somewhat as older "once through" plants are retired.

Table 3.5 shows the installed generating capacity of each steam electric power plant, greater than 50 megawatts, on the Ohio River in the years 1963, 1964, 1969, 1970, and 1971. Between 1963 and 1971, the installed generating capacity increased from over 13,500 MW to about 22,100 MW or 63 percent. Table 3.6 shows the planned generating capacity, by plant, for the years 1975, 1977, and 1983. Figure 3.3 gives a graphical portrayal of the total electrical generating capacity on the Ohio for the years tabulated in the two tables.

Table 3.5

Ohio River Steam-Electric Power Generating Plants
1963 - 1971

Mile Point	Station	Installed Generating Capacity (MW)					
		1963	1964	1969	1970	1971	Notes
2.3	J. H. REED	180	180	180	180	180	Standby 1973
15.6	F. PHILLIPS	315	387.8	417	417	411.2	
33.8	SHIPPINGPORT	100	100	90	90	100	
55.0	W. H. SAMMIS	740	740	1680	1680	2303.5	
59.1	TORONTO	315.8	315.8	316	316	175.8	
74.5	TIDD	222.2	222.2	222	222	226.3	
75.0	CARDINAL	–	–	1180	1180	1230.5	
79.5	WINDSOR	300	300	300	300	300	Retired Oct 73
101.9	MITCHELL	–	–	–	–	1632.6	
102.5	R. E. BURGER	544	544	544	544	544	
160.5	WILLOW ISLAND	215	215	215	215	215	
241.0	PHILIP SPORN	1060	1060	1060	1060	1105.5	
260.2	KYGER CREEK	1086.3	1086.3	1086.3	1086.3	1086.3	
405.7	J. M. STUART	–	–	–	–	1220.4	
453.3	W. C. BECKJORD	760.5	760.5	1221	1221	1220.3	
471.4	WEST END	224.3	219.3	219	219	219.3	
490.3	MIAMI FORT	539.2	519.2	519	519	393.2	
494.5	TANNER CREEK	518.0	1098	1098	1098	1100.3	
558.5	CLIFTY CREEK	1304	1303.6	1304	1304	1303.6	
604.0	PADDY'S RUN	337.5	337.5	338	338	337.5	
607.0	CANAL	50	50	50	50	50	Standby 1972
616.6	CANE RUN	535.3	535.3	1017	1017	1016.7	
618.0	GALLAGER	660	600	600	600	637	
728.0	COLEMAN	–	–	–	340	340	
752.8	OWENSBORO MUN #1	52.5	52.5	52.5	52.5	52.5	
755.3	ELMER SMITH	–	–	150	150	150	
773.0	WARRICK #1,2,3	125	432	432	432	432	
773.0	WARRICK #4	–	–	380	380	300	
773.8	CULLEY	50	40	136	136	149.7	
793.5	OHIO RIVER	121.5	112.5	112	112	121.5	
803.6	HENDERSON	24.0	24.0	24.0	50.6	50.6	
946.0	SHAWNEE	1500	1500	1750	1750	1750	
958.0	JOPPA	1100.3	1100.3	1100	1100	1100.3	

Sources of Data:

1971 figures: National Coal Association, Steam-Electric Plant Factors - 1972 Edition, December 1972.

1964, 1969, 1970 figures: Federal Power Commission

1963 figures: Ohio River Basin Survey Coordinating Committee, Ohio River Basin Comprehensive Survey, Volume X, Appendix 1, Electric Power, December 1968.

Table 3.6

Ohio River Steam-Electric Power Generating Plants
1975 - 1983

Mile Point	Station	Installed Generating Capacity (MW)		
		1975	1977	1983
2.3	J. H. REED	180	180	180
15.6	F. PHILLIPS	411.2	411.2	411.2
33.5	BRUCE MANSFIELD	825	1650	1650
33.8	SHIPPINGPORT	100	100	100
34.5	BEAVER VALLEY	856	856	1712
55.0	W. H. SAMMIS	2303.5	2303.5	2303.5
59.1	TORONTO	175.8	175.8	175.8
74.5	TIDD	226.3	226.3	0
75.0	CARDINAL	1230.5	1845.5	1845.5
101.9	MITCHELL	1632.6	1632.6	1632.6
102.5	R. E. BURGER	544	544	544
111.1	KAMMER	712.5	712.5	712.5
160.3	PLEASANTS	—	825	1650
160.5	WILLOW ISLAND	215	215	515
241	PHILIP SPORN	1105.5	1105.5	1105.5
258	GAVIN	1300	2600	2600
260.2	KYGER CREEK	1086.3	1086.3	1086.3
405.7	J. M. STUART	2400	2400	2400
414	CHARLESTON BOTTOMS	—	300	300
451	ZIMMER	—	—	2028
453.3	W. C. BECKJORD	1220.3	1220.3	1220.3
471.4	WEST END	219.3	219.3	219.3
490.3	MIAMI FORT	893.3	1393.3	1393.3
494.5	TANNER CREEK	1100.3	1100.3	1100.3
536	GHENT	559.9	1113.8	1113.8
558.5	CLIFTY CREEK	1303.6	1303.6	1303.6
600.6	MILL CREEK	321.1	746.1	1171.1
604.0	PADDY'S RUN	337.5	337.5	337.5
616.6	CANE RUN	1016.7	1016.7	1016.7
618	GALLAGER	637	637	637
728	COLEMAN	340	340	340
752.8	OWENSBORO MUN #1	52.5	52.5	52.5
755.3	ELMER SMITH	415	415	415
773.0	WARRICK #1,2,3	432	432	432
773.0	WARRICK #4	300	300	300
773.8	CULLEY	149.7	149.7	149.7
793.5	OHIO RIVER	121.5	121.5	121.5
803.6	HENDERSON	225.2	225.2	225.2
946.0	SHAWNEE	1750	1750	1750
958.0	JOPPA	1100.3	1100.3	1100.3

Source: Federal Power Commission

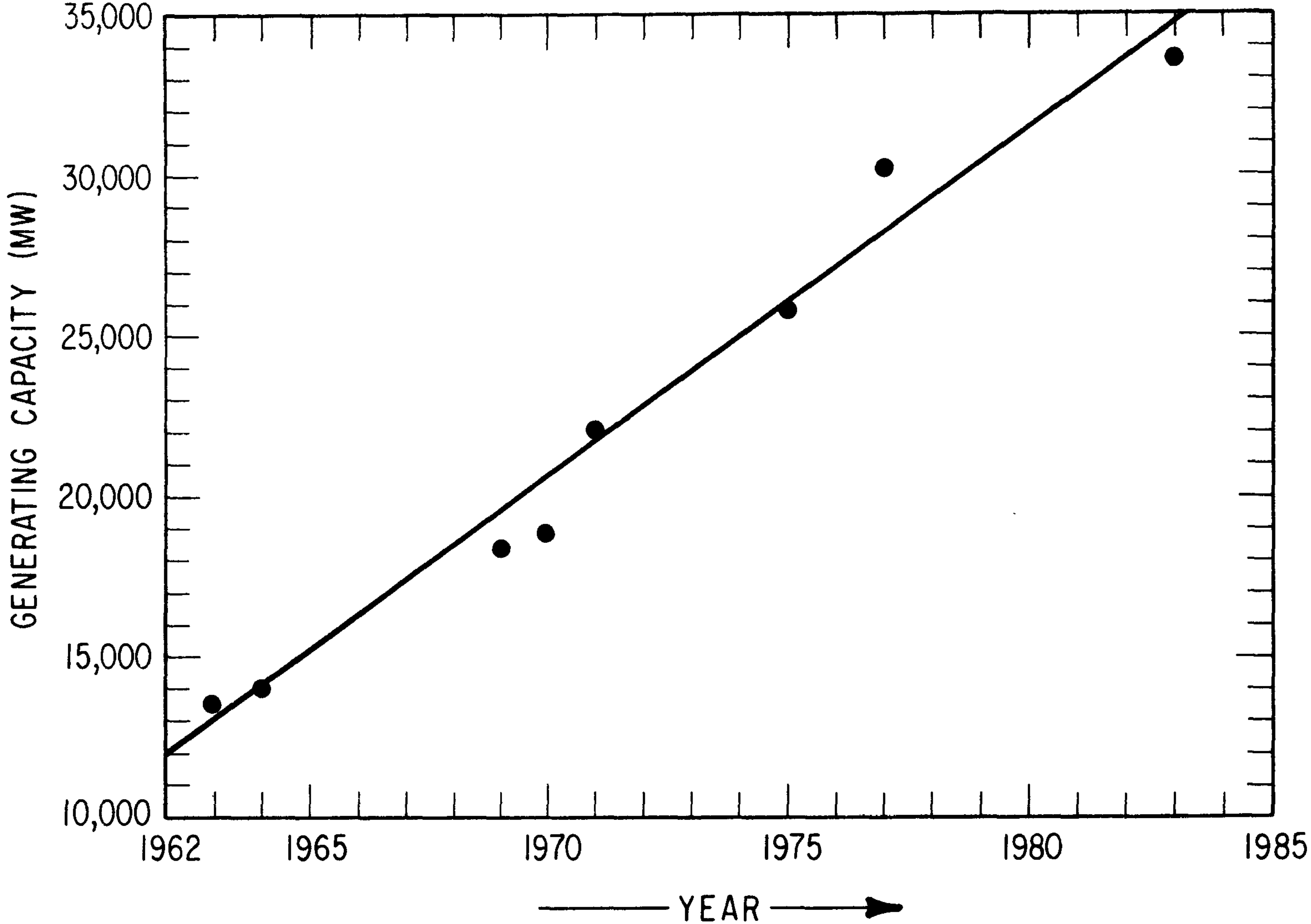

Figure 3.3
Total Steam-Electric Generating Capacity on the Ohio River

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4. BIOLOGICAL ASPECTS OF COOLING WATER USE

4.1 Thermal Effects

4.1.1 General Review

The effects of a thermal discharge on the biota of a receiving body of water will depend on the temperature of the receiving water, the temperature difference (Δt) between the receiving water and the discharge, and the particular organism and stage of its life cycle, among other physical, chemical, and biological factors. The effects can be directly lethal or sublethal. These are discussed briefly below.

a. Directly Lethal Effects

The lethal effects of excess heat and sudden changes in water temperature are gross effects which can often be readily observed. Such effects, when they occur, are normally confined to a relatively small volume of the receiving water, i.e., immediately adjacent to the outfall. The magnitude of the effect will depend on the particular group of organisms under consideration.

(i). Phytoplankton

It is not likely that phytoplankton carried through a thermal plume will be killed, unless temperatures exceed about 36°C (97°F). Temperatures found to be lethal to algae were 37-38°C (98-100°F) for large diatoms and about 44°C (111°F) for green algae. Freshwater algae are often able to endure temperatures which are adverse for growth by forming resting stages. After temperatures return to normal, the algae recover.[1]

(ii). Zooplankton

Passage of zooplankton through a thermal plume at temperatures greater than about 5°F above ambient may be lethal, particularly if the ambient temperature is high. (Upper temperature tolerance limits for several species of cyclops are 30-38.5°C (86-101°F), 31.5-40°C (89-104°F) for certain protozoans, and 30 C (86°F) for Daphnia pulex.[118] Temperature tolerance limits seem to depend, in large part, on the acclimation temperature of the organism, except in cases where the ambient temperature is close to the upper temperature tolerance limit.[74]) For certain species that reproduce throughout the year, populations are expected to recover downstream. Amphipods and euphausiids which have long generation times and reproduce only one season a year, may have limited capacity for population recovery.[2]

(iii). Benthos

Most benthic organisms, being relatively immobile, cannot avoid lethal temperatures. Certain species, however, appear to tolerate relatively high temperatures. For example, in an Alabama river where bottom temperatures can reach 90°F (about 32°C), there was a diverse fauna which included mosquito larvae, midge larvae, mayfly, dragonfly, and damselfly nymphs, fingernail clams, snails, water striders, water bugs, and water scorpions.[3] During the winter, an increase in numbers of caddisfly larvae in the heated zone of a thermal effluent was reported.[6] Above 90°F in the Delaware River, however, an extensive loss in numbers, diversity, and biomass of benthos occurred in a heated area below a power plant discharge.[4]

The benthos-poor conditions sometimes associated with heated waters are in large part due to the high BOD (biochemical oxygen demand) and low dissolved oxygen characteristics of the water into which thermal discharges are made. For example, the elimination of fingernail clams and other shellfish from the Illinois River, a warmwater stream, has been attributed to the high BOD waste discharges from the Chicago metropolitan area.[5]

With the exception of a sinking plume which may occur under winter conditions in a large lake, heated water usually floats. This will tend to decrease the number of benthos subjected to lethal temperatures. Of more significance, is the scouring action of the discharge, particularly a high-velocity jet close to the bottom. For example, the abundance of benthic invertebrates around four power plants on Lake Michigan was found to be slightly decreased close to the discharge structures. It was concluded that this was due to current scour rather than a purely thermal effect.[7]

(iv). Fish

The temperature extremes that will be directly lethal to a fish will depend, in general, on the species of the fish, its acclimation temperature, the stage of its life cycle, and time of exposure.

Fish, being mobile organisms, ordinarily avoid lethal temperatures. Adults can apparently sense a thermal gradient and if free to move, will seek preferred temperatures. Thermal death at heated discharges has been known to occur when the fish were trapped in the effluent canals[8,9] or subjected to a sudden release of hot water.[10] Juveniles of some species, however, may not avoid lethal temperatures. For example, a non-avoidance response was exhibited by young white perch and striped bass.[11] Mortality of young fish in the outfall area of the heated discharge may therefore occur if water currents do not carry them away. Breakdown of the avoidance response in adults can also occur. For example, summer water temperatures above 30.5°C (87°F) were actively avoided by 11 species of estuarine fishes. Short exposures to water at 34.4°C (94°F) resulted in breakdown of the avoidance response.[12] This phenomenon will ultimately result in death of the fish.

A thermal discharge into a spawning area may be directly lethal to most eggs and developing embryos if they are immersed in water at temperatures a few degrees greater than normal ambient fluctuations, and to adults entering the area to spawn despite elevated temperatures.[13]

A phenomenon sometimes observed is the apparent attraction of fish to heated discharges, particularly in the winter. This may be due to a preference for warmer water and/or to a better food supply (e.g., periphyton and caddisfly larvae) in the effluent area than in the colder ambient river.

In winter, decreases in temperature at the outfall of 8 to 16°C (15 to 30°F) in a matter of hours following shutdown will not be uncommon for a once-through cooling system on any body of water. Fish subjected to this cold shock would be severely stressed and death will very likely follow. Large fish kills in winter at the Oyster Creek power station, for example, have been reported following shutdown.[14] In late January, 1971, a kill of about 7,500 fish, primarily gizzard shad, occurred in Little Three Mile Creek, a tributary of the Ohio River. Mortality was attributed to a drop in water temperature within a 13 1/2-hour period, due to shutdown of the Stuart Plant.[15]

The travel time of the circulating water in a cooling tower is on the order of half an hour to an hour. This is insufficient time for gradual cooling of the blowdown, but because of the usually small volume of effluent involved, mixing zones are relatively small compared to a once-through system, and the adverse effects of cold shock are correspondingly reduced. Travel time of the circulating water in a cooling lake can be on the order of days before discharge to the receiving water, and cold shock in such a case should be virtually non-existent.

b. Sublethal Effects

Sublethal temperature increases brought about by a general warming of a large area and volume of the body of water can have a greater overall environmental impact than lethal temperatures. The effects of sublethal increases in temperature are often difficult, if not impossible, to detect. Such changes are related to the effect of temperature on metabolic and physiological processes of aquatic organisms.

(i). Phytoplankton and Periphyton

A common concern related to thermal discharges into natural bodies of water is that shifts in algal species from the more desirable diatoms to the less desirable blue green algae may occur. In oligotrophic waters, diatoms usually predominate the phytoplankton community at water temperatures below 30°C (86°F), green algae predominate between 30-35°C (86-94°F), and blue green algae above 35°C (95°F).[1] The latter are considered undesirable because they are not generally utilized by herbivores, certain species have a capacity to fix nitrogen and thus accelerate the eutrophication of a water body, and blooms can result in taste and odor problems of the water. Experience at power plant thermal discharges has indicated that these shifts can occur in the periphyton growing in the discharge area,[9,16] but that they do not always occur.[9] Water quality appears to be a major factor in the occurrence of algal shifts in heated waters.

(ii). Zooplankton and Benthos

Most freshwater zooplankton and macroinvertebrates do not appear to be adversely affected by waters warmed to less than 3°F above ambient, unless the ambient temperature is at or close to the upper temperature tolerance limit of the organism. One area of possible concern is insect pre-emergence during the cold months. The rate of growth of aquatic insects is related to their ambient temperature. For example, it has been reported that a temperature increase of only 1°C (1.8°F) caused hydropsychid caddis flies to emerge 2 weeks earlier on the Columbia River downstream from the Hanford reactor than upstream.[17] In a laboratory study, 10 species of aquatic insects exhibited premature emergence when subjected to unseasonably high winter water temperatures. The same experiments also indicated that the time between emergence of males and females of some species was increased by increased water temperatures.[17] In northern latitudes, where air temperatures are near or below freezing for several months, adult insects which emerge earlier than normal may freeze to death or be inactivated such that mating is prevented. Mating would also be prevented if the emergence of one sex occurred much earlier than the emergence of the other.[17] In areas where air temperatures remain fairly high throughout the year, insect pre-emergence may be unimportant.

(iii). Fish

Distribution --- Water temperature is a major factor in the geographical distribution of fish. Likewise, changes in water temperatures within a given body of water can lead to a redistribution of fish in localized areas. For example, in the Wabash River in Indiana, the effluent zone of a power plant harbored only about 50% of the species collected either above the plant or farther downstream. Most species which were absent during the summer returned in the fall when temperatures were lower.[18] In a body of water in which the collective effects of a number of thermal discharges is sufficient to raise the ambient temperature of the entire water by several degrees, some species will eventually be eliminated from such waters, and high-temperature tolerant species will ultimately predominate. Sensitive areas are those waters in which particular fishes are at the southern fringes of their ranges. It is doubtful that any natural body of water will become devoid of fish as a result of power plant thermal discharges alone. However, some of the fish species considered desirable by western man prefer cooler water.

Migration --- Movements to and from the sea and fresh water are an essential part of the life cycles of anadromous and catadromous fish species, and temperature is apparently involved in the stimulation and direction of migration.

Temperate stream fishes also migrate up and downstream. In New Hope Creek, North Carolina, such movement was studied in 1968-70. Most of 27 species had a consistent pattern of larger fish moving upstream and smaller fish moving downstream. Both upstream and downstream movements were greatest in the spring.[19] The necessity for restriction of a thermal plume to a minor width, area, and volume of a waterway is obvious. The extent of such restriction should depend on the specific site chosen, and on the habits of the fish using the particular waterway.

In the Ohio River, the greatest barriers to fish migrations are the dams; fish migration likely occurs into streams and creeks for spawning.

Reproduction --- Gonad development and spawning are highly temperature-dependent, but because this dependence is species specific,[12] it is difficult to make a definitive statement of an "adverse" temperature. For example, walleye require temperatures below 10°C (50°F) to spawn.[20] Carp and largemouth bass spawn at 15-25°C (59-77°F), smallmouth bass at 12-16°C (53-61°F), yellow perch at 10-15°C (50-59°F).[20]

Premature spawning of any fish species as a result of heated water discharges may put the larval development out of phase with the development of the normal food supply. The percent survival of the young may thus be decreased due to lack of proper food if an adequate variety of other food is not available. By this mechanism, water temperatures even slightly warmer than ambient in a spawning area may eventually lead to elimination of a species. Often, more than one species may use the same nesting site. For example, spring spawning suckers may use the same sites as fall-spawning brook trout.[21] This aspect of a thermal discharge could be thus of greater concern than the temperature of the hottest part of the discharge plume.

Fish metabolism, growth, and physiology --- Within limits, the feeding rates of fishes, food transport, absorption, and digestion apparently increase with increases in temperature.[12] It can be suggested, therefore, that when food is not limiting, increased water temperatures could result in an increased growth of fish. This increase in growth rate, however, may not always be beneficial. For example, Cyprinodon, a eury-thermal fish, showed a better initial growth rate at higher temperatures (to 30°C or 86°F), but the rates were not maintained later in life. The slower-growing fishes at lower temperatures grew larger and lived longer.[22] At a power plant on the Connecticut River, brown bullhead and white catfish resident in the thermal plume in winter, showed a decline in weight-length ratios (condition) despite an abundance of benthic invertebrates. (It was not established, however, that these organisms were desired as food by the fish). Channel catfish in the same study showed no decline in condition.[9]

Vulnerability of fish fry to predation --- Laboratory studies with rainbow trout and chinook salmon indicated that thermally shocked juveniles were selectively preyed upon by larger fishes. The relative vulnerability to predation increased with duration of sublethal exposure to lethal temperatures.[23] Similar results were obtained in laboratory studies of yearling coho salmon predation rates on sockeye salmon fry; predation rates increased with increasing acclimation temperature.[24]

Although laboratory studies may have limited application to field conditions, the potential for decreased survival of migrating or resident fry encountering a warm plume can not be discounted. It is thus necessary to stress the importance of maintaining a major portion of a river or estuary free of temperature increases above normal variations.

Incidence of fish diseases --- Reports have been cited[22,12] that implicate elevated water temperatures in increased rates of infestation by fish diseases and parasites. For example, near obliteration of a run of sockeye salmon in the Columbia River in 1941 was attributed to the combined effects of high temperature and bacterial infection. Columnaris disease has increased in the same river, reportedly due to river warming. Higher water temperatures also apparently increased the effect of kidney disease, vibrio disease and columnaris in young hatchery-reared salmonids. No relation has been found, however, between the occurrence of columnaris disease and power plant thermal effluents, as far as is known.

c. Other Temperature-Related Effects

In addition to the physiological effects discussed above, there are other temperature-related conditions that indirectly affect fish, including several discussed below.

(i). Gas Bubble "Disease" of Fish

The formation of gas bubbles in the blood of fish can occur when water becomes supersaturated with gases, usually nitrogen. This super saturation sometimes occurs when water that is close to air saturation is heated or when water cascades over a dam. If the degree of supersaturation is great enough, the fish may show external symptoms such as "pop-eye," caused by bubbles in the tissues in or behind the eye. Incidence of this "disease" in about a dozen species of warmwater fish in the heated effluent of a steam generating station has been reported.[25] This potential effect can be largely avoided by preventing fish access to the discharge.

(ii). Chemical Toxicity Synergism

Many chemicals, including pesticides, appear to affect aquatic life more acutely at higher temperatures,[22,26,27] either by increasing uptake, by lowering resistance to toxins, or by lowering tolerance to low oxygen levels in the water. These effects may become evident when the water receives run-off from agricultural areas or discharges from industries. Limitations on the use of pesticides and on the discharges of chemicals, can help to prevent these adverse effects.

(iii). Dissolved Oxygen

Depletion of the oxygen content of a receiving water to levels adverse for aquatic life is not expected to occur as a result of a thermal discharge alone. In some cases, the aerating action of cooling towers or sprays can, in fact, increase the dissolved oxygen concentrations in the discharge compared with the intake concentrations. Loss of dissolved oxygen occurs if water that is saturated or supersaturated with oxygen is heated. Even at a temperature of 40°C (104°F) the solubility of oxygen in water is about 6.5 mg/liter,[28] which should pose no threat to aquatic life. However, in a river that receives high BOD waste from other sources, or in impoundments with large algal blooms, low dissolved oxygen levels (less than 3 mg/liter) may occur, particularly at night due to phytoplankton respiration and the absence of photosynthesis. In these cases, elevated temperatures, which may increase a fish's metabolic rates and hence its oxygen requirement, can aggravate the stressed condition brought about by the low ambient dissolved oxygen.

4.1.2. Ohio River Studies

To date, there are few studies on the effects of thermal discharges on the biota of the Ohio River main stem. ORSANCO maintains temperature-monitoring stations along the river, but correlations with distribution and behavior of the aquatic organisms have not been undertaken on a river-wide basis. Isolated studies at individual power plants and miscellaneous studies by academic institutions have been carried out. These are summarized and discussed below.

a. Plankton

On the Ohio River near the Beckjord power plant (RM 451.0-452.0) studies were carried out in 1971 and 1972 to determine effects of the heated discharge on algae and zooplankton.[29,30] The plant uses a once-through cooling system, and weekly temperature measurements from June to August, 1971, indicated discharge temperatures of 84-91.5°F (Δt = 7 to 11.5°F), and in July to August, 1972, temperatures of 84-101°F (Δt = 9-23°F). The 1971 study concluded that there was no effect of the heated discharge on dissolved oxygen or phytoplankton in the river. In the 1972 study, decreases in zooplankton numbers, and phytoplankton populations and photosynthetic rates in the discharge area were observed. Neither of the reports indicated whether samplings were replicated or what measure of significance had been applied to the data. Plankton numbers can vary considerably under the conditions of variable flows that can occur in the river due to the lock and dam system. It was also not clear from the reports whether distinctions could be made between organisms affected in the river and those that had passed through the plant's condensers.

A rather extensive study was carried out by WAPORA in 1970 and 1971[34] at four power plants on the Ohio River, namely, W. H. Sammis (RM 54.4), Kyger Creek (RM 260.0), W. C. Beckjord (RM 452.9), and Cane Run (RM 616.7). All plants have once-through cooling systems. The Sammis and Beckjord plants discharge at the river bottom, while Kyger Creek and Cane Run have surface discharges. The investigators concluded that the heat added to the river by the four power plants had no measureable effect on phytoplankton populations or their composition (diatoms vs. green algae). Variations in phytoplankton populations were within the range of experimental error. It was observed that the normal dominance of diatoms was reversed (green algae became dominant) in the late summer of 1970 and 1971 at the Sammis station, but since the reversal occurred above the plant as well as below, it was attributed to some factor other than the thermal discharge. The numbers of diatoms remained relatively constant, but there was an upsurge in green algal numbers.

In 1972, the studies were essentially repeated, except that the Tanners Creek Station (RM 494) was added and the Cane Run station deleted from the study. The Tanners Creek plant has a once-through cooling system, with discharge close to the river bottom. Plankton populations were similar to those found in the 1970-71 study; additionally, two shifts in dominance from diatoms to green algae occurred at the Sammis station, and from greens to diatoms to greens at the Beckjord station. It was not possible to relate these shifts to power plant operation due to the variability and "patchiness" of phytoplankton populations.[35]

Zooplankton populations (rotifers, copepods, cladocerans, and nauplii) did not appear to be affected by the thermal discharges in these studies. Differences in total counts above and below the discharges appeared to be due to random fluctuations. The largest differences in population numbers occurred between seasons, i.e., numbers were lower in spring and fall than in summer.

b. Macroinvertebrates

In the WAPORA study mentioned above, sampling the benthic community at the power stations was carried out in 1970 and 1971 using a Ponar dredge. This method was later (1971-72) supplanted by the use of artificial substrates (fibrous plastic mats) anchored near the river bottom. Results indicated that other than oligochaete worms, there was little bottom fauna in the Ohio River at the sampling sites. Rocky bottoms in particular were "depauperate," and only the mud substrates contained organisms. Comparison of benthos up and downstream of the plants' discharges was difficult, since substrates were not usually the same. Results were therefore inconclusive. Comparisons of organisms on artificial substrates at the Sammis plant indicated a reduction in total numbers of individuals (diptera and ephemeroptera) in the discharge compared to ambient, although these were not totally eliminated from the discharge area. At the Beckjord and Kyger Creek plants, organism group diversity and total numbers of individuals increased in the discharge samples, as a result of a "tremendous increase" in the caddisfly (*Hydropsyche* and *Cheumatopsyche*) populations. At the Cane Run Station, organism group diversity[35] and total individuals were apparently unchanged by the thermal effluent. In 1972, due to flood conditions, artificial substrates were not recovered from any of the stations except from the Tanners Creek plant. At the latter, greater numbers of caddisfly larvae were observed at the discharge than either above or below it. The study points out that artificial substrates obtain a population of organisms distinct from that obtained in dredge samples, the former likely originating as drift fauna from streams tributary to the Ohio.

Examination of thermal effects on macroinvertebrates in waters tributary to the Ohio River is important, since these waters are the likely sources of drift organisms in the Ohio River mainstem.

At Petersburg, Indiana, in 1969 and 1970, modified Hester-Dendy samplers were submerged to depths of 1 foot in the White River, at various locations up and downstream of a thermal discharge from an electric generating station.[32] The river bottom in the area studied was described as rather soft, with clean shifting sand along the shallow stretches. The deeper holes tended to have bottoms of silt and "organic ooze". The major groups of invertebrates collected were chironomids, caddisworms, and mayfly nymphs. Numbers of macroinvertebrates were greater in 1970 than in 1969, a result attributed to differences in river flow and siltation. In the 10-acre area receiving the heated discharge, the chironomid larvae _Glyptotendipes lobiferus_ and the caddisworm _Psychomyia_ were more abundant than in upstream sampling locations. Another caddisworm, _Cheumatopsyche_ sp. was increased in numbers by an average temperature elevation of 5°F, but was depressed by 9°F. Numbers of mayflies were depressed at an average elevation of 5°F, with the possible exception of _Stenomema_ sp. and _Tricorythodes_ sp., which appeared to be unaffected. Continuous temperature recordings were not made; the maximum ambient temperature measured weekly was 84°F in July, 1969; the maximum discharge temperature was 103°F, and at 600 feet downstream of the outfall, water temperature was 90°F. The corresponding temperatures in August, 1970, were 86°F, 107°F, and 90°F

(1,900 feet downstream of the outfall), respectively.[32]

At the Cayuga Generating Station on the Wabash River in Indiana, effects of a thermal discharge on macroinvertebrates were studied in the summers of 1970, 1971 and 1972.[31] Modified Hester-Dendy samplers (masonite) were suspended about 1 foot below the water surface, at eight zones selected to represent distinct types of habitat. (Since the samplers were suspended in the water, only drift organisms were collected).

In 1971, the densities of Trichoptera were lower in the warmer segments of the river; chironomid densities were about the same, regardless of temperature, in samples collected for 4 weeks, and decreased with temperature in samples collected for 6 weeks. Temperatures were reported to range from 24 to about 32°C. Species of Ephemeroptera (mayfly nymphs) did not respond similarly, e.g., Stenonema increased in the zones where temperature increased, while Isonychia remained constant. An "extremely low flow" period which occurred in the summer of 1971, may have confounded the effects of temperature since, as was pointed out by the author, rapid flow of water over the gills of Ephemeroptera is necessary to obtain oxygen. Densities of Stenonema, Baetis, and Isonychia were "abnormally low" in samples located in low-flow reaches of the river. Tricorythodes was apparently unaffected by the low flows, and numbers increased with increasing temperature in the range 24 to 32°C. In 1972, numbers of Trichopteran larvae increased in zones with increased temperatures, within the range 20 to 30°C, in June and August, and decreased with increasing temperatures in July. (The apparently higher temperatures observed in the summer of 1971 compared to 1972, despite the addition of a second 500-Mw plant in May of 1972, could perhaps be attributed to the low flow that occurred in the summer of 1971). Contradictory responses were also observed in numbers of Isonychia, whose densities increased in the warmer zones in June and August but decreased in July.[31] These results are difficult to relate to temperature unless continuous temperature data are available.

The lack of temperature data is a primary deficiency in most studies of thermal effects on aquatic biota. At best, instantaneous temperature measurements are made on particular sampling dates, or discharge temperatures are obtained from the utility and plume temperature data are calculated or inferred from that information, taking flow rates into account. Continuous temperature measurements within the area of interest are essential, since factors such as flow rates, and meteorological conditions can change continuously, irregularly, and unpredictably, in addition to changes that occur in power plant loads. The temperatures that are measured at particular sampling locations on particular dates at particular times may not necessarily be representative of the temperatures prevailing during the entire period of study, nor even a major portion of it. Such information is particularly essential to the study of macroinvertebrates and periphyton.

On Little-Three-Mile Creek (LTMC), which joins the Ohio River near Aberdeen, Ohio, the effects of a thermal discharge from the J. M. Stuart Electrical Generating Station on aquatic biota were investigated in 1970 and 1971.[33] The station draws water from the Ohio River and discharges the heated effluent into LTMC, about 1.57 km from its mouth. A weir at the mouth of the creek appears to accelerate mixing of the heated discharge with the Ohio River. Drift invertebrates of LTMC were sampled in July, 1970, with Hester-Dendy samplers, while bottom fauna in four adjacent zones in the Ohio River mainstem were taken with a Petersen dredge in August, 1971. Drift samples which had not been subjected to the heated discharge from the station contained four orders and six genera of insects, of which chironomids comprised 81%. In the group of drift samples subjected to periodic temperature elevations due to the discharge, four orders and six genera were again present, but were dominated by trichopterans (52%). A dense algal covering was also found on the samplers. In the Ohio River mainstem, the dredge samples were dominated by oligochaetes, probably because the bottom substrate was mainly mud and detritus. Samples from Kennedy Creek, a backwater area across the Ohio River from LTMC, contained six times as many oligochaetes as did the river samples. Kennedy Creek does not receive a thermal discharge and was used in the study as a control area. The authors concluded that "the paucity of organisms in LTMC was probably the result of high temperatures". No continuous temperature measurements in the LTMC were made, but from temperatures measured daily at the condenser exit of the station, and from other information obtained from the utility, it was concluded that an average temperature increase of 20^{o}F above ambient existed in LTMC from the outfall to the weir throughout most of the study after October, 1970, when commercial operation began. Little cooling, up to a maximum of 4^{o}F, was observed in the mile between the outfall and the weir during the period of study.[33]

c. Fish

At the four power plants mentioned in (a) above, fish responses to the heated effluents were investigated. Sampling of fish populations in 1971 made use of gill nets, frame nets, and bag seines; the mesh sizes and net lengths selected depended on the species and size of fish expected. In 1972, electroshocking methods were used. Each method tends to sample particular species, i.e., electroshocking is more selective toward species near the surface or in shallower waters. (There are indications that fish can see and subsequently avoid electroshocking equipment, so that sampling at night or in highly turbid waters is more successful than daytime electrofishing in clear waters). Nets and traps are more selective for fish that move over a fairly large area of the water, and probably collect a higher percentage of bottom species.

In the summer of 1971, visual observations of young-of-the-year gizzard shad and emerald shiners indicated that current velocities at the discharge of the Beckjord and Kyger Creek plants prevented the fry from maintaining positions in the heated effluent. Adult shiners were observed to move into the heated effluent and discharge canal at Kyger Creek about the middle of June when temperatures in the discharge were 30.1°C (about 86°F). No mortalities were observed and captured specimens "revealed no physical damage or parasitic infestation and all fish appeared normal in appearance and condition."[34]

At the Beckjord plant, adult Notropis appeared to be more numerous in the heated effluent than elsewhere. It was estimated that the highest temperatures these fish were exposed to was approximately 32.5°C (about 90°F).

At Cane Run, no differences were apparent between the very few Notropis observed in the heated effluent and the ambient river. At the Sammis station, no attempt was made to compare abundance of Notropis in the ambient river and discharge due to the presence of the New Cumberland dam. Fish species caught in the discharge and in the ambient river are listed in Table 4.1. River fish which were not captured in the discharges were smallmouth buffalo, black bullhead, mooneye, golden redhorse, white bass, drum, and smallmouth bass. With the exception of the golden redhorse, the investigators did not consider the absence of these species from the discharge to be significant, considering catch records. Fish preferring the warmer water of the discharges during spring included carp

Table 4.1

Ambient Versus Discharge Fish Species
at Each Power Plant[a]

W. C. BECKJORD STATION		KYGER CREEK PLANT	
AMBIENT	DISCHARGE	AMBIENT	DISCHARGE
Species	Species	Species	Species
Sauger	Sauger	Carp	Spotted Sucker
Bluegill	Gizzard Shad	White Crappie	Carp
Mooneye	Channel Catfish	Channel Catfish	Channel Catfish
Golden Redhorse	Carp	Silver Chub	Spotted Bass
Channel Catfish	White Crappie	Brown Bullhead	Longnose Gar
Carpsucker	Bluegill	Goldfish	Gizzard Shad
Carp	Warmouth	Drum	White Crappie
Longnose Gar	Rockbass		Bluegill
White Crappie	Longnose Gar		Brown Bullhead
White Bass			
Gizzard Shad			

W. H. SAMMIS STATION		CANE RUN STATION	
ABOVE DAM	BELOW DAM	AMBIENT	DISCHARGE
Species	Species	Species	Species
Carp	Quillback Carpsucker	Silver Chub	Silver Chub
Brown Bullhead	Brown Bullhead	Channel Catfish	American Eel
Bluegill	White Crappie	Drum	Gizzard Shad
Black Bullhead	Carp		Carpsucker
Yellow Bullhead	Yellow Bullhead		Drum
	Channel Catfish		Channel Catfish
	Spotted Bass		
	Gizzard Shad		
	Bluegill		
	Yellow Perch		
	White Catfish		
	Redear Sunfish		
	Orangespotted Sunfish		

[a]WAPORA, Inc. The effect of temperature on aquatic life in the Ohio River - Final Report July 1970-September 1971.

and channel catfish. During warm summer weather, most species avoided the discharges except channel catfish, longnose gar, emerald shiners, and gizzard shad. From comparisons of gonad weight and body weight, the investigators concluded that the heated effluent either did not accelerate spawning, or fish residence time in the heated water was too short to cause an observable effect. No attempt was made, other than visual observations, to ascertain whether residence in the heated discharges had effects on fish condition (e.g., weight-length ratios) nor were there observations on the effects of rapid plant shutdown on fish resident in the discharge, which is presently a potential impact of major concern.

In the Wabash River, the distribution and abundance of fish populations near two electrical generating stations were studied during the summer and early fall from 1967 to 1972.[31] For purposes of the study, a segment of the river (about 3.47 km long) in the vicinity of the Wabash station was divided into three thermal zones, based on conditions found during the summer: a cool, upstream section, a short, hot section with temperatures 7 to 9°C (about 13 to 16°F) above ambient, and a long, downstream section usually 1 to 3°C (about 2 to 5°F) higher than ambient. Results of a variety of sampling methods indicated that the fish concentrated in areas of the river that were close to their optimum temperatures, and moved out of the area if temperatures exceeded a certain level. Based on his observations, Gammon [31] postulated thermal ranges for fish species common to the river (see Table 4.2). From results of electrofishing data, he also presented interesting graphs demonstrating the population response to temperature (see Figure 4.1). The number of species caught in the thermal zones decreased sharply above a temperature of about 31.5°C (88.7°F). The number of individuals caught was at maximum between 27 and 30°C (about 81

Table 4.2

Ranges of Temperature which Probably Include the Final Temperature Preferenda of Common Species in the Wabash River[a]

Common Name	Scientific Name	Optimum Temperature Range - °C
Carp	*Cyprinus carpio*	33.0 - 35.0
Longnose gar	*Lepisosteus osseus*	33.0 - 35.0
Shortnose gar	*Lepisosteus platostomus*	33.0 - 35.0
No. River carpsucker	*Carpiodes carpio*	31.5 - 34.5
Buffalofish	*Ictiobus* sp.	31.0 - 34.0
Flathead catfish	*Pylodictis olivaris*	31.5 - 33.5
Channel catfish	*Ictalurus punctatus*	30.0 - 32.0
Freshwater drum	*Aplodinotus grunniens*	29.0 - 31.0
Gizzard shad	*Dorosoma cepedianum*	28.5 - 31.0
Central Quillback	*Carpiodes cyprinus*	29.0 - 31.0
White crappie	*Pomoxis annularis*	27.0 - 31.0
Spotted bass	*Micropterus punctualatus*	28.0 - 30.0
White bass	*Morone chrysops*	28.0 - 29.5
Skipjack herring	*Alosa chrysochloris*	27.0 - 29.0
Sauger	*Stizostedion canadense*	27.0 - 29.0
Goldeye	*Hiodon alosoides*	27.5 - 29.0
Mooneye	*Hiodon tergisus*	27.5 - 29.0
Golden and Shorthead Redhorse	*Moxostoma erythrurum* & *M. breviceps*	26.0 - 27.5

[a]Gammon, J. R. The effect of thermal inputs on the populations of fish and macroinvertebrates in the Wabash River. Tech. Rept. No. 32. Purdue University Water Research Center (1973).

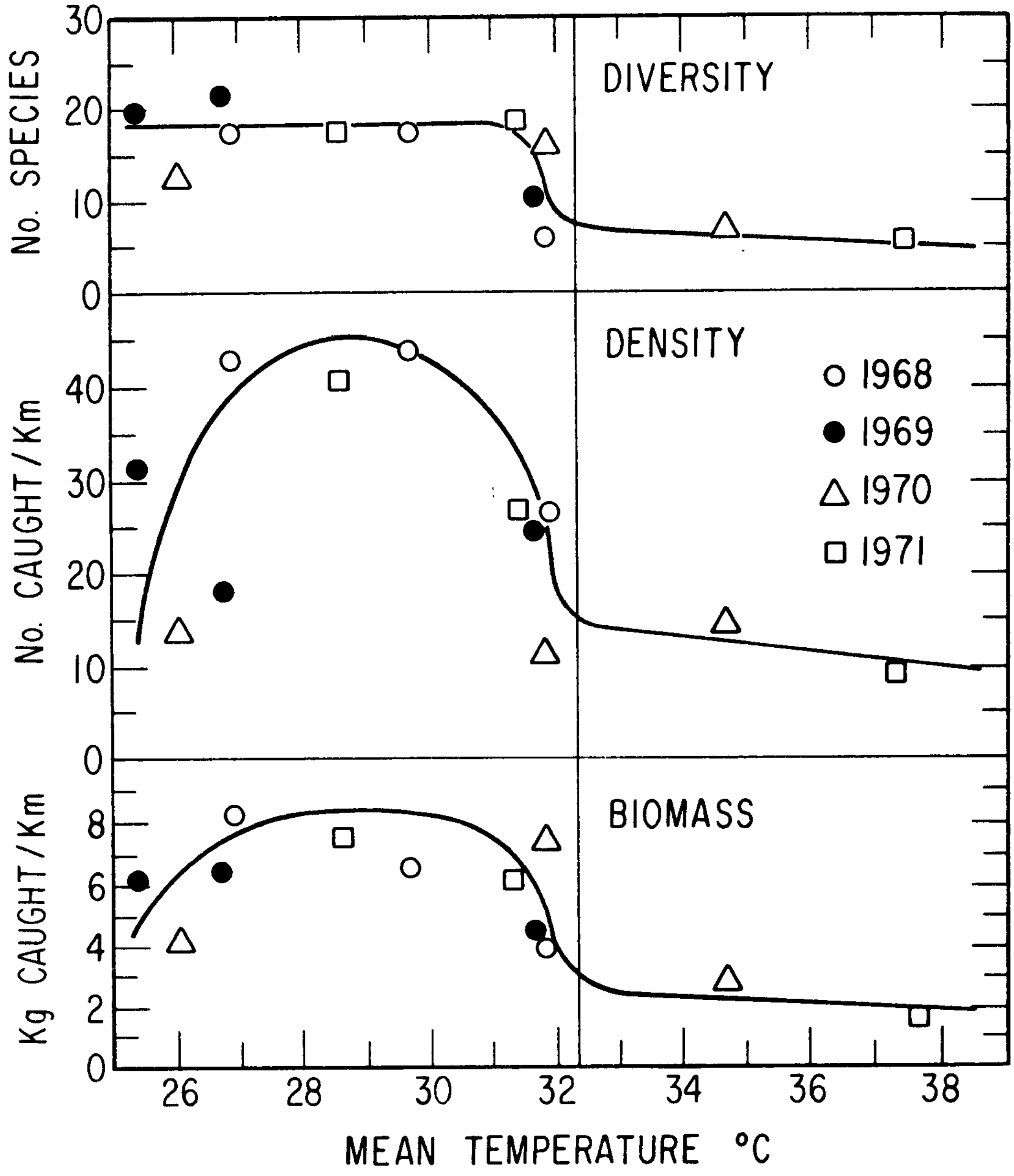

Figure 4.1

Diversity, Density, and Biomass of Fish in Three Thermal Zones of the Wabash Segment as Determined by D. C. Electrofishing. (The Vertical Line is the Current Thermal Maximum Allowed During Summer Months - 32.2°C. (90°F.))

° 1968; • 1969; + 1970; □ 1971.[a]

[a]Gammon, J. R. The effect of thermal inputs on the populations of fish and macroinvertebrates in the Wabash River. Tech. Rept. No. 32. Purdue University Water Research Center (1973).

to 86°F), and decreased markedly at temperatures above and below this range. Biomass decreased between 30 and 32°C (86 to 90°F) but the drop was less marked than the decrease in density at the same temperature because smaller species such as crappie, white and spotted bass, skipjack herring, goldeye, and mooneye moved out due to lower temperature preferenda, while larger species such as carp, gar, buffalofish, and catfish, which prefer higher temperatures, moved in. During cool summers, when normal river temperature was less than 25°C (77°F), most of the species preferred the warm segments of the river, while during hot spells, the fish moved completely out of the effluent stream to cooler segments of the river.[31]

At the Cayuga Generating Station, also on the Wabash River, a 5.2 km segment was subdivided into 8 subareas representing various habitats. Most fish were collected by electrofishing, although hoop and "D" nets were used in certain years. The density of most species populations in the Cayuga study was directly proportional to velocity of the current, except for a few species such as gizzard shad, white bass, and longnose gar which were more numerous in shallow, slow-moving areas. Of the species encountered, two groups appeared to be permanently affected by the thermal conditions, i.e., flathead catfish which responded to higher temperatures with enhanced reproductive success, and redhorse which appeared to be the most thermally sensitive species. It was suggested[31] that the population density of this latter species could be reduced as a result of higher temperatures. Long-term changes in the density of other species were not detected.

In the vicinity of a heated discharge into the White River in Indiana, fish were collected by electroshocking methods in the summer of 1969 and 1970.[32] It was estimated that there were 20% fewer centrarchids (bass, sunfish, crappie) per acre in the mixing zone than upstream. Estimated populations in 1970 showed no decrease in numbers of centrarchids from those of 1969, despite operation of an additional generator. Based on population estimates, catch statistics, and sighting of young-of-year fishes, the investigators concluded that fish reproduction in the area was "as successful" as in the years immediately prior to plant operation.[32] No increased occurrence of fish diseases was indicated as a result of the heated effluent.

Near Aberdeen, Ohio, the J. M. Stuart Electrical Generating Station pumps cooling water from the Ohio River and discharges the heated water to Little-Three-Mile Creek (LTMC). As was mentioned previously, the discharge flows into the Ohio River through a weir at the mouth of the creek.[33] In 1970 and 1971, sampling of fish in LTMC by several methods indicated that prior to startup of the station, a variety of fish, mainly young-of-year gizzard shad, preferred this stream to normal Ohio River conditions, apparently because of the increased current in the creek brought about by unheated water being pumped through the Station and into the creek. After startup, sauger, bluegill sunfish, and white crappie were apparently forced out of LTMC by elevated temperatures. Flathead catfish, spotted bass, white bass, and longear sunfish moved from the Ohio into LTMC in the fall of 1970 when only one unit was operating. In the fall of 1971 with two units operating and twice the volume of water flowing through the weir at the mouth of LTMC, the movement of some species was apparently blocked by the higher exit velocity. Channel catfish and carp moved in and out of LTMC in response to temperature levels; a few were killed when trapped in an isolated pocket of cooler water.

A kill of about 7,500 fish, mainly 1970 year-class gizzard shad, occurred in January, 1971, probably the result of rapid decrease in temperature from 25.6°C (78°F) to 8.9°C (48°F).[33]

4.2 Entrainment and Condenser Passage Effects

4.2.1 General Review

a. Introduction

Water taken into an installation for cooling purposes must be cleaned of debris that can clog condenser tubes or damage pumps. It is common practice at water intakes to construct a grill or bar rack to prevent large material such as floating logs from entering the intake. A second screening device is used to remove smaller debris. Organisms, mostly fish, which are too large to pass through these devices can be drawn against them due to the intake flow velocity and killed by starvation, exhaustion, or asphyxiation. The numbers and species of fish that are killed by impingement will depend on the intake velocities, the swimming speeds of the various individuals, their size, and their physical condition. These numbers can be unacceptably large from any reasonable point of view, or small enough to have no effect on a given population. Whatever the case, any loss of fish by impingement can be considered undesirable. A good review of the problem and methods of minimizing this adverse effect of cooling water use has been prepared by the Office of Air and Water Programs of the U.S. Environmental Protection Agency,[96] and will not be discussed here. Instead, discussion in this section will concentrate on condenser passage effects.

In current industry practice, the smallest mesh size commonly used in power plant intake screening devices is 3/8". Thus, any aquatic organisms small enough to pass through 3/8" openings are potentially subject to entrainment and passage through the pumps and condensers of a power plant's circulating water system. A hypothetical time-course of temperature change to which such organisms become subjected is presented graphically in Figure 4.2.

Entrainable organisms include (a) phytoplankton; (b) zooplankton; (c) the meroplanktonic eggs and larvae of certain fish and invertebrates; (d) the accidental and transient plankters such as normally-benthic invertebrates and normally-demersal fish eggs and larvae; (e) the fry and juveniles of many species of fish; and (f) other groups such as the protozoa, bacteria, and aquatic fungi.

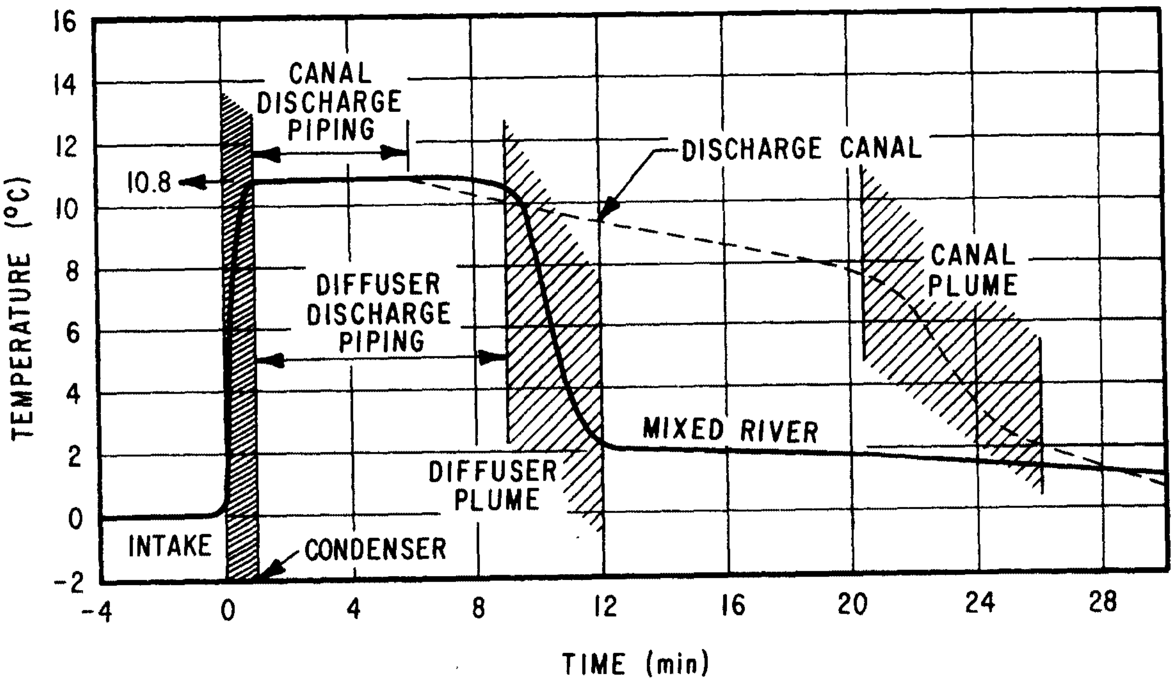

Figure 4.2

Hypothetical Time-Course of Acute Thermal Shock to Organisms Entrained in Condenser Cooling Water and Discharged by Diffuser or Via a Discharge Canal[a]

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[a]Coutant, C. C. Biological aspects of thermal pollution. I. Entrainment and discharge canal effects, CRC Crit. Rev. in Environ., Control. 1:341-381

In a power plant which employs a wet "closed-cycle" cooling system, aquatic microbiota are entrained in a makeup flow which is small in comparison with the flow through a plant which uses once-through cooling. Although the distribution of plankton in natural waters is stratified and clumped (patchy), rather than uniform or random, a general assumption can be made that in most cases, the quantity of aquatic microbiota entrained will proportionately reflect the rate of intake or makeup flow (for the same aquatic ecosystem and amount of care in designing and locating the intake).

On the other hand, mortality of entrained multicellular organisms is nearly total in evaporative cooling towers or spray canal cooling systems, due to high temperatures, prolonged residence in the system and recirculation through the condensers, and chemical conditions in such systems. Regarding power plants which employ cooling lakes, the differences (in species composition and quantities of organisms) between makeup flow entrainment and blowdown return depend upon lake surface area, turnover, winds, dew points, makeup temperatures, chemical conditions, and other factors. Such are not normal objects of studies of entrainment effects, but rather of cooling lake management. Consequently, the effects of entrainment and condenser passage discussed in the present section will be related to power plants which employ once-through cooling.

During condenser passage, entrained organisms may be subjected to (a) thermal shock, due to heat transfer in the condenser; (b) mechanical shocks and abrasion, due to turbulence, cavitation, and collision with pump impellers and irregular surfaces in the system; (c) pressure changes, due to pumping and hydrostatic head differences; (d) toxic chemicals inculding chlorine or other biocides used for shock defouling of condenser tubes; and (e) additional thermal stress, turbulence, and heavy predation in the discharge area.

Considering primarily the effects of thermal shock, Coutant[9] suggested that a power plant could be visualized as a "large artificial predator" acting on populations of entrainable organisms. He noted that thermal shocks could be lethal to entrained organisms or could produce sublethal effects which ultimately affected the survival of the organism or the dynamics of its population. However, Coutant further proposed that such adverse thermal effects were not obligatory to the entrainment process, but occurred rather as a result of sufficient combinations of temperature elevation and duration of exposure.

Although the effects of thermal shock on entrained organisms have received considerable attention in recent years, and although many direct studies of entrainment damage have been conducted at various power plants, there remains a paucity of physiological and toxicological data on the effects of thermal shock on most species of plankton. However, heuristic attempts have been made[9,36,37,38] to employ thermal tolerance and thermal resistance principles, derived from studies of fish physiology[39] in the interpretation and prediction of thermal effects of condenser passage on diverse kinds of aquatic biota.

Figure 4.3 provides a basic graphic representation of such principles. A hypothetical organism's "zone of thermal tolerance" is shown to be bounded by upper and lower "incipient lethal temperatures," which are simplistically represented here as functions of the temperatures to which the organism is acclimated (although in reality there are many other influences). Within the zone of thermal tolerance, the organism (or, rigorously, 50% or some other fraction of the organisms tested) theoretically

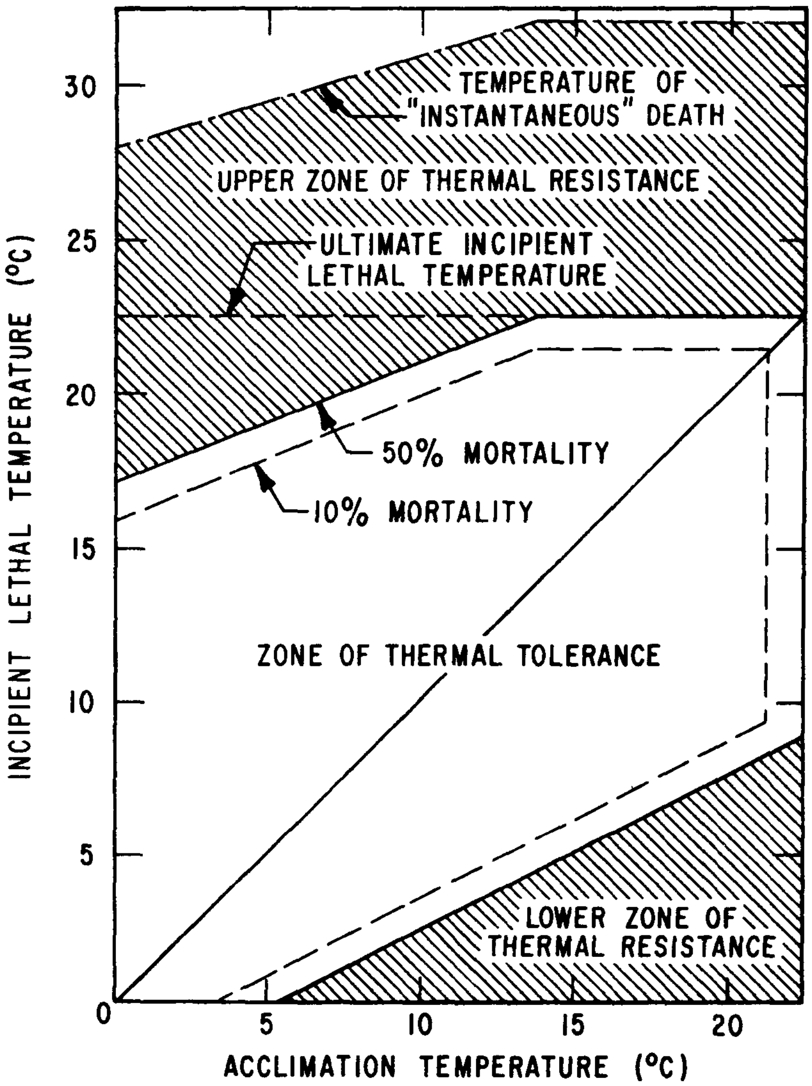

Figure 4.3

Thermal Tolerance of a Hypothetical Fish in Relation to Thermal Acclimation[a]

[a]Fry, F. E., Hart, J. S., and Walker, K. F. Lethal temperature reactions for a sample of young speckled trout (Salvelinus fontinalis). Univ. of Toronto Studies, Biol. Series. Publ. Ontario Fish. Res. Lab. 66: 5-35 (1946).

can live indefinitely (by operational definition). In the "zones of thermal resistance," located outside the lethal temperature boundaries in Figure 4.3, the organism can survive only for a certain period of time, which becomes progressively shorter the more the incipient lethal temperature is exceeded (of course, only the upper zone is pertinent to discussion of entrainment effects). Such "resistance time" can be expressed another way (Figure 4.4)in a "survival nomogram," which graphically represents what might be termed the "rate of dying" of an organism in its zone of thermal resistance.[36]

When an organism becomes entrained in a power plant cooling system and subjected to one of the time-temperature courses shown in Figure 4.2, the experience is more complex than the step-function single temperature changes on which were based the principles underlying Figures 4.3 and 4.4. Rather, the initial quick temperature elevation experienced by an entrained organism in the condenser tubes is followed by a decline back to ambient water temperatures. The rate of such decline depends mostly on the design and location of the plant's discharge. Assuming that the ambient water temperature is within the entrained organism's zone of thermal tolerance, and the maximum cooling water temperature reached is within the zone of thermal resistance, then the "thermal dose" experienced by the organism will depend both upon the amount by which the upper incipient lethal temperature is exceeded and the length of time during which it is exceeded. This "thermal dose" may be viewed as one critical determinor of the fate of an entrained organism, with regard both to lethal and certain sublethal effects. Coutant[9,36] has discussed the desirability of employing this concept in the design of power plant cooling systems, to minimize damage.

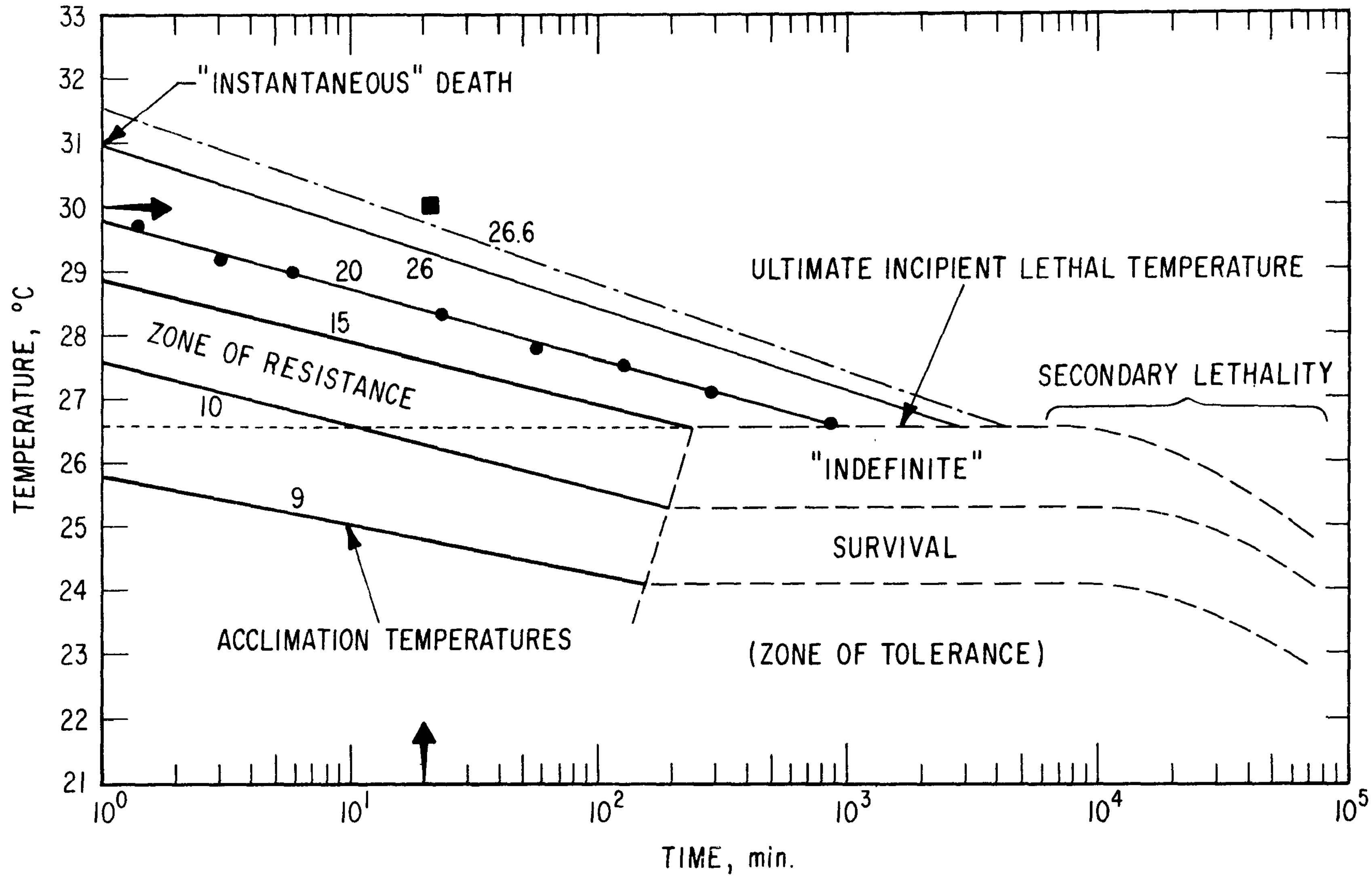

Figure 4.4

Median Resistance Times to High Temperatures by a Hypothetical Organism[a]

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[a] Coutant, C. C. Biological aspects of thermal pollution. I. Entrainment and discharge canal effects. CRC Crit. Rev. in Environ. Control. 1:341-381 (1970).

In the following discussions, the results of a number of power plant entrainment studies are considered. Such studies, in the aggregate, provide descriptions of entrainment effects regarding diverse combinations of cooling system designs (ΔT, times of exposure, biocide use, types of discharges, etc.), types of aquatic ecosystems, and methods of investigation. In general, these studies verify that in many instances, considerable damage to entrained organisms has resulted from thermal stress, as well as from other types of stresses and shocks listed previously. In other cases, however, measurable damage has been slight. By examining these studies in the aggregate, it appears that some general principles can be discerned regarding the causes and extent of entrainment damage.

b. Effects on Phytoplankton

Direct microscopic observation of net phytoplankton cell numbers and species composition has been employed by a few investigators[40,41] as a principal method for studying effects of condenser passage. However, although widely used in field studies, such an approach is exceptionally demanding of time and technical personnel. Moreover, it is often not possible in microscopic observation to accurately determine proportions of live and dead cells in phytoplankton samples, nor is it normally feasible to perform meaningful study of the physiologically-responsive nanoplankton (less than 10 microns in cell diameter) by such a method, due to taxonomic and methodological limitations. Consequently, most studies of the effects of condenser passage on phytoplankton have principally employed various indirect physiological measurements, including those of primary productivity (usually by some modification of the methods of Strickland and Parsons,[42,43] and chlorophyll *a* concentration.

The most frequently-reported major effect of condenser passage on phytoplankton, observed in comparisons of primary productivities in condenser discharge samples with those in condenser intake samples, has been the apparent stimulation of photosynthesis during months when ambient (intake) water temperatures are low, and the apparent partial inhibition of photosynthesis during warmer months. Although most such data exhibit considerable variability, this type of effect has been evident in a number of studies.

For example, in both laboratory simulations and actual entrainment studies at the Chalk Point power plant on the Patuxent River estuary in Maryland, Morgan and Stross[44] found that at an average ΔT of 8°C, productivity of phytoplankton usually increased somewhat during condenser transit at times when intake water temperatures were below 16°C. When intake water temperatures exceeded 20°C, however, photosynthetic inhibition was observed in discharge samples. At the Indian River power plant in Delaware, at an average ΔT of 6-7°C and a condenser transit time of approximately two minutes, photosynthetic rates of entrained plankton reportedly were stimulated (as much as doubled) during most of the year, when ambient water temperatures were below 22°C. During the summer months, however, reduced photosynthesis was observed in discharge samples.[45,46] From studies at the Indian Point power plant on the Hudson River, Lauer[47] reported that at a ΔT of approximately 8°C, condenser passage resulted in increased productivity during most of the year, but productivity was reduced somewhat in summer, when discharge temperatures exceeded 32°C. At the Crane power plant, located on a Chesapeake Bay tributary, primary production was increased in discharge samples (ΔT - 10°C) during most of the year, but was reduced in summer, whenever ambient water temperatures exceeded 26°C.[48]

At the Millstone Point power plant on the Niantic River estuary (Long Island Sound), with an average ΔT of approximately 13°C, photosynthetic inhibiton of 25-29% was observed[49,50] in spring and summer, with inhibition being more pronounced at higher temperatures. Reductions in ΔT below 7°C lessened the inhibition. In the cooler months, photosynthetic stimulation up to 200-300% of intake values (winter average approximately 25%) was reported.

In studies regarding the York River power plant in Virginia, discharge sample productivity was higher than that of intake samples in the cooler months, when intake water temperatures were below 10°C. When intake temperatures were in the 15-20°C range, inhibition was observed at ΔT's exceeding 5.6°C, with inhibition generally greater at higher intake temperatures and ΔT's.[51] In special operation of part of the Waukegan Station (Lake Michigan) at a 12°C ΔT, reduction in productivity of condenser-passed phytoplankton samples generally occured only when intake water temperatures exceeded 8°C.[52] At the Allen power station on Lake Wylie, North Carolina, neither thermal stimulation nor inhibition of photosynthesis was evident in entrained algae when intake water temperatures were less than 9°C. ΔT ranged from 5.5-17°C. With increase in intake temperatures, however, inhibition occurred and became progressively pronounced. At intake temperatures above 28°C, productivity reduction was observed at ΔT's of 5.5-11°C.[53]

From studies such as the preceding, it appears that such increases and decreases in primary productivity, observable in comparisons of condenser intake and discharge samples, primarily represent sublethal, physiological effects on the phytoplankton, and that decreases are produced mainly by thermal stress during condenser transit. Except during periods of condenser chlorination, chlorophyll *a* concentrations have not been observed to decline when reductions in productivity were measured.[44,52,54,55,56] Since chlorophyll *a* degrades upon cell death, it appears that the cells become metabolically impaired in such cases, but not killed. Thus, these effects have been interpreted by most investigators as stimulation and inhibition of photosynthesis. The higher the discharge temperature or ΔT at a given power plant and aquatic system, the more generally pronounced is the photosynthetic inhibition observed. Apparently consistent also with the "thermal dose" concept discussed earlier, more pronounced inhibition also has resulted from post-discharge storage of condenser-passed phytoplankton at discharge (vs. ambient control) temperatures.[55] In addition, Gurtz and Weiss[53] found progressively greater inhibition as discharged phytoplankton flowed down the long discharge canal of the Allen power plant.

A number of investigators have reported that photosynthetic inhibition in condenser-passed phytoplankton may not become fully evident immediately after discharge. In addition to such delayed expression, there also is evidence that inhibition may be persistent in the affected cells.

In studies at the Waukegan station, inhibition was not measurable until after the first 24 hours of storage at ambient (intake) temperatures. Afterwards, such inhibition persisted during the 75-hour period of observation.[52,56] Ayers,[57] also observed delayed phytoplankton damage at the Waukegan station. Morgan and Stross[44] reported no recovery of photosynthetic ability in their samples from the Chalk Point power plant, during 4 hours of observation.

Most power plant entrainment studies have included observation of condenser-passed organisms at times when the plant is producing no power.

By running the circulating water pumps without transfer of heat in the condensers, the effects of mechanical damage to entrained organisms can be studied for comparison with the combined thermal-mechanical effects measured during normal plant operation.

Mechanical damage to entrained phytoplankton has been studied by productivity and chlorophyll assays, as well as by microscopic observation for broken diatom frustules or other signs of structural cell damage. Although some cases of mechanical damage to phytoplankton have been reported, however, such effects seem not to be nearly as evident or significant as those apparently due to thermal stresses.

At the Indian River power plant, some mechanical damage to fragile phytoplankters such as small flagellates and dinoflagellates was observed but it was concluded that these effects were much less significant than were those of thermal stress in the warmer months.[46] On Lake Michigan, variable reductions in productivity were reported in entrainment studies conducted when the Palisades power station was pumping unheated water[58,59] but at the Waukegan Station, broken diatom frustules were not observed during unheated circulation.[52]

At the Allen power plant on Lake Wylie, North Carolina, some photosynthetic stimulation appeared to result from mechanical effects.[53] The possibility was suggested by these investigations that the mechanical shocks in the cooling system of the Allen plant may have produced fragmentation of chains of filamentous algae, thereby increasing cell surface areas and, consequently, metabolic potentials.

Severe reductions in productivity of phytoplankton entrained during condenser chlorination also has been observed in many studies.[44,47,49,50,54,55,60]

In a number of such observations, observed cell damage and loss, as well as reduction in chlorophyll a content of discharge samples, accompanied the reduced productivity[44,54,55] implying that such chlorination practices were destroying phytoplankton, rather than only producing sublethal metabolic depression.

Additional considerations regarding chlorine and other toxic chemicals are discussed in Section 4.3.

c. Effects on Zooplankton and Other Crustacea

In most studies of the effects of cooling water entrainment on zooplanktonic crustacea, observed mobility of individual organisms has been employed as the criterion signifying their viable condition. A plankter observed to be immobile (sometimes after probing by the observer), is operationally counted as "dead," by consideration similar to that of Reeve and Cooper,[61] who demonstrated that loss of swimming ability was mostly irreversible and usually followed by death of the organism. In some entrainment studies, an intermediate, (even more subjectively-determined) "distressed" category also has been used for descriptive purposes.

In attempts to reduce observer - subjectivity and other problems, some investigators[50,59,62] recently have employed a vital staining technique using neutral red dye.[63] With this technique, living microcrustacea quickly stain red, whereas dead organisms remain unstained or very lightly stained. This type of technique shows some promise, although it reportedly appears not to be as effective with cyclopod copepods as it is with calanoids, and cladocera appear to stain quickly only in their digestive tracts.[59] Of course, the determination of degree of staining of plankton also involves some observer subjectivity.

Both thermal and mechanical stresses have been observed by various investigators to be lethal to entrained crustacea. Lethal "thermal doses" for entrained opossum shrimp (Neomysis awatschensis) were exceeded for example, in laboratory simulations and condenser passage studies at the Pittsburgh and Contra Costa power plants on the Sacramento - San Joaquin estuary in California, when discharge temperatures exceeded 30°C.[64,65,66] At discharge temperatures below this level entrainment mortality of entrained Neomysis usually was less than 10%.[a] At 32°C, mortality usually exceeded 65%. (See Figure 4.5). In these studies, the ΔT and condenser transit time were approximately 9-10.5°C and 5 minutes, respectively. However, Neomysis mortality was described by these workers as being influenced more by absolute discharge temperature than by ΔT, presumably due to the relative independence of this organism's upper lethal temperature from modification by acclimation. From studies at the Indian Point power plant on the Hudson River, Lauer[47] also reported increased entrainment mortality of Neomysis and other crustacea when discharge temperatures exceeded 32°C in summer.

The potential significance of the duration of condenser transit, as well as of temperature, in the effects of entrainment on zooplankton was emphasized by Icanberry, et al.,[67] and Jensen, et al.[55] In studies at

[a]That is, there was a 10%, difference between the mean percentate of dead Neomysis observed in condenser discharge samples and that seen in intake samples, by a commonly-employed procedure of correcting mortalities to allow for dead organisms which enter the system.

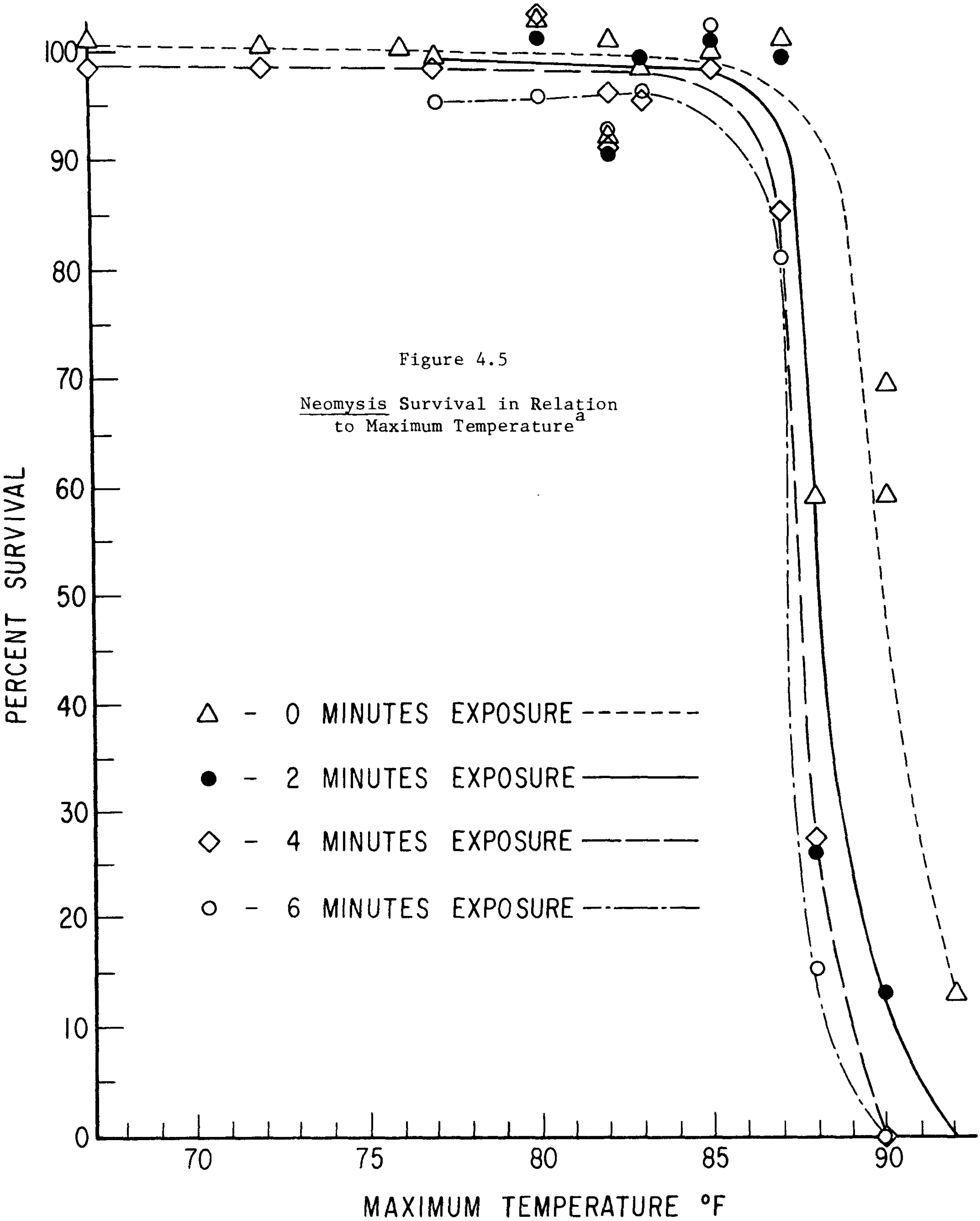

Figure 4.5

Neomysis Survival in Relation to Maximum Temperature[a]

[a] Hair, J. R. Upper lethal temperature and thermal shock tolerances of the opossum shrimp, Neomysis awatschensis, from the Sacramento-San Joaquin estuary, California. Calif. Fish and Game 57:17-27 (1971)

four coastal power plants in California, a regression analysis of absolute discharge temperatures vs. zooplankton entrainment mortalities (mostly of copepods) was significant and linear.[67] With average ΔT's at the Potreo, Humboldt Bay, Mass Landing, and Morro Bay power plants of 9, 15, 13 and 13°C, respectively, and condenser transit times of 1.4, 3.4, 11.6, and 11.9 minutes, respectively, average zooplankton entrainment mortalities were reported as 1.3, 5.9, 10.7 and 6.7%, respectively. When discharged zooplankton were held for 24 hours at discharge temperatures, further increase in % mortality were observed. When held similarly at intake temperatures, neither significant recovery nor delayed mortality were noted.

Some mechanical damage to entrainment zooplankton also has been reported. At the Waukegan power station on Lake Michigan, for example, lethal time-temperature conditions apparently are not reached in condenser transit, since increases in the ΔT did not produce increased zooplankton mortalities.[52,68] In these studies, an average zooplankton mortality of approximately 6% was observed during circulation of unheated water, as compared with an average mortality of approximately 8% during normal station operation. Mortalities of entrained zooplankton at other operating power plants on Lake Michigan, including those at Palisades[58,59,69] Point Beach[70,71] and Escanaba[72] also have been reported to average 7-12%; and mechanical damage also has been identified as the principal factor in zooplankton entrainment mortalities in the Palisades studies, even at a 14°C ΔT.

With regard to Coutant's[9] analogy of a power plant as a "large, artificial predator" upon populations of entrainable organisms, it is noteworthy that such obviously would be a somewhat selective predator. Entrainment damage which results from lethal time-temperature combinations at various power plants obviously is skewed against stenothermal species of plankton. Similarly, for power plants in which entrainment damage to zooplankton is primarily mechanical, the "predation" also is selective, skewed against the larger entrained organisms. In the Waukegan studies, for example, average condenser-passage mortality to zooplankters larger than 0.9 mm was approximately 17%; mortality to those smaller averaged less than 5%.[52]

As was reported for entrained phytoplankton, delayed effects also have been reported for zooplankton. From investigations at the Millstone Point power plant on Long Island Sound, Carpenter, et al.,[50] observed on eventual zooplankton entrainment mortality of approximately 70%. Immediate examination of samples at the condenser discharge, however, showed only a 15% kill. On the other hand, a significant recovery of condenser-passed zooplankton, sometimes exceeding 20% of those observed to be immobile immediately after discharge, was reported to occur after 4 hours of storage at intake water temperatures in the Waukegan power plant study.[52,68]

Reduced hatchability of entrained zooplankton eggs was reported by Mihursky.[73] In addition, Heinle[74] observed reduced reproductive success in laboratory cultures of zooplankton collected from the Chalk Point station (although this effect was attributed in part to chlorination effects). On the other hand, a slight increase in viability of discharged zooplankton eggs were reported at Waukegan[52] although details of the study were not described.

High entrainment mortality of zooplankton during condenser chlorination has been observed in a number of studies.[47,62,74,75] Additional considerations regarding chlorine and other toxic chemicals are discussed in Section 4.3.

d. Effects on Fish Eggs, Larvae and Young

Damage to the eggs, larvae, and entrainable young of fishes in a power plant cooling water system is a potentially serious problem, for which in many cases, the possibilities of corrective cooling water system design do no appear able to provide adequate solutions. Rather, every attempt should be made to avoid such problems, by judicious design and location of intakes.

Although Kerr[76] reported high survival of entrained chinook salmon and striped bass fry collected at the condenser discharge of the Contra Costa power plant, Coutant[9] has observed that Kerr failed to (a) provide information on intake or discharge temperatures, (b) consider the stresses experienced by the fry, or additional mortality, in the plants long discharge canal, and (c) consider sublethal effects on the fry.

At the Millstone Point[50] and Chalk Point[77] power plants, mortality to entrained fish larval was reported at and above 90%. At the Indian Point station, approximately 46% of entrained white perch and striped bass larvae reportedly were killed[47] and considerable concern has been expressed regarding the impact of this loss.[78] Chadwick[66] has identified 30-32°C as the condenser discharge temperature range which, if exceeded, can result in mortality of most entrained striped bass larvae from thermal effects alone.

In a preliminary report on his investigations at the Connecticut Yankee power plant, (Connecticut River), Marcy[79] stated that at condenser discharge temperatures of 28, 33, and 35°C, the 93-second condenser transit at the plant was survived by only 35, 19 and 0% respectively of entrained fish larvae and fry (mostly alewives and blueback herring). In addition, almost none of the young fish were observed to survive subsequent transit down the long (1.83 km) discharge canal in summer, when condenser discharge temperatures exceeded 30°C. In a later report, Marcy[80] attributed 72-87% of the observed mortalities to mechanical damage, with thermal stress responsible for the rest.

As with zooplankton, mechanical damage to entrained young fish increases with size of the fish.[80,81] On the other hand, mechanical destruction of entrained fish eggs also appears to occur. At the Vienna, Maryland, power plant, 99.7% average mortality of striped bass eggs was reported by Flemer, et al.,[82] who observed large differences in the numbers of eggs entering and leaving the cooling system.

e. Additional Considerations

The kinds of aquatic organisms which become entrained in power plant cooling water systems are vital to the energy flow, nutrient budget, and dynamic stability of the aquatic ecosystem affected, as well as to the production of various species of commercial and recreational importance to man. In any case in which ecological damage resulting from such entrainment may reasonably be expected to have a potentially significant adverse effect on any of these important natural processes, remedial measures must be taken.

Coutant[9] has observed "clearly, the impact of entraining suspended organisms, in the cooling water flow (assuming some damage is incurred thereby) will depend upon the proportion of total volume of the receiving body that is diverted through the condensers. There is potential for more serious ecological implications at locations where a substantial portion of a total stream flow is diverted for cooling, or where a substantial proportion of a lake or estuary is recirculated in cooling flow, than where this percentage is low."

In every aquatic ecosystem, certain kinds and amounts of biotic damage can be inflicted without resulting in significant or detectable ecological impact. Planktonic populations for example, are naturally exposed to considerable grazing or predation (which dramatically affects the abundance); seasonal and transient changes in the physical, chemical, and biological characteristics of their environments; and many other natural stresses and limiting influences. The life span of most plankters in natural waters is less than a month, but density dependent phenomena such as rates of reproduction and natural mortality enable populations to compensate for large losses. With regard to entrainment losses of fish eggs, larvae, and young, it is noteworthy that in species which have pelagic eggs and larvae, natural survival rates from egg to adult are characteristically low, 0.001% being not uncommon.[83,84,85]

In view of considerations such as these, it is not surprising that in many aquatic studies conducted at power plant sites, even in cases where comparatively high entrainment damage had been observed, no ecologically significant effects were measurable.[49,52,74,75,86,87,88,89]

On the other hand, although a number of general principles concerning entrainment effects apparently can be surmised from studies such as those previously discussed in this section, it also is true that many important questions regarding investigative methods and ecological significances of entrainment damage remain largely unanswered. Examples are listed below:

(1) Diel variations in the physiology, behavior, and distribution of en-entrainable organisms can profoundly affect the results of sampling, as well as of measurements of lethal and sublethal effects of entrainment. Examples of these include the heterotrophic activity of phytoplankton and the vertical distribution of zooplankton. Influence

of such phenomena on the results of entrainment studies need to be better characterized.

(2) Microbial groups such as the protozoa, natural bacteria, and nannoplankton are important in the dynamics of aquatic ecosystems and are generally characterized by high physiological responsiveness. Effects of entrainment on these organisms need to be investigated further.

(3) Influences of sampling mortality, as well as sampling gear efficiency and selectivity, need to be further characterized and/or reduced. In zooplankton entrainment studies, for example, mortality in intake samples commonly is subtracted from that in discharge samples. Since sampling mortality largely affects fragile organisms, estimations of entrainment damage can thereby be influenced. In addition, studies are needed regarding the influences of sublethal stresses to entrained zooplankters on their abilities to evade sampling gear. Such stresses can appreciably reduce gear evasion in condenser discharge samples, resulting in higher collections of live (albeit stressed) plankters after condenser passage.

(4) Delayed effects of entrainment, including moribundity, sublethal stress, and recovery, need to be further investigated.

(5) More information is needed on the ecological significances of increased susceptibility of entrained organisms to predation losses.[23,24,90,91,92]

(6) Influences of skewed entrainment mortality and changes in reproductive potentials on plankton community dynamics warrant further study.

(7) Better characterization of compensatory population response potentials is needed.

It should be obvious from the proceeding examples (which are by no means comprehensive) that although a great deal of work is needed to enable better characterization and assessment of the effects of cooling water system entrainment on aquatic biota, most of the areas of uncertainty reflect limitations in state-of-the-art biological methodology and knowledge. It also should be apparent that it is not necessary that every question which biologists can pose be answered before certain general conclusions can be reached regarding effects of entrainment.

4.2.2 Ohio River Studies

Although the effects of entrainment and condenser passage have been studied extensively at power plants elsewhere in the nation, this type of potential damage apparently has been omitted from investigation at Ohio River plants. The preceding general review therefore was presented as background for consideration of entrainment effects of Ohio River power plants which utilize once-through cooling.

Entrainment losses to Ohio River biota can be expected to include the planktonic and drift organisms, including insect life forms and normally-benthic accidentals. The composition and abundance of these are highly variable with flow, season, and river segment. Most of the river's fishes cast demersal eggs which are only accidentally susceptible to entrainment (although this does not always imply insignificance), and much tributary spawning apparently occurs. However, the freshwater drum (*Aplodinotus grunniens*) is an important Ohio River species with pelagic eggs, and of course the fry, larvae, and dislodged eggs of other species are entrainable.

Although some of the WAPORA[35] data at the Cane Run, Kyger Creek, Sammis, and Beckjord plants can be considered marginally pertinent to the question of entrainment damage, in that phytoplankton and zooplankton samples were collected at locations upstream and downstream of the plants' discharges, no direct intake-discharge observations or measurements of viable plankters were made in these studies. No significant effects on plankton abundance and composition were observed at these plants during the studies. The designs of these plants can be characterized as subjecting entrained organisms to relatively low time-temperature combinations, i.e., Cane Run -- 40 seconds, 10°C ΔT, 600,000 gpm; Kyger Creek -- 3 minutes, 6.6°C ΔT, 820,000 gpm; Sammis -- 4 minutes, 9°C ΔT, 805,000 gpm; Beckjord -- 11°C, 510,000 gpm.

Organisms entrained at the J. M. Stuart plant, in contrast, are subjected to markedly higher time-temperature "doses," i.e., 8 minutes, 13°C ΔT. Limited sampling of the intake and effluent stream at this plant was made during 4 days in the summer of 1972. High mortalities of zooplankton were observed after condenser transit. In June, with intake temperatures of 22 to 23°C (about 71 to 73°F) and ΔT's of 8 to 16.5°C (14 to 30°F), most microcrustacea in the discharge were dead.[93] Most of the mortality observed was for Cyclops. In August, when intake temperature was 27°C (80.6°F) and ΔT was 13.7°C (about 25°F), 91% of the zooplankton in the discharge were dead, compared to 35% dead in the intake samples. Most of the dead organisms were Ceriodaphnia, Cyclops, Diaptomus, and Daphnia.[93]

More extensive work at the Stuart plant, supplemented by laboratory studies, was carried out in 1970 to 1973 by workers at the University of Cincinnati.[94,95] Results of the 1970-71 study indicated that increases in temperature up to 18°C ΔT (32.4°F ΔT) tended to increase the rates of algal primary production, when the ambient water temperatures were less than 10°C (50°F). At ambient temperatures greater than this value, any temperature elevations decreased the rates of primary production. Bacterial metabolism, as measured by uptake of glucose, was decreased or unchanged by temperature increases up to 8°C (14.4°F), and increased in most cases with temperature elevations greater than 8°C (14.4°F). Periphyton growth was inhibited by the warmer waters, although earlier spring and higher winter biomass accumulations occurred at these stations than in the cold water stations. In laboratory experiments, the zooplankton *Daphnia magna* was acclimated to several temperatures and then subjected to 2-hour thermal shocks at temperatures up to 32°C (89.6°F). Filtering rates were decreased, respiration rates were increased, and longevity decreased by the temperature shock treatments.[94]

In 1972, increased generating capacity at the Stuart plant resulted in a range of temperature increases at the outfall of 7.0 to 25.0°C (12.6 to 45°F) above ambient, with a mean of 15°C (27°F). The corresponding range for 1970-71 was 1.5 to 20.0°C (2.7 to 36°F), with a mean of 8.5°C (15.3°F) above ambient. Passage through the plant's condensers reduced algal photosynthesis rates more severely in 1972 than in 1971. Maximal rates of bacterial uptake of glucose were inhibited when water temperatures exceeded 34°C (93.2°F). Zooplankton numbers were not significantly different in the outfall area from those in the intake area, during a period when the maximum temperature at the outfall reached 26°C (about 79°F). A possible exception was the number of *Cyclops*, which showed decreases 75% of the time. The workers postulated that severe zooplankton mortality would occur during the periods when outfall temperatures reached 40°C (104°F). Data collected during this latter period were not included in the report.[95] No significant effects of the thermal effluent exiting from the weir were observed on the flora and zooplankton at the sampling stations 1000 feet below the weir, in the Ohio River mainstem.

4.3 Chemical Discharge Effects

4.3.1 General Review

Cooling water use presently requires the addition of chemicals to water to maintain heat transfer surfaces free of biological growths, silt, and salt deposits, and to prevent or retard corrosion. Chemicals are also needed in cooling towers to prevent microbial deterioration of the tower fill. (Operation of cooling towers additionally increases the concentrations of salts and other compounds already present in the water due to evaporative loss of water. This concentration effect is particularly important in an estuary, where a discharge of abnormally saline water can have detrimental effects on the resident biota.) Closed-cycle operation with cooling ponds can require treatment of the ponds with algicides to prevent blooms of undesirable algae. The number, nature and concentrations of the chemicals required for these purposes will depend primarily on the chemical and biological characteristics of the water at a particular site.

Chemicals that are commonly added to cooling water include chromates, zinc, phosphates, and silicates for corrosion control; chlorine, hypochlorite, chlorophenols, quaternary amines, and organometallic compounds for bacterial growth control; acids and alkalis for pH control necessary to prevent scale formation; lignin-tannins, polyacrylamides, polyethylene amines, and other polyelectrolytes to reduce silt deposition. Treatment of boilers to prevent scale, corrosion, and cracking, involves the use of di-or trisodium phosphates, sodium nitrate, ammonia or cyclohexylamine.[97] Hydrazine and morpholine, which are used to scavenge oxygen, should not appear in the water discharge since these compounds form gaseous decomposition products. Various chemicals are also used for pre-operational and occasional cleaning of piping and other surfaces. The most common algicide added to cooling ponds is copper sulfate. Descriptions of the various chemicals and methodology of use in power plant operation, as well as data on toxicity concentration levels for aquatic biota, are available[98,99,100] and will not be reviewed here.

When discharged to the receiving water, these chemicals and/or their reaction products can have toxic effects on aquatic life, particularly on those organisms such as fish which are resident in the plume area and thus subjected to chemical discharges before the latter are diluted in the ambient river. Most chemicals added to cooling water are, under normal power plant practice, discharged at concentrations below laboratory-determined toxicity levels. However, the latter may not always be an adequate measure of toxicity effects under field conditions due to (a) possible synergistic effects of the higher water temperatures in a cooling water discharge, (b) possible synergistic and/or cumulative effects of other chemicals already present in the water and in the tissues of the organism, (c) presence of untested species or individuals more sensitive to a particular chemical than the tested individuals, (d) possible long-term sublethal effects that may not manifest themselves until later in the life cycle of the organism. Characteristics of the water, such as pH and hardness, can also effect toxicity responses. For example, trivalent chromium seems to be more toxic to fish than hexavalent chromium. In hard water, however, the solubility of trivalent chromium is reduced by precipitation, depending on the pH and mineral content of the water. Hexavalent chromium then becomes more lethal to fish than trivalent chromium.[98]

Cooling water treatment is thus a site-specific problem that may often be only cursorily investigated, resulting in addition of unnecessary chemicals or excessive amounts of necessary ones.

Careless or accidental additions can be a major cause of detrimental effects. For example, at a power plant discharge on the Saginaw River in Michigan, intermittent chlorination on a day in October, 1971, resulted in the death of several thousand fish. The highest total residual chlorine,[a] measured 20 feet downstream from the outfall, was 1.36 mg/l,[101] indicating that chlorination had probably been in excess of what was necessary.

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[a]Terminology:

free chlorine: Hypochlorous acid (HOCl), hypochlorite ion (OCl^-), or a mixture of both. Chlorine is added either as Cl_2, which quickly hydrolyzes in water to form HOCl, or is added as sodium hypochlorite, NaOCl.

combined chlorine: Compounds formed from the reaction of free chlorine with ammonia, phenols, ammonia-containing compounds, or any other compounds in which some of the oxidizing power of chlorine is retained.

residual chlorine: The concentration of chlorine measured at the sampling point. In the case of cooling water, this point is usually after the condenser exit or in the discharge canal.

free residual chlorine: HOCl or OCl^- remaining in the water at the sampling point.

total residual chlorine: the sum of the free and combined residual chlorine.

On another occasion at a power plant on Lake Michigan, about 800 to 120(fish were killed in the discharge channel as a result of the chlorination prc cedure. Measurements of total residual chlorine by personnel of the Michigar Department of Natural Resources using a portable amperometric titrator, indicated a maximum free chlorine concentration of 2.93 mg/l and a maximum total residual chlorine concentration of 3.05 mg/l in the discharge canal. The highest reading obtained in the plant by company personnel was 0.2 mg/l total residual chlorine, using the orthotolidine color comparator.[102] This inciden points out the importance of adequate measuring instruments and the calibrati of such. The amperometric method has been recommended[103] as the most accurat for determination of free and combined chlorine.

More attention has been paid to the effects of chlorine on aquatic biota than to other cooling water chemicals because this is the most commonly used biocide in either once-thru or closed-cycle systems to prevent slime formation on condenser surfaces and deterioration of cooling tower wood fill. Since effective condenser desliming requires only that there be some free residual chlorine (e.g., 0.1 mg/l) at the exit of the condenser, excessive residual chlorine concentrations in the discharge should not ordinarily occur if chlorination is carefully controlled. However, under conditions where the cooling water contains unusually high levels of ammonia (e.g., >0.1 mg/l) or organic compounds containing amino or phenolic groups, reactions with the chlorine will produce combined chlorine compounds (e.g., chloramines and chlorophenols) that are toxic to fish and other aquatic organisms, and which do not degrade or dissipate as rapidly in water as free chlorine.

Additionally, high ammonia concentrations in the makeup water require high levels of chlorination, since it is the free, not the combined chlorine that is most effective in slime control. Circumstances of high concentrations of ammonia and/or ammonia-containing compounds can occur when the source of cooling water also serves as receiving water for upstream sewage effluent, or during periods of high run-off from agricultural or dairy lands. In some cases, dechlorination of the effluent may be necessary to protect aquatic life. At a paper mill in Toledo, Oregon, the addition of 3.8 parts of sodium bisulfite to 1 part of residual chlorine decreased the latter level in boiler feed water from 1 mg/liter to less than 0.1 mg/l in less than 5 seconds.[104] Other dechlorinating agents include sodium thiosulfate and sulfur dioxide. Use of dechlorinating agents, which also tend to remove oxygen from the water, needs investigation as to their effects on organisms entrained in the cooling water. Alternative methods of condenser slime control involve mechanical scrubbing techniques;[105] the effectiveness of these methods, with or without concurrent chlorination, will depend on the characteristics of the water and season of the year. In some cases, the addition of a biocide to a condenser system may not be necessary. At the Oswego Steam Station on Lake Ontario in upstate New York, for example, the low level of nutrients in the intake water and the abrasive effect of fine suspended particles of glacial till in the water, make the use of biocides unnecessary.[106]

The EPA National Water Quality Laboratory has recommended criteria for chlorine concentrations that provide some protection for freshwater aquatic life.[103] These are presented in Table 4.3. To date, there are no federal or state standards that are specific for chlorine,* although there are prohibitions

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*On March 4, 1974, the U.S.EPA published in the Federal Register proposed effluent guidelines for steam electric power plants. These proposed guidelines do contain standards specific for chlorine.

Table 4.3

Residual Chlorine Criteria for Freshwater Aquatic Life[a]

Type of Chlorine Use	Concentration of Total Residual Chlorine	Degree of Protection
Continuous	Not to exceed 0.01 mg/l	This concentration would not protect trout and salmon and some important fish-food organisma; it could be partially lethal to sensitive life stages of sensitive fish species.
	Not to exceed 0.002 mg/l	This concentration should protect most aquatic organisms.
Intermittent	For a period of 2 hr/day, up to, but not to exceed 0.2 mg/l	This concentration would not protect trout and salmon.
	For a period of 2 hr/day, up to, but not to exceed, 0.04 mg/l	This concentration should protect most species of fish.

[a]From Brungs, W. A. Effects of residual chlorine on aquatic life. J. Water Pol. Contr. Fed. 45:2180-2193 (1973).

against discharging substances toxic to aquatic life. It is likely that the criteria set forth in Table 4.3 will serve as a basis for future standards. A problem in the interpretation of the criteria concerns the question of where in the receiving water should the criteria be applied, i.e., before mixing or after mixing with the ambient stream? The lower limit of accurate field measurement of total chlorine using present techniques is 0.1 mg/l. Standards of 0.04, 0.01, and 0.002 mg/l, for example, will present difficulties in determination of compliance. For this reason, standards for chlorine that require measurement in the effluent before outfall to the receiving water may be more useful.

A point that should be kept in mind is that attempts to regulate the discharge of chlorine in cooling water may have little effect on the upgrading of a river as a whole if chlorinated sewage discharges are allowed at present residual chlorine concentrations. It has been shown, for example, that fish species diversity was markedly reduced in stream locations immediately below the outfalls of 149 sewage treatment plants, compared to upstream locations. Chlorine concentrations up to 2.0 mg/l were maintained in these discharges, and were determined to be a major cause of the reduction in species diversity.[107] Since public health is of primary importance, chlorination of sewage should not presently be terminated. Dechlorination or alternative disinfection methods need to be investigated. Ozonation is one such alternative that may prove even more effective for disinfection than chlorination (it has been shown that chlorination at the usual rate does not kill all pathogenic organisms in sewage).[108,109] In the meantime, control of chlorine in cooling water discharges can certainly prevent injury to aquatic life in the vicinity of the discharges.

Discharge of sublethal concentrations of chemicals does not ensure absence of undesirable effects on a receiving water and its biota. Heavy metals such as Hg, Zn, Cr, and Cu have been shown to accumulate in sediments and bottom-dwelling organisms.[110] Enrichment of heavy metals and some organic compounds was also observed in the surface microlayer of water in Narragansett Bay, Rhode Island.[111] Bioaccumulation can lead to toxic concentrations higher up the food chain. Long-term exposure of aquatic organisms to sublethal concentrations of cooling water chemicals has been little studied, if at all. Claims by manufacturers of "environmentally safe" or "non-polluting" biocides should be carefully investigated.

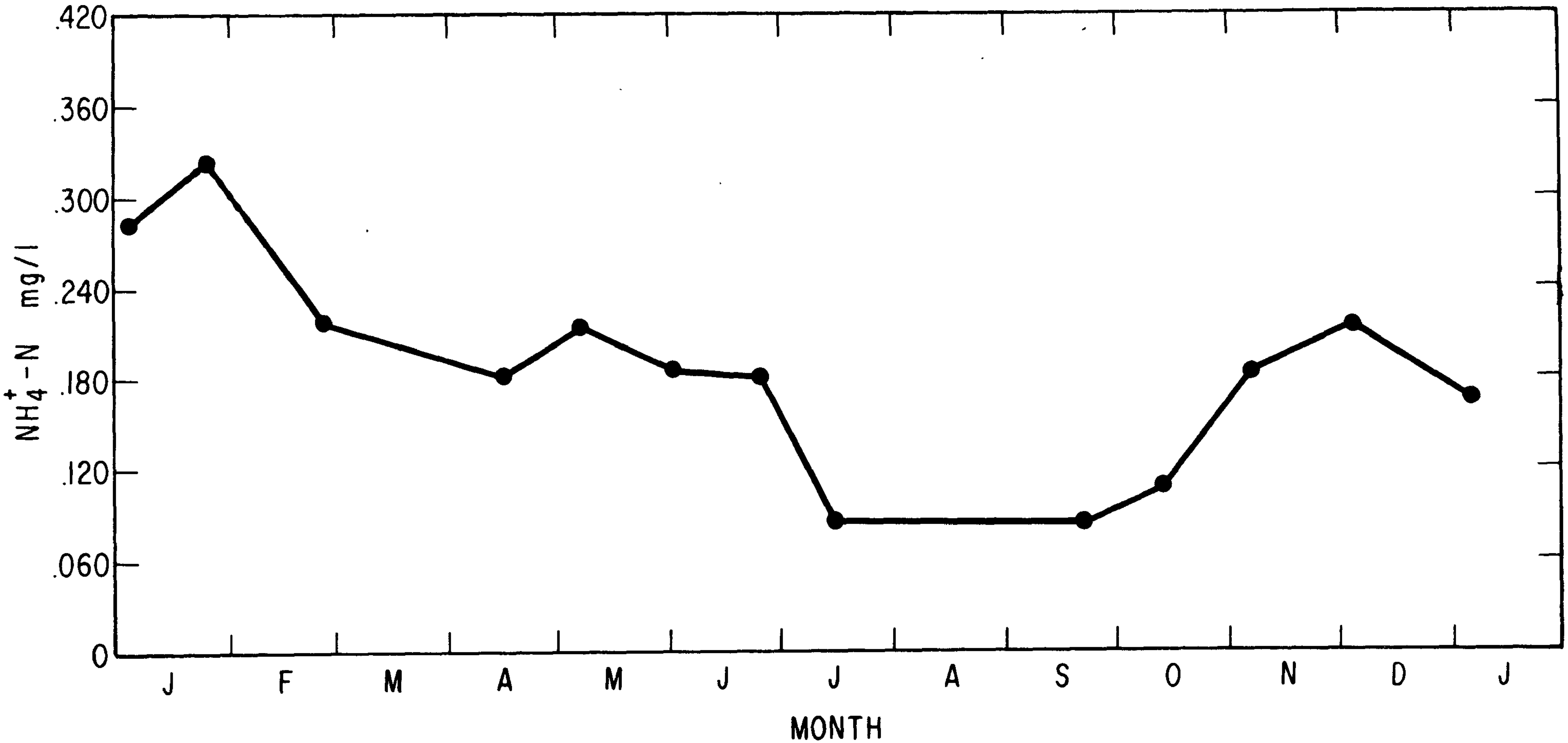
4.3.2 Ohio River Studies

On the Ohio River and tributaries little effort has been made to evaluate the effects of chemical constituents of cooling water discharges on the river's ecosystems. The relatively detailed studies at four power plants carried out by WAPORA in 1971 and 1972[34,35] apparently did not include chlorination effects, although the Kyger Creek, Tanners Creek, Beckjord, Sammis, and Cane Run plants all chlorinate their cooling water.[112] Similarly, Gammon[15,31] did not report any observations of chlorination effects on the biota of the Wabash River. This is unfortunate, because incidents of avoidance and mortality may have been related to discharges of chlorine as has been observed elsewhere. Bryant and co-workers made some attempts to include effects of chlorination in their study at the Beckjord plant[30] but little can be concluded from the study since chlorination occurred simultaneously with the discharge of heated water, and it was not possible to separate the effects of the two. Additionally, the few number of samples taken did not warrant making any statistically significant conclusions.

As was mentioned in Section 4.3.1 above, the presence of ammonia (NH_4^+) in the cooling water will affect the nature of the residual chlorine discharged to the receiving water. A portion of the data obtained by Miller and Kallendorf[94] in 1971 and 1972 on ammonia in the Ohio River is shown in Figure 4.6, and indicates that in the stretch of the river near River Mile 405.7, ammonia (NH_4^+-N) concentrations ranged from 0.1 to about 0.33 mg/l. If such water is chlorinated upon intake into the condensers of a cooling system, concentrations of monochloramine (NH_2Cl) up to about 1.2 mg/l (equivalent to about 1.6 mg/l molecular chlorine) can appear in the discharge. This concentration is many times the maximum recommended criteria for protection of warmwater fish species during intermittent chlorination (see Table 4.3). Some fish species have been shown to avoid lethal concentrations of chlorine if they can sense a chlorine gradient,[113] and it would seem safe to assume that other fish species in the Ohio River could do likewise. However, since chlorination of cooling water is

Figure 4.6

Annual Cycle of the Variation of NH_4 + - N (mg/l) in the Ohio River near RM 405.7[a]



[a]From Miller, M. C. and Kallendorf, R. J. The Effect of a Thermal Effluent on the Aquatic Microflora and Zooplankton of Little-Three-Mile Creek and the Ohio River at Aberdeen, Ohio. Dept. of Biol. Sciences, Univ. of Cincinnati, Cincinnati, Ohio (1973).

intermittent, fish resident in a thermal plume may be shocked by the sudden discharge of chlorinated effluent and be unable to move away, resulting in injury or death.

It is common practice at some power plants to chlorinate only a portion (e.g., half) of the cooling water stream (split-stream chlorination). Upon remixing with the unchlorinated portion after passage through the condensers, some of the residual chlorine in the free and combined forms reacts with chlorine-demanding substances in the unchlorinated stream, with the result that the total residual chlorine concentration in the effluent to the receiving body of water is substantially decreased. Information obtained from some power plants on the Ohio River indicates that not all practice split-stream chlorination. Residual chlorine in the discharges appear to range from 1.4 mg/l to "nil" (see Table 4.4). It would be interesting to examine the experiences and circumstances at the West End station, whose cooling water is apparently not chlorinated.

Passage of cooling water containing monochloramine through a cooling tower results in the removal of some of the combined chlorine due to the tendency of monochloramine to form dichloramine ($NHCl_2$) if free chlorine is present, by the reaction:

$$NH_2Cl + HOCl \rightarrow NHCl_2 + H_2O$$

The dichloramine is volatile and is scrubbed out of the cooling water in the tower, leading to a shift in equilibrium and the formation of more dichloramine.

Table 4.4

Residual Chlorine at Ohio River Power Plants[a]

Name and River Mile Location of Plant	Residual Chlorine[b] (mg/1)	Comments
Phillips, RM 15.8	nil	
Beaver Valley, RM 35 (with cooling towers)	0.1	Predicted concentration
Kammer, RM 111.1	0.5 - 0.75	
Mitchell, RM 101.9 (with cooling towers)	Just above 0	Measured in cooling tower blowdown.
Willow Island, RM 160.5	1.0	
Philip Sporn, RM 241.6	0.5 - 1.0	
Joppa, RM 951.2	0 - 1.0	
J. M. Stuart, RM 405.7	0.05	Uses mechanical cleaning for condenser tubes.
Clifty Creek, RM 558.4	0.2 - 1.5	Before mixing with unchlorinated discharge.
Ohio River, RM 777	0.4	
Culley, RM 773.4	0.2	
Gallager, RM 531.5	0.75	
West End, RM 471.4	-	Condenser cooling water is not chlorinated.
Miami Fort, RM 490.3	0.5 or 1 (free)	
W. C. Beckjord, RM 453.0	0.5	
Tidd, RM 75.0	0.35	Before mixing with unchlorinated discharge.
Cardinal, RM 74.4	0.35	Before mixing with unchlorinated discharge.
Toronto, RM 57.5	1.5	
R. E. Burger, RM 97.6	0.5	
Kyger Creek, RM 260.2	0.4 (free) 0.8 (total)	Before mixing with unchlorinated discharge.
Tanners Creek, RM 495.5	0.75 - 1.4	
W. H. Sammis, RM 55.0	0.1 - 0.5	

[a]Table prepared from information supplied to the U. S. Environmental Protection Agency by the corresponding utilities, and discharge permit applications.

[b]Unless otherwise specified in parenthesis, values are for total residual chlorine at the discharge from the condenser.

The proportions of mono- and dichloramine in chlorinated water will depend on the concentrations of the chloride ion, ammonia, chlorine, and pH.[114] For example, given a chloride ion concentration of 10 mg/l, ammonia concentration of 1.0 mg/l, a residual chlorine concentration of 1.0 mg/l, and a pH of 7.5, about 97.3% of the residual chlorine will be in the form of monochloramine, and about 2.6% in the form of dichloramine.[114]

It is sometimes assumed that most of the chloramines in cooling water will be lost in cooling towers by the reactions given above, but there is little hard data to support this. Draley[115] conducted a limited study of chlorination at the J. E. Amos power plant on the Kanawha River, a tributary to the Ohio River at about River Mile 270, and calculated that 40% of the chloramines were lost per pass through the cooling tower circulating-water system. The chlorination procedure consisted of injecting aqueous chlorine for half an hour at the rate of about 1.3 to 1.6 mg/l. The concentration of free chlorine at the condenser was about 0.1 mg/l; the total residual chlorine concentration reached a maximum of 0.63 mg/l at the condenser discharge, and 0.32 mg/l in the discharge from the cooling tower basin. After addition of chlorine was stopped, free chlorine was undetectable within 10 minutes, but more than two hours elapsed before total residual chlorine could no longer be detected in the cooling tower sluice by the amperometric titration method (sensitivity perhaps 0.01 or 0.02 mg/l).[115]

The importance of controlling all chemical discharges rather than simply those in cooling water is illustrated by the effect on water quality and fish life of a 16-week shutdown of steel mills on the upper Ohio River in 1959.[116] Steel mills discharge not only heated water but iron, dissolved solids, acids, and phenolic-type materials. Sampling by ORSANCO, and comparison with many years of data, showed conclusively that there was a decrease in phenolic compounds, threshold-odor intensity and dissolved iron content during the shutdown. When the mills resumed operation, the values of these indicators more than doubled at most sampling stations. Manganese concentrations in the upper river system were also lower during the shutdown period than in previous years. Cessation of mill operations resulted in only minor changes in the hardness, sulfate and dissolved-solids concentrations in the Monongahela and Allegheny Rivers, but there were marked reductions in the concentrations of these indicators in the Mahoning Rivers. These effects were attributed to the impact of acid coal mine drainage which apparently masked the effects of steel-mill wastes in the Monongahela and Allegheny Rivers. Fluoride concentrations in the upper Ohio River and tributaries during the shutdown averaged 0.4 ppm, which is about one-half the average value observed in previous years when the mills were operating.

Changes in the fish fauna in this stretch of the river as a result of the steel mill shutdown were investigated by Krumholz and Minckley.[117] Collection of fish with rotenone from the auxiliary lock chamber at Montgomery Lock and Dam yielded more than twice as many different kinds of fish and more than five times as many individuals within 11 days after the beginning of the shutdown, than comparable samples taken from the same area before the shutdown. There was no substantial change in the numbers of the "usual" river fish such as the emerald shiner, the carp, the catfishes and some of the sunfishes, but there was an increased abundance of bigeye chub, common sucker, the stoneroller, the creek chub, and several shiners, all of which can be classified as "clean-water" fishes. It was concluded[116] that these species had moved into this stretch of the river from clear backwaters and creeks, rather than from less polluted parts of the main channel.

Because a decrease in water temperature occurred coincidentally with the reduction in chemical additions to the river, it is not possible to state unequivocally that the appearance of a more diverse fish fauna occurred as a result of one change rather than the other. It seems safe to conclude that abatement of both thermal and chemical additions is necessary if a diverse fauna is to exist in the Ohio River.

Conclusions and Recommendations

Some aspects of the present water quality and aquatic life of the Ohio River are unsatisfactory, and can be traced to one or more of the following:

a. Construction of dams and modification of the river channel for navigation.

b. Heavy silt loads in run-off, due mainly to deforestation, agriculture, and construction.

c. Discharge of effluents from coal mines.

d. Discharge of municipal waste.

e. Discharge of industrial waste chemicals.

f. Discharge of heated water.

If it is assumed that further degradation is to be prevented, and that, additionally, present water quality conditions are to be changed for the better, then each of the above factors needs to be scrutinized as to the feasibility of reversing present trends.

For all practical purposes, the presence of the locks and dams must be considered irreversible. Similarly, control of run-off would involve concerted efforts of a large number of private and public enterprise throughout the river basin and is presently beyond the realistic control of Ohio River agencies such as ORSANCO, USEPA, and the individual states.

The last four factors, however, appear to be capable of control by these agencies. Concentration of efforts on just one of these four, e.g., thermal discharges, will have limited effect on upgrading the river as a whole, but can have significant effect on local conditions.

Reports of studies on the biological effects of cooling water use on the Ohio River and tributaries have provided good insight into some aspects of the problem, but suffer from one or more deficiencies, including:

a. Lack of continuous or frequent plume temperature measurements.

b. Lack of statistical treatment of phytoplankton and zooplankton data to determine significance of effects.

c. Exclusion of chlorine and other chemical discharges from consideration of discharge plume effects.

d. Little information on effects of plant shutdown or variations in plant loads.

e. Little information on migration habits, movements, and spawning sites of river fish.

f. Lack of water quality considerations in plume effects.

g. Little characterization and measurement of natural seasonal variations in populations of river biota.

h. Little attempt to separate condenser passage effects from plume effects.

Despite difficulties inherent in the study of complex life systems such as the Ohio River and its biota, several well-established relationships and effects have been observed with regard to cooling water use. It is thus no longer excusable to cite the lack of information as a basis for inaction. Even in the so-called "grey areas," action can be taken that can minimize adverse effects until more conclusive results are obtained. The following is a list, by no means complete, of measures that can be taken to prevent or minimize adverse effects of cooling water use on the Ohio River:

a. Proper siting and design of intake structures.

Details of the problem are discussed in reference 96. Selection of intake velocities and the placement and type of screening device best suited for a particular site should be made primarily on the basis of biological effects, and only secondarily on economic factors. A knowledge of the river flow characteristics, and the species and habits of fish in the area is essential. This will involve a preconstruction survey of fish populations and habits.

b. Minimization of entrainment effects.

Loss of phytoplankton productivity from the Ohio River due to entrainment will usually be a minor effect regardless of the nature of the cooling system, since algae have relatively short generation times (hours) and populations bypassing the plant can quickly recover. Loss of zooplankton, pelagic fish eggs and fry, however, is undesirable, and at sites where this loss can occur, intake volumes should be kept low, e.g., less than 1% of the river flow (cumulative effects of other water intakes on the river should be considered in this regard). Also, shortening the exposure times to elevated temperatures can reduce zooplankton mortalities due to condenser passage effects. The responses of a particular zooplankton population to a given time-temperature condition are specific, and can only be determined by condenser passage studies such as are outlined in Section 4.2. Implicit in these studies is statistical validity of the results.

c. Design of discharge structures such that fish do not have access to the discharge canals, and cannot be trapped in small bays.

d. Avoidance of spawning areas.

It is apparent from the few studies made on the Ohio River and tributaries that spawning and nursery habitats occur mainly in the creeks and backwaters. Siting of intakes or discharges on creeks or streams should therefore be avoided. Similarly, thermal plumes should not intersect these tributaries. Before a decision is made as to the location of a discharge, the spawning habits and movements of the fish in the area should be investigated. Construction of weirs or other obstruction across the mouth of a tributary creek should also be avoided.

e. Maintenance of a zone of passage.

This is a parameter that is not always clearly defined. One estimate would restrict a thermal discharge to 25% or less, of the river volume and area. In terms of blocking fish movement, this could be regarded as too severe a restriction of the discharge; however, in terms of protecting a major portion of the river plankton from the effects of the thermal plume, this does not appear to be an unreasonable standard. A zone of passage should take into account the habits of the particular fish moving through the area. For example, if most of the fish migrate close to the shore and avoid the mid channel because of barge traffic, a thermal plume that hugs the shore for a considerable distance would hamper fish movement, even if the 25% standard was complied with. This stresses the importance of preconstruction fish studies.

f. Gradual shutdown.

By allowing routine shutdown of a power plant to proceed slowly, e.g., not over 2°F/hr* rate of temperature decrease, cold-kill of fish in winter can be largely avoided. During an emergency shutdown, this rate cannot usually be achieved, and mortality of some resident fish can be expected.

g. Careful control of chlorination.

If intermittent chlorination is used to control condenser sliming, a concentration of 0.1 mg/l free residual chlorine at the condenser exit

*This figure is only an estimate and may be too high for some species. No investigation has been made on the decreased rate that could be tolerated by most fish species.

should not be exceeded. Injection of the chlorine immediately upstream of the condensers would be the optimum location to give the maximum concentration of chlorine where it is needed. Injection of chlorine too far upstream of the condensers could lead to excessive chlorination if ammonia is present. Hold-up of blowdown (from cooling towers) during the chlorination period, dilution with unchlorinated discharge, or dechlorination, are methods that can be used to reduce the residual chlorine concentration in the effluent to the river. A total residual chlorine concentration not to exceed 0.2 mg/l in the effluent, would provide protection of Ohio River fish even at the immediate outfall.

The question of whether or not to require backfitting of power plants already in operation needs a case by case analysis. Intake structures can be modified to minimize impingement effects if unacceptable fish kills occur regularly. The criteria of unacceptability is presently subjective. For example, here are several points of view:

a. The death of even one gizzard shad is unacceptable.

b. Mortality of a number of fish such that the population's compensatory response can not make up for it, is unacceptable.

c. Kills of "rough" or "trash" fish are acceptable. Kills of more "desirable" fish such as walleye and sauger are unacceptable.

The study of a given fish population to determine compensatory ability is expensive and would require many years of work. It appears simpler to apply the available information to minimize impingement mortalities. Similarly, modification of existing discharge canals to prevent fish access would be a major factor in reducing thermal death.

The necessity to backfit with supplemental cooling systems also requires individual site study. The conditions which might require such backfitting include circumstances where, for example,

a. The thermal discharge occupies a major portion (area and volume) of the river.

b. The intake volume and time-temperature conditions are such as to expose a large fraction (e.g., 10% or more) of the river plankton to lethal conditions. This can only be determined by careful condenser-passage studies.

c. It is desired to add additional electrical generating capacity while maintaining a diverse fish fauna in the mainstem and tributaries that will include species that prefer cool water.

In all cases, the environmental effects of the alternative cooling systems should be carefully considered.

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5. RIVER TEMPERATURE MODELS

This section details the theoretical development of each of the models chosen by the U.S. Environmental Protection Agency to be evaluated by Argonne. Of the three models chosen (STREAM, COLHEAT and Edinger-Geyer) both the COLHEAT and Edinger-Geyer models belong to a category of models generally termed heat budget models. Since the heat budget concept is central in the development of these two models, Section 5.1 is devoted to the theory underlying the heat budget concept. Section 5.2 presents the theoretical foundation of each of the models in some detail.

5.1 The Heat Budget

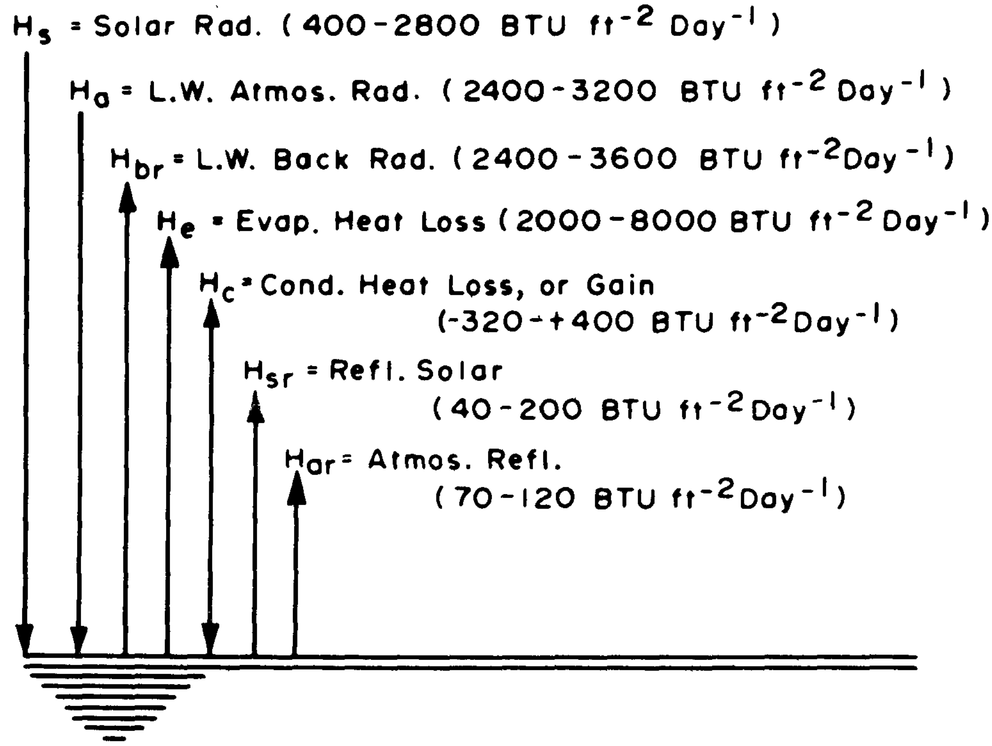
All bodies of water exchange heat with the atmosphere surrounding them. Hence, the simplest method of disposing of heated waste waters is to discharge them directly into a water body and then allow natural forces to bring the water body to an equilibrium temperature. Since the various mechanisms by which heat is exchanged with the atmosphere are well known, a heat budget can be used to calculate the change in temperature of the affected water body.

Oddly enough, heat budget studies were not initiated to predict water temperatures, but were undertaken by hydrologists and hydraulic engineers to determine evaporation rates. Schmidt used the heat budget approach to approximate ocean evaporation in 1915[1] and since then it has been applied many times to many different bodies of water including the well known studies made at Lake Hefner[2] and Lake Colorado City.[3]

The heat exchange mechanisms, shown in Figs. 5.1 and 5.2 along with their range in magnitude of monthly average values for northern latitudes,

Figure 5.1*

MECHANISMS OF HEAT TRANSFER ACROSS A WATER SURFACE



NET RATE AT WHICH HEAT CROSSES WATER SURFACE

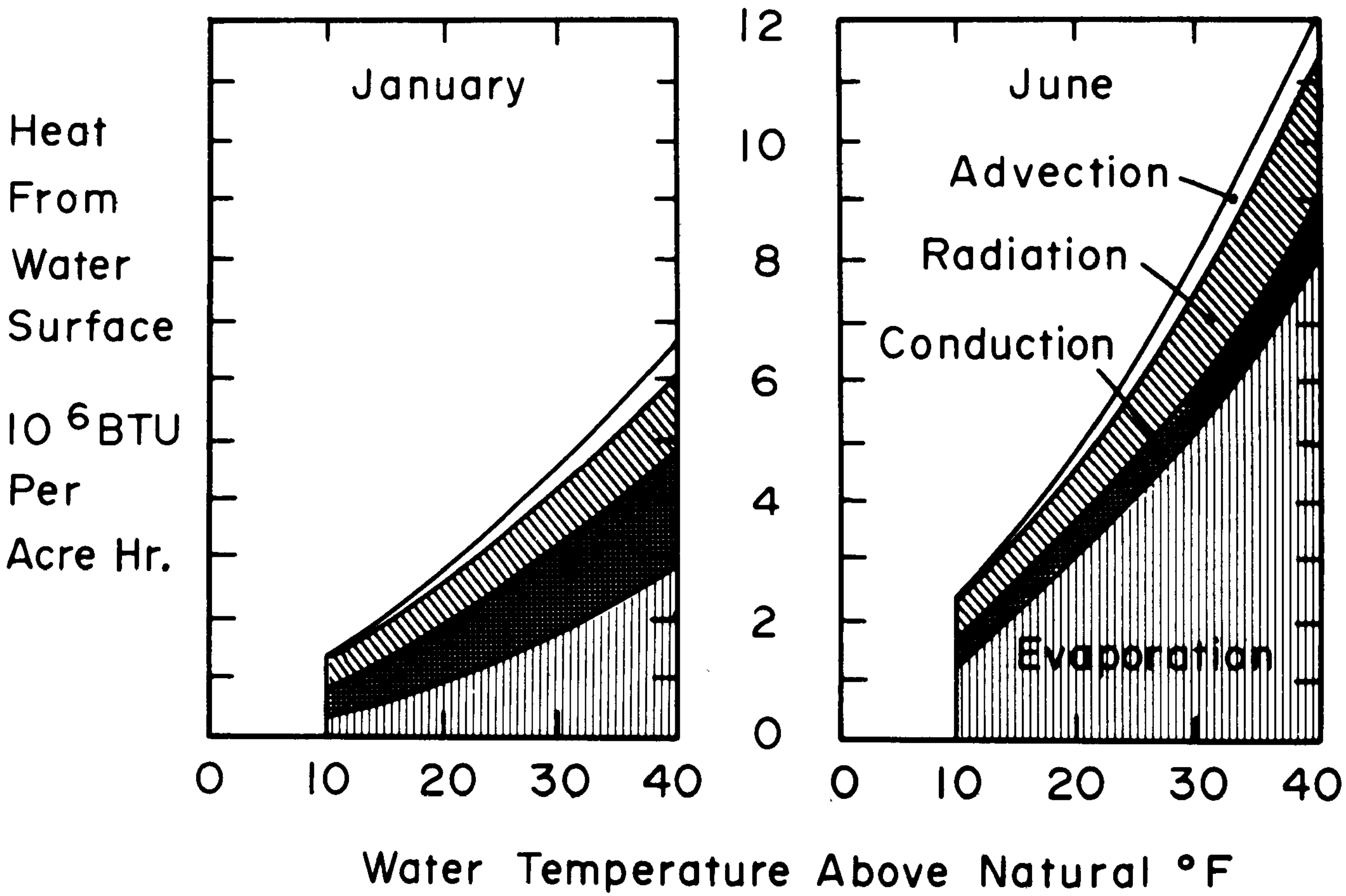
$$\Delta H = (H_s + H_a - H_{sr} - H_{ar}) - (H_{br} \pm H_c + H_e) \text{ BTU ft}^{-2} \text{ Day}^{-1}$$

H_R	Temp. Dependent Terms
Absorbed Radiation Independent of Temp.	$H_{br} \sim (T_s + 460)^4$ $H_c \sim (T_s - T_a)$ $H_e \sim W(e_s - e_a)$

*From: J. E. Edinger and J. C. Geyer, Heat Exchange in the Environment, Edison Electric Institute, New York, June 1965.

Figure 5.2*

Heat Dissipation From Water Surface By Evaporation, Radiation, Conduction and Advection During January and June



*From: F. L. Parker and P. A. Krenkel, Physical and Engineering Aspects of Thermal Pollution, CRC Press, Cleveland, Ohio, 1970.

are: incoming short-wave solar radiation (H_s); long-wave atmospheric radiation (H_a); outgoing long-wave back radiation (H_{br}); heat loss due to evaporation (H_e); reflected solar and atmospheric radiation (H_{sr} and H_{ar}); and loss or gain by conduction (H_c). The relationship among these mechanisms which describes the net rate at which heat crosses the air-water interface can be written as:

$$\Delta H = H_s + H_a - H_{sr} - H_{ar} - (H_{br} \pm H_c + H_e) \left(\frac{BTU}{ft^2 - day}\right) \qquad (5.1)$$

where ΔH is the net heat change.

Short-Wave Solar Radiation, H_e

The incoming solar radiation is short wave radiation (.14 $\leq$ wavelength $\leq$ 4 microns) which originates directly at the sun and is passed to the earth's surface. Not all the sun's shortwave energy directed towards the earth reaches the earth's surface because it is depleted by absorption by ozone, scattering by dry air, absorption and scattering by particulates, and absorption and scattering by water vapor. In addition, factors such as latitude, time of day, season, and cloud cover determine just how much short wave solar radiation actually touches the earth's surface. For these reasons, even though techniques have been developed to calculate empirically the quantity of solar radiation reaching the earth's surface, this quantity can be measured to a greater degree of accuracy with a Pyrheliometer.

Long-Wave Atmospheric Radiation, H_a

Long wave atmospheric radiation (4 $\leq$ wavelength $\leq$ 120 microns) depends primarily on air-temperature and humidity, and increases as the air moisture content increases. It may often constitute the major input on warm cloudy days when the amount of direct solar radiation has decreased to zero. It is a function of many variables, principally the distributions of moisture, temperature, ozone, and carbon dioxide. Although it is possible to measure H_a directly, it is more convenient to calculate than measure it.

Reflected Solar and Atmospheric Radiation, H_{sr} and H_{ar}

The amounts of solar and atmospheric energy reflected from a water surface are calculated using a reflectivity coefficient which is the ratio of reflected to incident radiation. Hence solar reflectivity is defined as:

$$R_{sr} = \frac{H_{sr}}{H_s} \tag{5.2}$$

Similarly, atmospheric reflectivity is defined as:

$$R_{ar} = \frac{H_{ar}}{H_a} \tag{5.3}$$

Solar reflectivity is more variable than atmospheric reflectivity because solar reflectivity is a function of the sun's attitude and the type and amount of cloud cover, while atmospheric reflectivity remains relatively constant and is usually taken to be equal to 0.03.

Absorbed Radiation, H_r

The four preceeding radiation terms, which are all independent of water temperature, can be lumped together and called absorbed radiation H_r so

$$H_r = H_s + H_a - H_{sr} - H_{ar} \left(\frac{BTU}{ft^2 - day}\right) \tag{5.4}$$

Likewise (5.1) can be rewritten as

$$\Delta H = H_r - (H_{br} \pm H_c + H_e) \left(\frac{BTU}{ft^2 - day}\right) \tag{5.5}$$

Back Radiation, H_{br}

Water returns energy to the atmosphere in the form of long wave radiation (4 $\leq$ wavelength $\leq$ 120 microns) and radiates as almost a perfect black body. Hence, the rate at which heat is lost due to back radiation can be computed from the Stefan-Boltzman fourth-power radiation law:

$$H_{br} = 0.97\ \sigma(T_s + 460)^4 \qquad (5.6)$$

where

H_{br} = Rate of back radiation, $\left(\frac{BTU}{ft^2 - day}\right)$

0.97 = emissivity of water

σ = Stefan-Boltzman constant = 4.15×10^{-8} $\left(\frac{BTU}{ft\text{-}day\text{-}°F^4}\right)$

T_s = Water surface Temperature, °F

Evaporation, H_e

Each pound of water that is evaporated from a water body carries its latent heat of vaporization of 1054 BTU's at 68°F. Though there are many empirical methods for estimating evaporation, there are no methods of measuring evaporation directly. The Lake Hefner studies were set up explicitly for determining correct evaporation relationships by utilizing the water budget approach to measure evaporation "directly".

A general evaporation formula, which assumes a linear relationship between the rate of evaporation, water vapor pressure and wind speed is:

$$H_e = (a + bW)\ (e_s - e_a)\ \left(\frac{BTU}{ft^2 - day}\right) \qquad (5.7)$$

where

a,b = empirical coefficients

W = wind speed, mph

e_a = air vapor pressure, mm Hg.

e_s = saturation vapor pressure of water determined from water surface temperature, mm Hg.

Three evaporation formulae which are used frequently are the Lake Hefner equation;

$$H_e = 11.4\ W(e_s - e_a) \left(\frac{BTU}{ft^2 - day}\right) \tag{5.8}$$

the Lake Colorado City equation,

$$H_e = 16.8\ W(e_s - e_a) \left(\frac{BTU}{ft^2 - day}\right) \tag{5.9}$$

and the Meyer equation

$$H_e = (73 + 7.3W)\ (e_s - e_a) \left(\frac{BTU}{ft^2 - day}\right) \tag{5.10}$$

The empirical coefficients, a and b, are different for the different equations because (1) of differences in the local topography of the three areas, (2) the data was averaged over different time periods in each study, and (3) the reference height at which the wind and air-vapor pressure measurements are made in the Meyer equation formulation is different than the reference height used in formulating the other two equations.

Edinger and Geyer[4] make a point concerning evaporation coefficients that is particularly noteworthy.

> "It would also be expected that the (evaporation) coefficients would be much different for rivers and streams than for lakes and might well be dependent on water velocity and turbulence, particularly in the case of smaller rivers".

Heat Conduction, H_c

Heat is exchanged between water and air when the air temperature is greater or less than the water temperature. The rate at which heat is conducted between air and water is equal to the product of a heat transfer coefficient and the temperature differential.

There is no single direct method to measure the rate at which heat is conducted between air and water. However, heat transfer by conduction has been likened to heat transfer by evaporation by Bowen[5] and he has arrived at a proportionality factor relating heat conduction and evaporation, namely:

$$B = \frac{H_c}{H_e} \qquad (5.11)$$

where B (the Bowen ratio) is given by

$$B = \frac{C' \, (T_s - T_a) \, P}{1000 \, (e_s - e_a)} \qquad (5.12)$$

and

T_a = air temperature, °F

T_s = water temperature, °F

e_a = air vapor pressure, mm Hg.

e_s = saturated water vapor pressure, mm Hg.

P = barometric pressure, mm Hg.

C' = empirical coefficient

Hence, the rate of heat conduction can be written, using (5.7, 5.11 and 5.12) as

$$H_c = \frac{C' \, (a + bW) \, (T_s - T_a) \, P}{1000} \qquad (5.13)$$

Studies have shown that C' varies from about 0.24 to 0.28.

<u>The Net Rate of Heat Transfer, ΔH</u>

The rate at which heat is entering or leaving a water body is given by (5.1), using the notation that the net rate of heat transfer is negative when heat is being lost across the water surface, and positive when being gained across the water surface. Substitution of the expressions developed above into (5.1) yields

$$\Delta H = H_r - 0.97\ \sigma(T_s + 460)^4 - (a + bW)\ (e_s - e_a)$$

$$- \frac{C'}{1000}\ (a + bw)\ (T_s - T_a)\ P \qquad (5.14)$$

where H_r is the absorbed radiation and is independent of water temperature. The three remaining terms on the right hand side of (5.14) are, respectively, back radiation, evaporative heat loss, and the conductive heat loss, and all are dependent on the water surface temperature.

5.2 River Temperature Prediction Models

Three river temperature prediction models were chosen by the United States Environmental Protection Agency, Region V to be evaluated for use on the Ohio River by the Argonne National Laboratory. The models selected were the COLHEAT model developed by the Hanford Engineering Development Laboratory for the U.S. Atomic Energy Commission; the Edinger-Geyer One Dimensional Model which is named after its developers and which has been coded by the U.S. Environmental Protection Agency, Region V; and the STREAM model developed by the Ohio River Valley Water Sanitation Commission (ORSANCO) specifically for use on the Ohio River. Each model chosen for this study has been documented, verified to some extent by its developers, and described in the literature. The remainder of this section is devoted to a description of each of the study models. However, since each model has been documented, no attempt is made in this report to present a user's guide to each of the models.

5.2.1 The COLHEAT River Simulation Model[6]

The COLHEAT River Simulation Model was formulated by the Hanford Engineering Development Laboratory under a contract with the U.S. Atomic

Energy Commission. Initially, a model was needed to evaluate the effects of cold water discharges from the depths of Lake Roosevelt behind Grand Coulee Dam during periods when the impoundment became stratified. As more and more impoundments were placed between the Hanford project (river mile 390) and Grand Coulee Dam (river mile 597), the demand for a simulation model to evaluate the effects of these impoundments became even greater. The COLHEAT Model was developed to meet this demand.

Since its development, the model has been verified with data recorded on the Columbia River beginning in 1966. Following the Columbia River application, the Division of Reactor Development and Technology of the U.S. Atomic Energy Commission requested that the simulation capabilities of COLHEAT be applied to other river systems. Consequently, it was used in 1967 to simulate temperature profiles of the Deerfield River in Vermont,[7] in 1968 of the Illinois River;[8] and in 1970 for the simulation of temperatures in an irrigation canal.[9] More recently COLHEAT has been used in conjunction with a subprogram called MAXPWR (maximum power) which estimates the total potential direct cooling capacity of major U.S. rivers.[10]

COLHEAT is a far-field, one-dimensional model designed to simulate temperatures along a river. The computational procedures are based on a fixed volume approach to river modeling wherein a river reach is divided into segments through which water is transported, acted upon, and modified by the local environment which is introduced by means of an explicit heat budget. Typically, the operation of the model consists of providing temperatures and flows at an upstream location and simulating the subsequent temperature history at one or more downstream locations. Routinely, average temperatures are computed for a time period of one day. During the computational procedures the time period is divided into equal increments called steps during which heat is exchanged with the atmosphere, water is transported downstream, and advected energy is added to the river. (Each of these three model components is described below.)

Operation of COLHEAT requires the following information:

- River dimensions reduced to equivalent nonparallel trapezoidal cross sections
- Water temperatures at the upstream end of the simulation
- River flows
- Meteorological data (air temperature, dew point temperature, wind speed, cloud cover, solar radiation)
- Tributary flows and temperatures
- Advected heat loads

The output of the model consists of a temperature record over time at a specified location.

COLHEAT Heat Budget

COLHEAT employs a heat budget to simulate the affect of the local environment on the rate of heat exchanged between the water body and the atmosphere. The particular heat budget used by COLHEAT was originally devised by Raphael[11] and will be discussed using the terms defined in Section 5.1.

The rate of heat exchange between air and water that is used by COLHEAT can be written as

$$\Delta H = H_r' - H_{br} \pm H_c - H_e + H_A \qquad (5.15)$$

where

H_A = advected heat rate

$H_r' = H_s - H_{sr}$

and the other terms are defined in Section 5.1. Note that H_r' does not include the long wave atmospheric radiation H_a nor the long wave atmospheric reflected radiation, H_{ar}, however these terms are included in H_{br}.

Solar radiation, H_s, can be obtained directly from the U.S. Weather Bureau. Solar reflected radiation is obtained from the relationship $H_{sr} = R_{sr} H_s$, where R_{sr} is the solar reflectivity. The COLHEAT model uses an R_{sr} between 0.84 and 0.94, based on studies by Budyko.[12]

The COLHEAT model includes the effects of emission and reception of long wave radiation (H_a, H_{ar} and H_{br}) in the familiar Stefan-Boltzman fourth power relationship and calls the resultant radiation term back radiation. Hence, for COLHEAT,

$$H_{br} = 0.97\ \sigma(T_s^4 + \beta T_a^4) \left(\frac{\text{BTU}}{\text{ft}^2 - \text{day}}\right) \qquad (5.16)$$

where

σ is the Stefan Boltzman constant

T_s is the absolute water surface temperature, °F

T_a is the absolute air temperature, °F

The value of β is a function of the amount of cloud cover and the water vapor pressure in the air and can be determined from standard charts.[11]

The evaporative heat loss, H_e, is computed by the COLHEAT model using the Lake Hefner evaporation formula

$$H_e = 11.4\ W(e_s - e_a) \left(\frac{BTU}{ft^2 - day}\right) \quad (5.8)$$

where

W = wind speed, mph

e_a = air vapor pressure, mm Hg.

e_s = saturation vapor pressure of water determined from water surface temperature, mm Hg.

To account for conduction, COLHEAT relies on the Bowen ratio as discussed in Section 5.1. Using the Hefner information for the wind function and choosing a value of 0.61 for the Bowen coefficient- the conduction term, (5.13), becomes,

$$H_e = 0.00707\ WP(T_s - T_a) \left(\frac{BTU}{ft^2 - hr}\right) \quad (5.17)$$

where

W is the wind speed, mph

P is the atmospheric pressure, in Hg.

T_a is the mean air temperature above 20 m, °C

T_s is the mean water surface temperature, °C

The advected heat, H_A, will be discussed under the heading "transport mechanism" because that is when the advected heat is added to the river segment under study.

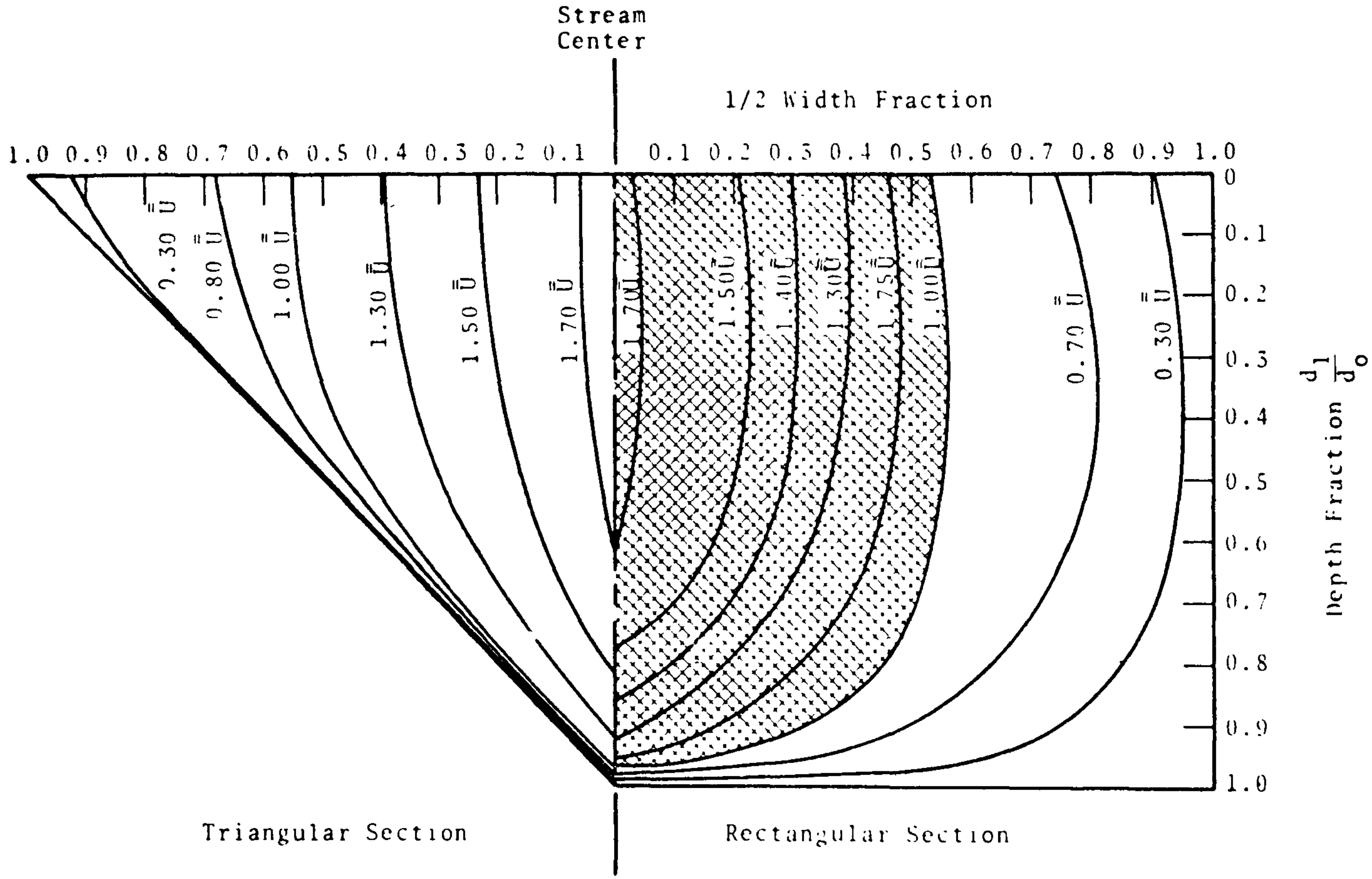
Transport Mechanism

In order to successfully simulate temperature, it is necessary to accurately represent the hydraulic characteristic of a river. In particular a surface area, volume, and velocity or travel time must be defined before the heat budget discussed in the previous section may be applied.

In the COLHEAT model a river is divided lengthwise into segments, the cross section of which is approximated by a trapezoid with the river bottom parallel to the water surface. Values representative of the surface and bottom width, and the depth at both the upstream and downstream end of the segment as well as the segment length must be input to the code. The values are used in computing the surface area and volume associated with each segment.

Typically, all the water moving past a point on a river is not traveling at the same velocity. In general, the velocity of the water traveling near the banks of the river is less than the velocity of the water in the central portions of the river. The results of a study conducted by Wasley[13] of shallow triangular channels along with the mathematical models developed by Matalas and Conover[14] led to the construction of the cross sectional velocity distribution shown in Fig. 5.3, for systems bounded by frictional constraints. Assuming this cross sectional representation, Jaske[15] used the average velocity contour $\overline{\overline{U}}$ in Fig. 5.3 to define two regions:

1. A central region (shaded portion) wherein water traveling at velocities greater than $\overline{\overline{U}}$ is represented by an average velocity which is equal to 1.37 $\overline{\overline{U}}$. This portion contains 53% of the stream cross section.
2. Adjacent regions wherein water traveling at velocities less than $\overline{\overline{U}}$ are represented by an average velocity which is equal to 0.60 $\overline{\overline{U}}$. This portion contains 47% of the stream cross section.



Contours Expressed as $\frac{U_1}{\bar{\bar{U}}}$ - Fraction of $\bar{\bar{U}}_1$

Figure 5.3*
Theoretical Velocity Contours

*From: R. T. Jaske, "The Use of Digital Systems Modeling in the Evaluation of Regional Water Quality Involving Single or Multiple Releases," Chemical Engineering Progress, No. 90 Vol. 64, 1968.

The ratio of the velocities in these two regions is approximately $(1.37\bar{\bar{U}}/.60\ \bar{\bar{U}} \simeq 2.)$.

In order to account for this information a "parallel trough" river representation is utilized by the CRSM. For such an abstraction the river is divided crosswise into three parallel troughs, an inner trough containing rapidly moving water and two identical outer troughs containing slower moving water, as is shown in Fig. 5.4.

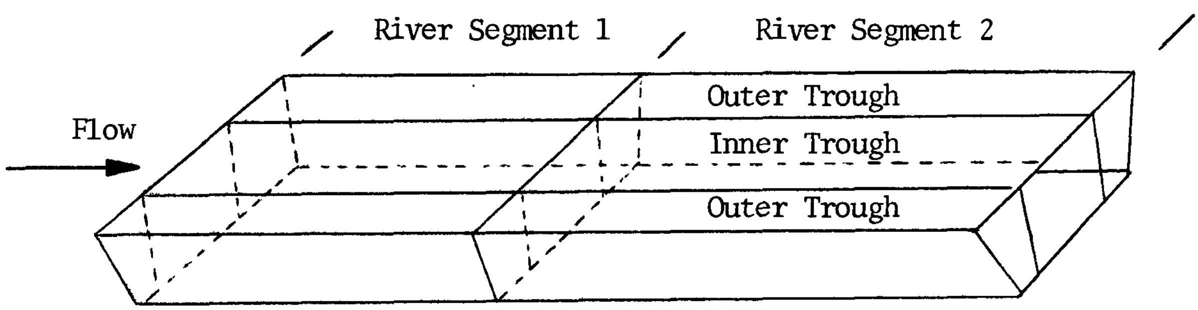


Figure 5.4

Coded River Configuration

The velocity of the water in the inner trough is assumed to be twice the velocity of the water in the outer two troughs. Unless different ratios are input to the code the inner trough is assumed to be comprised of 1/2 the total cross sectional area with each outer trough containing 1/4 of the total area. The ratio of velocities and of cross sectional areas are used to compute the fraction of the total flow moving through each trough.

During a specified time increment, defined previously as a time step, a certain volume of water flows into and out of each river segment. Associated with this flow and with the water residing in each river segment is a bulk temperature. Initially all temperatures are equated to a representative input value. Subsequently, according to conservation of mass and assuming no storage within a section, the code steps backwards (upstream) starting at the end of a reach to determine where the volume of water presently located in a particular river segment was located in the previous step. Complete mixing is assumed and conservation of energy is used to arrive at the "new" bulk temperature of the river segment section.

To clarify this explanation an example of how a river reach is coded is presented in Fig. 5.5; and the calculations associated with determining the temperature in the last river section are shown in Table 5.1.

At points of confluence of a tributary with the mainstream the assumption is made that the water in the mainstream at the confluence precedes the water in the triburary.

A temperature simulation model must contain the capability to estimate the effect of thermal discharges into a river. Advected energy can be input into COLHEAT enabling the temperature rise and subsequent decay resulting from the thermal loading of a river to be investigated. Assuming complete mixing at the discharge point, the rise in temperature of a particular river section due to the effect of advected energy can be found from

$$\Delta T = \frac{H_A}{C'V} \tag{5.18}$$

where

ΔT = rise in temperature of a particular river section in one time step, °F

H_A = the amount of advected energy added per time step, BTU/step

V = the volume of the river section into which the thermal discharge is being made, ft^3

Following the insertion of energy into a river, complete mixing is assumed and conservation of energy is used to estimate the bulk temperature

V_i = Volume of section i

F_i = Flow out of section i per time step

T_i = Bulk temperature of section i

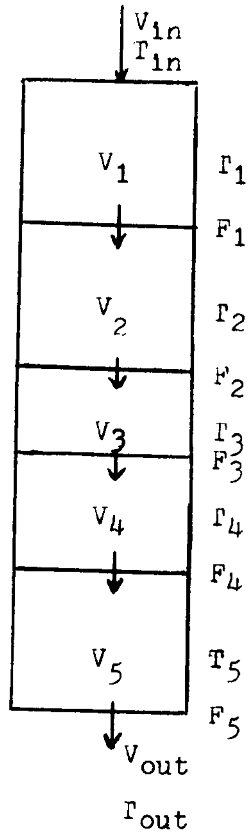


Figure 5.5*
Water Transport in Idealized Trough

Table 5.1*
SUMMARY OF CALCULATIONS WITHOUT TRIBUTARIES

CASE		REMARKS
1. $F_5 \leq V_5$	Tout = T_5	All water leaving system is from V_5
1a. $F_4 \leq V_4$	$T_v'V_5' = T_5(V_5-F_5) + T_4F_4$	All water entering V_5 is from V_4
1b. $\sum_4^{i+1} < F_4 \leq \sum_4^{i}$	$T_5'V_5' = T_5(V_5-F_5)+T_4V_4+\ldots T_i (F_4-\sum_4^{i+1})$	Water in V_5' consists of V_5-F_5 originally in V_5, plus V_4, plus V_3, . . ., plus an amount $F_4\sum_4^{i+1}$ that comes from V_i
2. $\sum_5^{i+1} < F_5 \leq \sum_5^{i}$	Tout $F_5 = T_5V_5+T_4V_4+\ldots+T_i (F_5 \sum_4^{i+1})$	Water leaving V_5 includes that in all sections from 5 to i+1, plus an amount $F_5 - \sum_5^{i+1}$ that was in V_i
2a. $F_4 \leq \sum_4^{i} - V_5$	$T_5' = T_i$	Water in V_5' all comes from V_i
2b. $\sum_4^{i+1} < F_4 \leq \sum_4^{i}$	$T_5'V_5' = T_i(\sum_5^{i} - F_5) + T_{i-1}V_{i-1} + \ldots + T_j(F_4 - \sum_4^{i+1})$	Water in V_5' consists of $\sum_5^{i} - F_5$ from V_i plus V_{i-1}, . . ., plus an amount $F_4 - \sum_4^{i+1}$ from V_j

Notes: $\sum_n^k = V_n+V_{n-1}+\ldots+V_{k+1}+V_k$. In other words $\sum_n^k$ is the total volume of all reservoirs between n and k inclusive. Thus $\sum_5^3$ is the total volume of reservoirs 5, 4, and 3.
Primed quantities (T_5', V_5') refer to values at the end of the time step. In every case $V_5' = V_5+F_4-F_5$

*From: HEDL Engineering Staff, The COLHEAT River Simulation Model, Report No. HEDL-TME-72-103, Hanford Engineering Development Laboratory, August 1972.

for each river section. Partial mixing routines which incorporate the phenomena of diffusion between adjacent troughs may be inserted into the model, however, in this study only the complete mixing routine is used.

The procedures discussed above are computed during each time step with the order of computation represented by Fig. 5.6. The computational procedure represents a numerical estimation of the solution to the differential form of the conservation of energy equation. Assuming that no significant amount of energy is lost to the river banks, the conservation equation is

$$\frac{d(V_i C'T)}{dt} = H_t A + q_i C' T_i - q_o C' \; T_s + H_A \tag{5.19}$$

where

t = time

V_i = volume of water in river section i

C' = heat capacity of water

q_i = flow of water into section i

q_o = flow of water out of section i

T_i = temperature of water entering section i

T_s = temperature of water residing in section i

H_t = heat exchange rate at the air/water interface

H_A = rate at which advected energy is being added to the system

Assuming a constant volume and heat capacity (5.19) reduces to

$$\frac{dT_s}{dt} = \frac{H_t A}{C'V} + \frac{q_i}{V} (T_i - T_s) + \frac{H_A}{C'V} \tag{5.20}$$

The COLHEAT code computes a term-by-term numerical approximation of the solution to this equation to simulate temperatures in each river section.

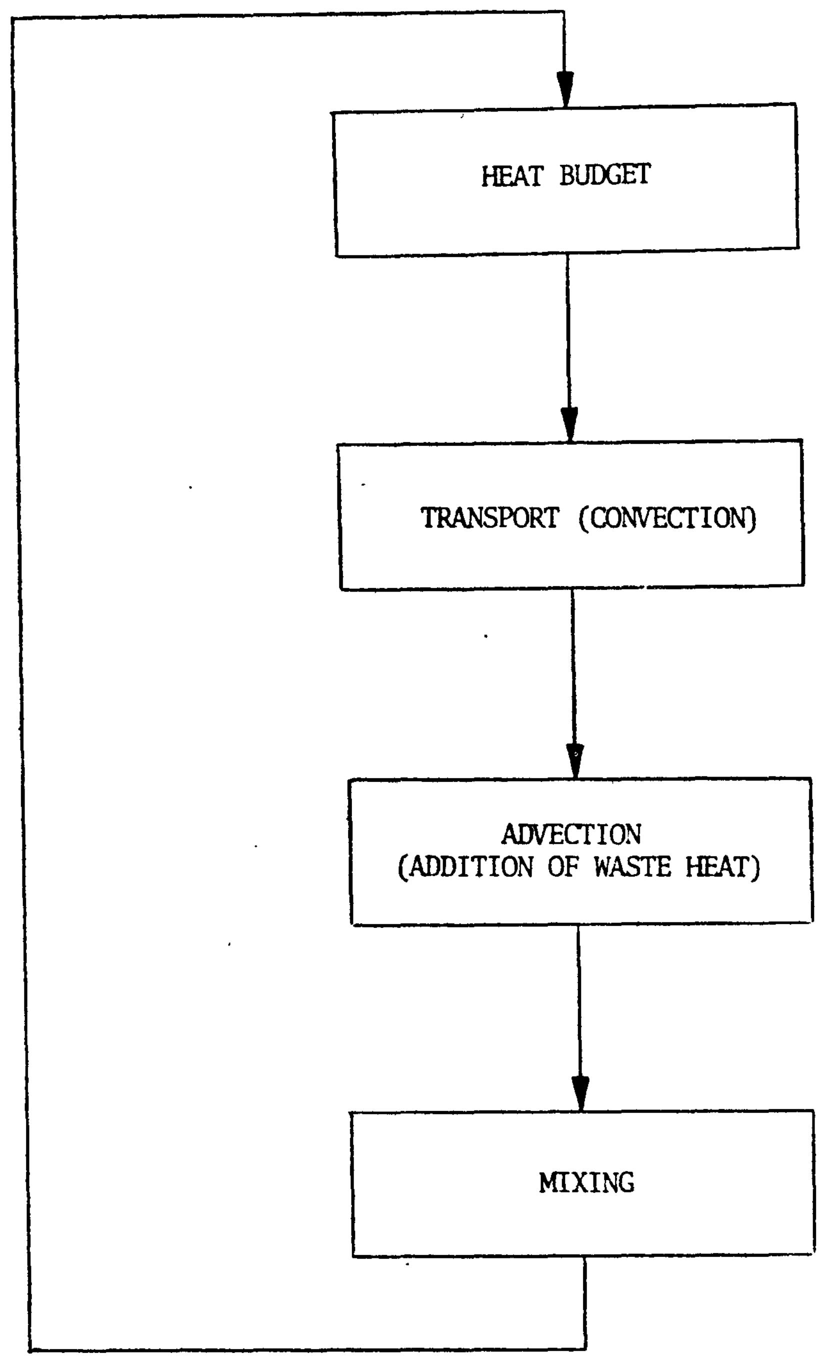


Figure 5.6

Block Diagram of COLHEAT Computational Procedure
During a Given Time Step

5.2.2 Edinger-Geyer One-Dimensional River Model[4]

The Edinger-Geyer one-dimensional river model is formulated using the standard heat budget technique. It was developed for the use of individual power companies so that they could estimate by means of desk top calculations the temperature distribution which occurred in the vicinity of a power plant and which resulted from heated water being discharged into the river. Hence, as is described below, the equations in the heat budget analysis are linearized for computational simplicity with knowledge of their approximate nature. Likewise, the simple hydrodynamic approach of assuming mean velocities in rectangular channels was to allow slide rule calculations in lieu of digital computer use.

The model is a far field, one-dimensional, steady-state model that can be used to predict temperatures along a river. The theoretical basis of the model is a heat budget which is used to determine an equilibrium temperature, E, and a heat exchange coefficient, K. To simulate river temperatures the model analyzes a slug of water as it flows downstream, making sure that the meteorological parameters and the advected heat are updated at prescribed intervals.

Operation of the model requires:

- Meteorological data (air temperature, dew point temperature, wind speed, and solar radiation).
- River dimensions (surface width and hydrologic depth)
- River flows
- Quantity of advected heat
- Water temperatures at the upstream end of the simulation.

Heat Budget

The basic heat budget equation used in the Edinger-Geyer formulation is:

$$\Delta H = H_r - H_{br} \pm H_c - H_e \left(\frac{BTU}{ft^2 - day}\right) \tag{5.21}$$

where

$$H_r = H_s + H_a - H_{sr} - H_{ar}$$

and

H_s = Short wave solar radiation

H_a = Long wave atmospheric radiation

H_{sr} = Reflected solar radiation

H_{ar} = Reflected atmospheric radiation

H_{br} = Long wave back radiation

H_c = Conductive heat loss or gain

H_e = Evaporative heat loss

Solar radiation, H_s, is measured directly by the U.S. Weather Bureau and usually this measured value is employed in the model.

The magnitude of the long wave radiation is estimated in the Edinger-Geyer formulation through the use of Brunts formula[16] which is

$$H_a = 4.5 \times 10^{-8} (T_a + 460)^4 (c + 0.031 \sqrt{e_a}) \left(\frac{BTU}{ft^2 - day}\right) \tag{5.22}$$

where

H_a = Long-wave atmospheric radiation, $\left(\frac{BTU}{ft^2 - day}\right)$

T_a = Air temperature measured about six feet above the water surface, °F.

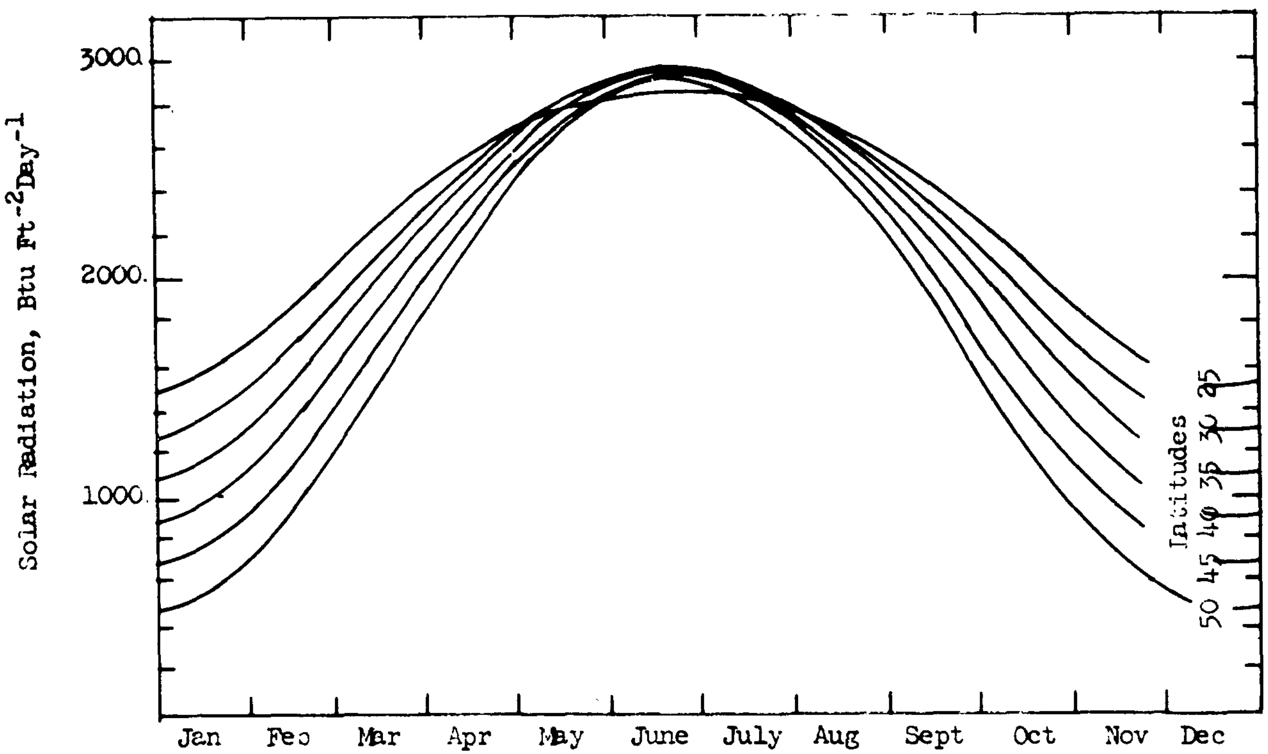
e_a = Air vapor pressure measured about six feet above water surface, mm Hg.

c = A coefficient determined from the air temperature and ratio of the measured solar radiation to the clear sky solar radiation (see Figs. 5.7 and 5.8).

The fractions of the solar and atmospheric radiant energy that is reflected from a water surface are calculated using solar and atmospheric reflectivity coefficients which are defined as:

Figure 5.7*

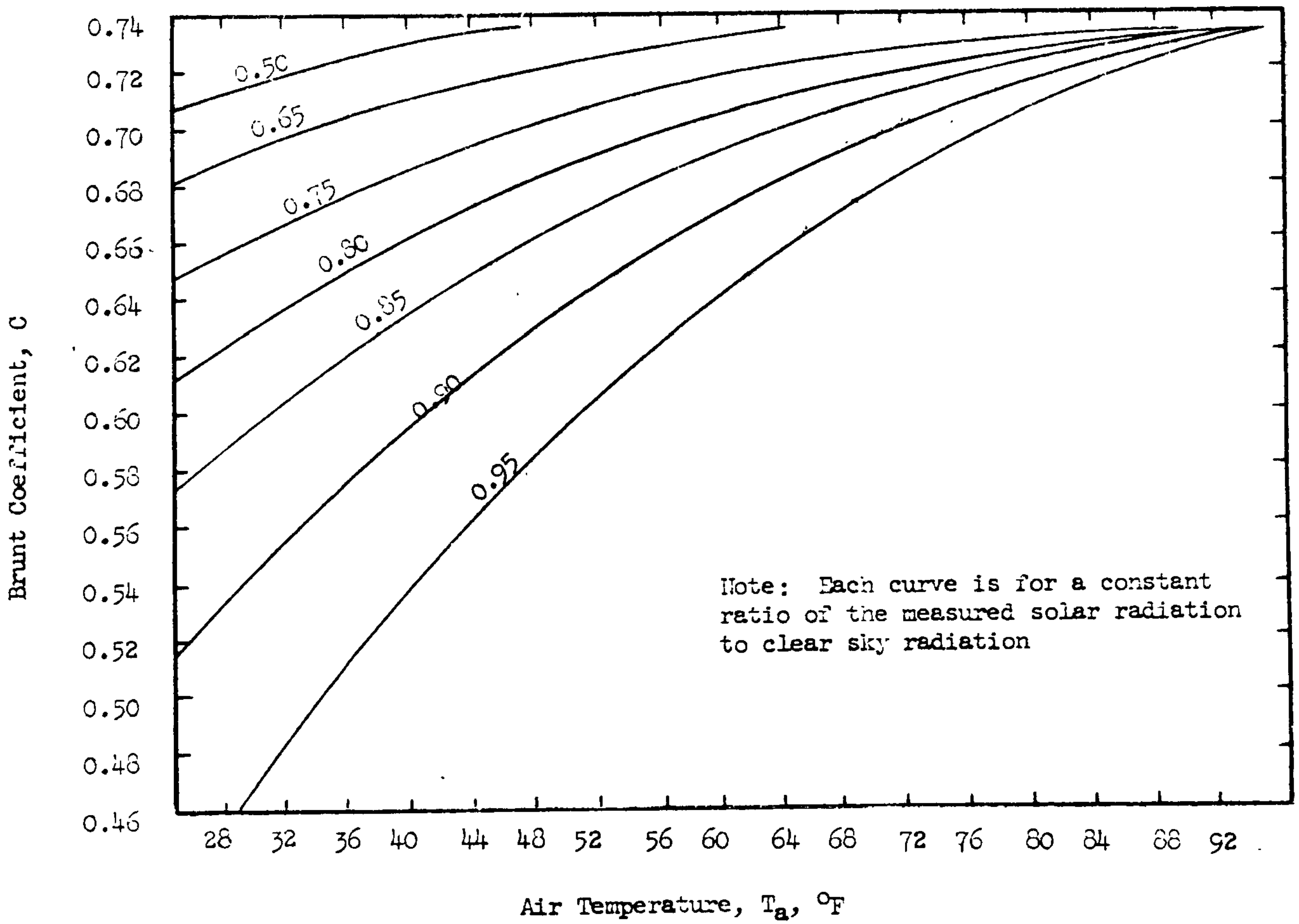
CLEAR SKY SOLAR RADIATION
(After Koberg, 1962)



*From: J. E. Edinger and J. C. Geyer, Heat Exchange in the Environment, Edison Electric Institute, New York, June 1965.

Figure 5.8*

BRUNT C COEFFICIENT FROM AIR TEMPERATURE, T_a, AND
RATIO MEASURED SOLAR RADIATION TO CLEAR SKY RADIATION
(After Koberg, 1962)



*From: J. E. Edinger and J. C. Geyer, Heat Exchange in the Environment, Edison Electric Institute, New York, June 1965.

$$R_s = \frac{H_{sr}}{H_s}\,, \qquad \text{Solar Reflectivity} \tag{5.23}$$

$$R_{ar} = \frac{H_{ar}}{H_a}\,, \qquad \text{Atmospheric Reflectivity}$$

Both of these coefficients are constants in the Edinger-Geyer formulation with $R_{sr} = 0.05$ and $R_{ar} = 0.03$.

The back radiation term, H_{br}, is computed from the Stefan-Boltzman fourth-power radiation law:

$$H_{br} = 0.97\ \sigma(T_s + 460)^4 \tag{5.24}$$

where

H_{br} = Rate of back radiation, $\left(\frac{\text{BTU}}{\text{ft}^2 - \text{day}}\right)$

σ = Stefan-Boltzman constant

T_s = Water surface temperature, °F

The Edinger-Geyer formulation approximates (5.24) by expanding the terms in parenthesis and dropping all terms except the first order term. This approximation yields

$$H_{br} = 0.97\ \sigma(460)^4 \left[4\ \frac{T_s}{460} + 1\right] \left(\frac{\text{BTU}}{\text{ft}^2 - \text{day}}\right), \tag{5.25}$$

a result which is low by 4.9% at T_s = 50°F and low by 14.9% at T_s = 100°F.

The evaporative heat, H_e, is represented in the Edinger-Geyer model by the general equation:

$$H_e = (a + bW)\ (e_a - e_a) \left(\frac{\text{BTU}}{\text{ft}^2 - \text{day}}\right) \tag{5.26}$$

where

a,b = coefficients depending on evaporation formula used

W = wind speed, mph

e_a = air vapor pressure, mm Hg.

e_s = the saturation vapor pressure determined from water surface temperature, mm Hg.

The user of the model supplies the a and b coefficients.*

The heat conduction term, H_c, is found using the Bowen ratio, where the Bowen coefficient is set equal to 0.26. Hence, H_c at atmospheric pressure is:

$$H_c = 0.26\ (a + bW)\ (T_s - T_a)\ \left(\frac{BTU}{ft^2 - day}\right) \tag{5.27}$$

Using the expressions obtained above, the net rate of heat transfer, ΔH shown in (5.21), can be written as:

$$\Delta H = H_R - \underset{I}{0.97\ \sigma} \left[\left(T_s + 460\right)^4\right] - \underset{II}{(a + b_W)\ (e_s - e_a)}$$

$$- \underset{III}{0.26\ (a + bw)}\ (T_s - T_a)\ \left(\frac{BTU}{ft^2 - day}\right) \tag{5.28}$$

Equation (5.28) is the basic equation for the heat budget used by the Edinger-Geyer model. The heat loss terms in (5.28) are: (I) the back radiation, H_{br}, (II) the evaporative heat loss in its general form, H_e, and (III) the conductive heat loss, H_c. The assumption that only the linear term of the back radiation formula is retained will be re-introduced later.

Equation (5.28) serves as the first step in the equilibrium temperature approach which was introduced by Edinger-Geyer to aid in the prediction of water temperatures.

<u>Equilibrium Temperature and the Exchange Coefficient</u>

The equilibrium temperature is defined as that water surface temperature for which the net exchange of heat at the air-water interface is zero. Hence, at the equilibrium temperature, $T_s = E$, $\Delta H = 0$ and there is a corresponding saturation vapor pressure, $e_s = e_E$. Then (5.28) can be written as:

*For this study a = 0 and b = 11.4, the Lake Heffner coefficients.

$$H_R = 0.97\ \sigma \left[\left(E + 460\right)^4\right] + (a + bW)\ (e_E - e_a)$$

$$+ 0.26\ (a + bW)\ (E - T_a) \left(\frac{BTU}{ft^2 - day}\right) \qquad (5.29)$$

Note that for a given set of conditions (H_r, T_a, e_a, and W), a body of water that has a temperature below equilibrium temperature will approach equlibrium temperature by warming, and a body above equilibrium will approach equilibrium temperature by cooling. The absorption radiation term, H_R, can be removed from (5.29) by subtracting (5.29) from (5.28) to yield:

$$\Delta H = - \left[0.97\ \sigma \left\{ \left(T_s + 460\right)^4 - \left(E + 460\right)^4 \right\} \right.$$

$$\left. + (a + bW)\ (e_s - e_E) + (a + bw)\ 0.26\ (T_s - E) \right] \qquad (5.30)$$

The relationship between water temperature and its saturation vapor pressure is shown in Fig. 5.9. If it is assumed that the vapor pressure difference is proportional to the temperature difference for 10°F temperature increments, then a linear relationship can be established:

$$(e_s - e_E) = \beta\ (T_s - E) \qquad (5.31)$$

where

$e_s - e_E$ = vapor pressure difference, mm Hg.

$T_s - E$ = temperature difference, °F

β = proportionality factor, $\frac{\text{mm Hg}}{°F}$

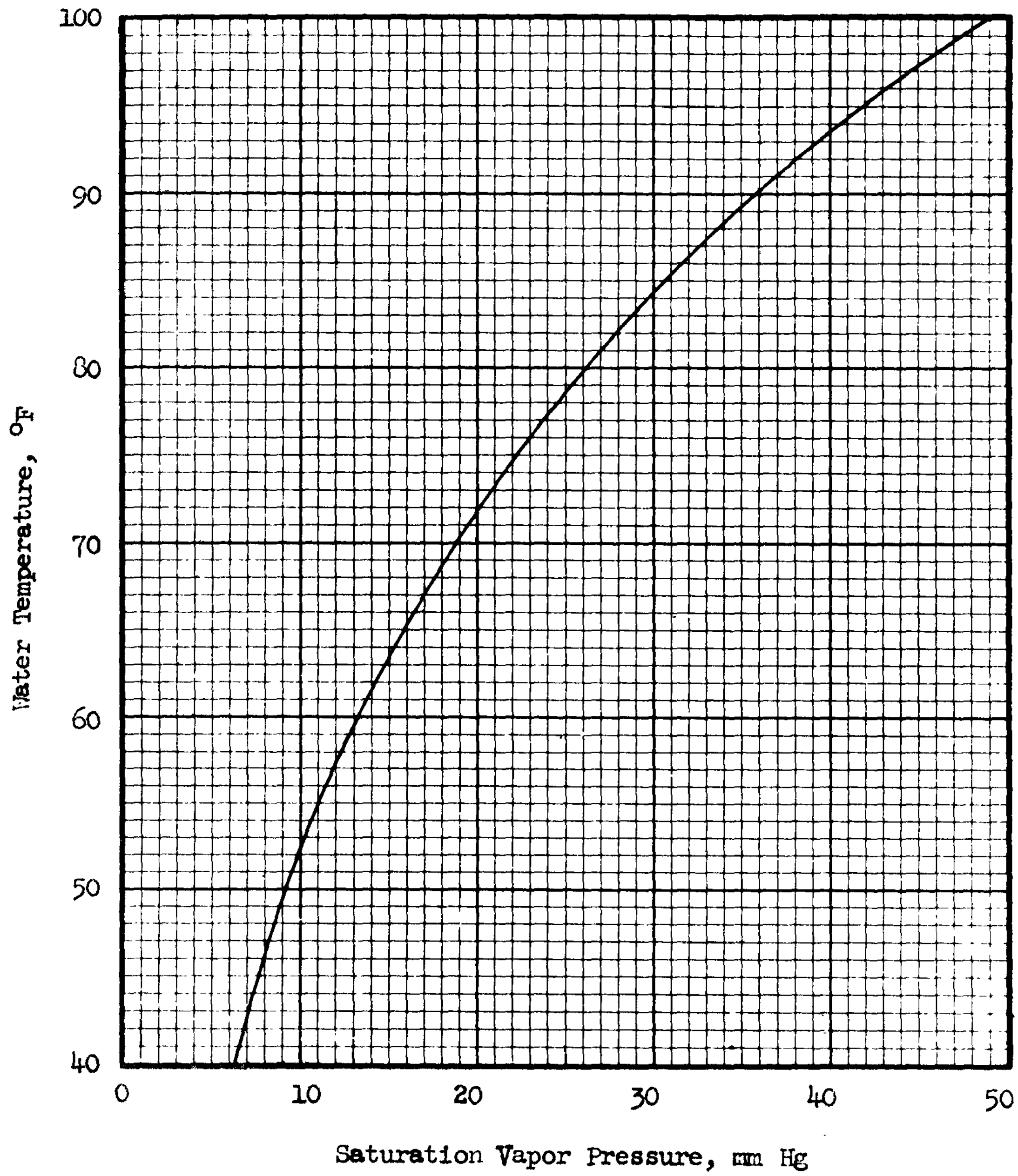
Also, the fourth power radiation terms can be expanded and, it has been shown,[4] that if the linear term of the expansion is retained, the fourth order power term is approximated to within 15% accuracy.

When the two above approximations are inserted into (5.30), it becomes

$$\Delta H = - \left\{ \left[15.7 + (0.26 + \beta)\ (a + bW) \right] (T_s - E) \right\} \left(\frac{BTU}{ft^2 - day}\right) \qquad (5.32)$$

Figure 5.9*

SATURATION VAPOR PRESSURE VS WATER TEMPERATURE
(OR DEW POINT TEMPERATURE)



*From: J. E. Edinger and J. C. Geyer, Heat Exchange in the Environment, Edison Electric Institute, New York, June 1965.

The exchange coefficient, K, is defined as the net rate at which heat is lost or gained by a body of water for a unit temperature difference and is given by:

$$K = 15.7 + (0.26 + \beta)\ (a + bw)\ \left(\frac{BTU}{ft^2 - day - °F}\right) \qquad (5.33)$$

Hence, (5.32) can be written compactly as

$$\Delta H = - K\ (T_s - E)\ \left(\frac{BTU}{ft^2 - day}\right) \qquad (5.34)$$

The exchange coefficient should be evaluated for each 10°F temperature range for each of the evaporation formulae. When the exchange coefficient is evaluated for a particular evaporation formula, it is no more reliable than the evaporation formula itself. Edinger-Geyer[4] present a series of figures, tables, and equations which systematize the calculation of the exchange coefficient, K, and the determination of the equilibrium temperature, E.*

Non-Stratified One-Dimensional Temperature Distribution

In the non-stratified one-dimensional temperature distribution, water temperatures vary longitudinally along the river, but are constant with river depth and width. Raised temperatures, resulting from the addition of heat (advected heat) to the water body by a heat source such as a power plant, decay in the downstream direction and attempt to approach the equilibrium temperature by heat exchange between the water and the atmosphere. Since the heat added to the water body is assumed to be thoroughly mixed, the rate at which the temperature changes in the downstream direction can be considered as being proportional to the product of the exchange coefficient and the temperature excess. If longitudinal advection is the dominating transport mechanism, under steady-state conditions, the equation for the

*Some of the tables and graphs in Reference 4 are in error and an errata sheet has been issued by Johns Hopkins.

rate of temperature change in the longitudinal direction, assuming a rectangular cross-section, is

$$\rho C_p DU \frac{dT}{dx_1} = - K(T - E) \tag{5.35}$$

where

ρ = density of water, 62.4 lbs/ft^3

C_p = specific heat of water, 1.0 $\frac{BTU}{lb}$

D = mean depth, ft

U = mean stream velocity, ft/sec

$\frac{dT}{dx_1}$ = longitudinal temperature gradient, $\frac{°F}{ft}$

T = stream temperature, °F

x_1 = distance, ft

The solution of (5.35) is

$$T = E + (T_m - E) e^{-\frac{Kx_1}{\rho C_p DU}} \tag{5.36}$$

where T_m is the mixed temperature at the heat source discharge and can be found from

$$T_m = \frac{Q_p}{Q_R} T_o + \left(1 - \frac{Q_p}{Q_R}\right) T_R \ (°F) \tag{5.37}$$

where

Q_p = source withdrawal, $\frac{ft^3}{sec}$

Q_R = total river flow, ft^3/sec

T_o = temperature of source discharge, °F

T_R = temperature of river before heat is added, °F

Noting that

$$x_1 W^1 = A$$

where

W^1 = width of river

A = surface area, ft^2

(5.36) becomes

$$T = E + (T_m - E)\, e^{-\frac{KA}{\rho C_p Q_R}} \tag{5.38}$$

Equation (5.36) or (5.38) can be used to calculate temperatures in a river downstream from a heat source. Either (5.36) or (5.38) along with the heat budget, the selection of the equilibrium temperature E, and the calculation of the heat exchange coefficient, K, form the basis of the Edinger-Geyer one-dimensional river model.

Transport Mechanism

Equations (5.36) and (5.38) are steady-state equations since they do not take into account the time variation of temperature in the stream, nor the time variation of any of the physical parameters. As an approximation, it can be assumed that if the time of water travel between two points is less than the period of averaging used for all the time varying parameters (K, E, T_R, T_o, T_m) then the steady-state equation can be used. The time of travel is

$$t = \frac{x_1}{U} \text{ days} \tag{5.39}$$

Hence, if a daily average value is computed then the equation can be applied for a distance between two points equal to one day of water travel. Also the application of (5.36) or (5.38) does not depend on beginning a reach at the source discharge but can be applied between reaches of the stream. The temperature is first computed between the plant discharge and the first reach, then the computed temperature at the end of the first reach is taken as the mixed temperature for the beginning of the second reach and so on downstream until the allowable time of travel (say 1 day) has expired. At this point all the time varying parameters are updated and the model continues calculating temperatures as it proceeds downstream. New sources of heat are assimilated by the river as they are encountered.

5.2.3 The STREAM River Simulation Package[17]

The STREAM River Simulation Package was developed by the Ohio River Valley Water Sanitation Commission (ORSANCO) to enhance the application of electronic river quality monitor systems in the operation of water quality management programs. STREAM is different from the other two models reviewed in this study in that it is a water quality model rather than solely a river temperature prediction model. Hence, river temperature is but one output parameter available from the model, the others being parameters such as dissolved oxygen, conductivity, chorides, etc.* Though the model was designed specifically for use on the Ohio River, the authors[17] claim that it is applicable to any free flowing or canalized river.

Essentially, the river temperature prediction module incorporated within STREAM is a one dimensional, steady state, far field model. The model has three modes of operation.

PROFILE -- The temperature profile along the river is given on a specified date.

FORECAST -- A particular point along the river is selected and the temperature variation as a function of time is given for that locale.

RUN -- The model follows a slug of water downstream and predicts the temperature of that slug as it moves downstream. Both time and location are output variables.

Operation of the STREAM temperature module requires the following information

- The ambient temperature of the mainstream
- River flow
- River velocity as a function of the river mile

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*However, since this study is concerned only with the river temperature prediction capability of STREAM, no further mention of the model's other output parameters will be made.

- The rate and location of heat discharged into the river
- Tributary flows and temperatures
- Specification of heat die-away constant.

The Temperature Module

The temperature module within STREAM calculates temperature rise and die-away resulting from thermal discharges or from tributary discharges. The module does not use an explicit heat budget as do the other two models reviewed for the following reasons:

> "Many temperature models were examined in the course of developing 'STREAM' and all were found unsuitable because copious meteorological data, most of which is not readily available, were required to calculate heat budgets, and then temperatures. In addition, many stream temperature models require physical cross-section data for purposes of determining diffusion characteristics. Since these types of temperature models did not readily lend themselves to an efficient modeling mechanism, particularly a mechanism involving only water quality data, another approach was tried."[18]

The other approach tried was the formulation of the postulate that within the time frame of one day, unnatural stream temperatures will exponentially approach natural stream temperatures. For the purposes of the STREAM model natural temperature is defined as the river temperature measured at monitoring stations having no apparent heat sources immediately upstream from them.[18]

Consequently, the temperature change resulting as the river flows downstream is calculated based on the exponential die-away of the difference between the river temperature and the estimated normal temperature of the river. This relationship is given by

$$T = T_n + (\Delta T)\ 10^{-Kt}\ (^\circ F) \qquad (5.40)$$

T = temperature of the river downstream from a tributary or heat discharge point, °F

T_n = normal temperature of the river, ^0F

ΔT = temperature differential $(T_o - T_n)$, ^0F

K = decay constant, day $^{-1}$

t = travel time, day

T_o = temperature at heat discharge point or at tributary inflow, ^0F

The decay constant, K, is usually chosen to be 1.0.[18]

Hence, the STREAM temperature module is rather unique since it is independent of day-by-day detailed weather variables, such as wind speed, humidity, cloud cover, solar radiation etc.

The Transport Mechanism

The transport mechanism consists of a travel time module which calculates the time of travel to the next model discontinuity* as well as the distance traveled by the end of the day. An assumption basic to the travel time module is that velocity at a constant flow can always be defined as a linear function of river milepoint. More simply, this means that given the velocity at two consecutive discontinuites, the velocity between these two discontinuites is assumed to vary linearly, that is

$$V = a + bx \quad \text{(mi/day)} \tag{5.41}$$

where

a is the V intercept, mile/day

b is the slope, 1/day

x is the milepoint, miles

Once the velocity coefficients, a and b, are specified by the user, the model uses these values until a different set is specified at some downstream mile point.

*By discontinuities are meant place dependent events such as location of power plants, location of dams, changes in the river channel, etc.

The calculation of travel time to the next discontinuity is based upon

$$t = \frac{d}{\bar{V}} \text{ (days)} \tag{5.42}$$

where

t = time, days

d = distance between the upstream discontinuity and the downstream discontinuity, mi

$\bar{V}$ = the arithmetic average of the velocities at the upstream and downstream discontinuity points, mi/day

The transport mechanism works as follows: the time increment calculated by (5.42) is added to the accumulated elapsed time within the day being simulated and checks to determine if the total elapsed time exceeds one day. If not the temperature is calculated. If the elapsed time exceeds one day, the downstream mile point reached at the end of the day is determined, the temperature parameters are updated, and the travel time module initiated for the new day.

Section 5 References

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17. Ohio River Valley Water Sanitation Commission, Automated Forecast Procedures for River Quality Management - Volume I: Project Report, June 1972.

18. D. A. Dunsmore and W. A. Bonvillain, "STREAM - A Generalized Dynamic Working River Model," Paper presented at COMMON meeting, Miami Beach, Florida, October 1972.

6. MODEL EVALUATION

Three river temperature prediction models (COLHEAT, Edinger-Geyer*, and STREAM) were chosen by the United States Environmental Protection Agency, Region V, for evaluation by the Argonne National Laboratory. The purpose of the evaluation is to select the most appropriate model for use as a river temperature prediction mechanism for various river conditions. The first part of this section describes the model evaluation strategy that was adopted as well as the data which were used in the evaluation procedure. The second part of this section presents the results of the evaluation.

6.1 Evaluation Design

As each model was obtained it was placed on Argonne's IBM 360/195 digital computer. The COLHEAT model was obtained directly from the Hanford Engineering Development Laboratory while the STREAM model was obtained from the Ohio River Valley Water Sanitation Commission (ORSANCO) by way of the U.S. EPA Region V. Both of these models were programmed for computers** other than an IBM 360 so some modifications in the code had to be made before the models could be tested on Argonne's computer. Only the temperature and the several travel modules of STREAM were placed on Argonne's computer since the water quality routines were of no interest in this study. The EPA Region V version of the Edinger-Geyer model was written for an IBM 360 computer and was easily implemented on the Argonne system.

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*In this report the "Edinger-Geyer Model" means the U.S. EPA Region V computer program version of the Edinger-Geyer one-dimensional river temperature prediction model described in reference 3 of this section.

**COLHEAT was programmed for a Univac 1108 while STREAM was programmed for an IBM 1130.

The year 1964 was chosen as the base year for the purpose of model evaluation. Three events led to the selection of 1964 as the base year; first, the most recently published soundings of the entire Ohio River by the Corps of Engineers are for 1964; second, a previous study[1] of the Ohio River used 1964 as a base year and part of the data collected for that study was made available to Argonne; and third, the year 1969 was also considered as a potential base year, but because of the rather lengthy period of time (relative to the length of this program) required by some of the power companies to compile and transmit advected heat data to Argonne, this alternative was rejected.

Each model was tested on the Ohio River in the 300 mile reach between Pittsburgh, Pennsylvania and Huntington, West Virginia (see Fig. 6.1). This reach was chosen in order to present the models with a stringent test. It was felt that the numerous thermal discharges occuring within the reach coupled with the lower flows relative to the remaining 700 miles of the river would test each model's precision* to the utmost since there are five measuring stations located along this reach

Data Acquisition

In order to apply the river temperature prediction models to the Ohio River, the following data is needed:

- Meteorological data (air temperature, dew point temperature, cloud cover, wind speed, and solar radiation)
- River dimensions
- Flow data for the Ohio River main stem and its major tributaries
- Measured water temperature
- Major heat inputs into the river

*Precision is defined herein as the ability of a model to replicate field measurements.

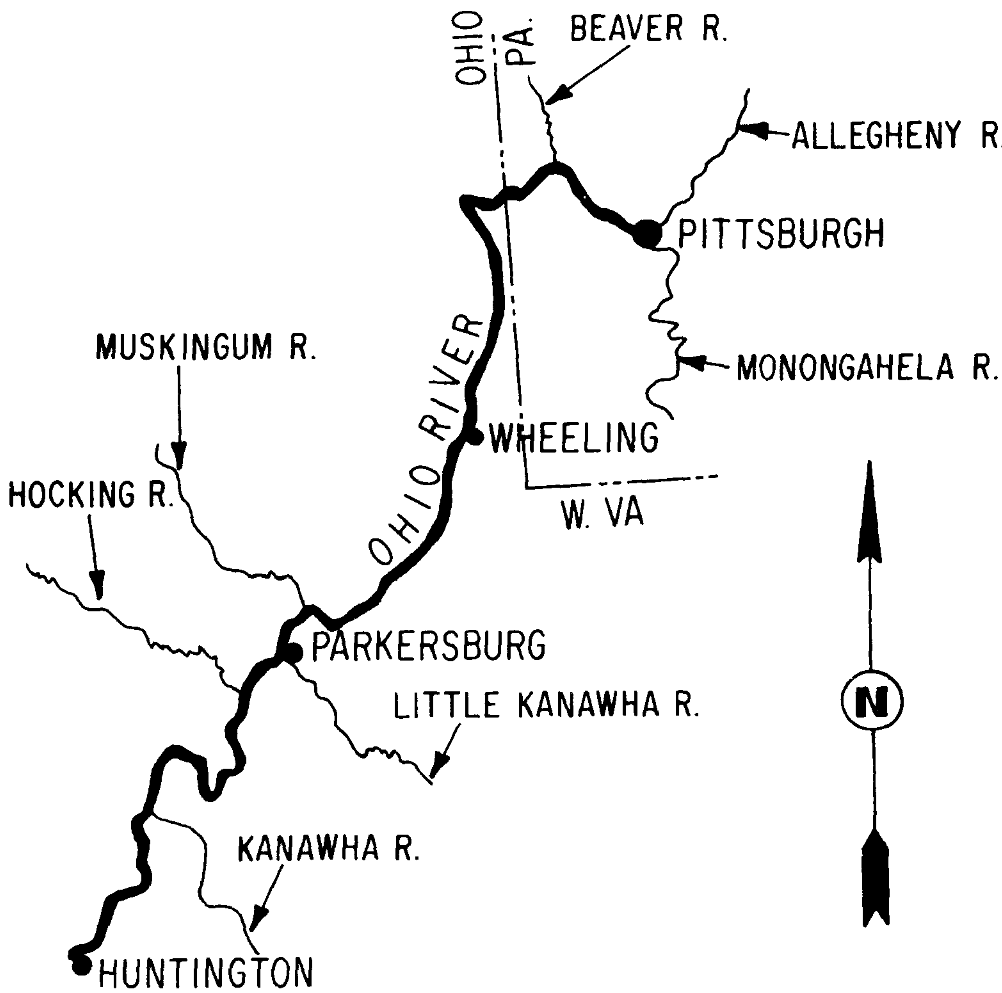


Figure 6.1

The Ohio River from Pittsburgh to Huntington

a. Meteorological Data

Meteorological information recorded at weather stations located along the Ohio River was obtained from the National Weather Record Center at Asheville, North Carolina. Along the first three hundred mile reach of the Ohio, daily values of air temperature, dew point temperature, wind speed and cloud cover are recorded at Pittsburgh, Pennsylvania and Huntington, West Virginia. Daily values of solar radiation are not measured along this river reach, but can be approximated by values measured elsewhere, such as State College, Pennsylvania. For model evaluation, the meteorological data recorded at Huntington, West Virginia Tri-State Airport Station were used and the solar radiation data were taken from the State College, Pennsylvania Station. At both Huntington and State College the daily average values obtained were used in both the COLHEAT and Edinger-Geyer Models (meteorological data is not necessary for the STREAM Model).

The 1964 average monthly and normal average monthly air temperatures, precipitation amounts and wind speeds for Huntington, West Virginia are shown in Table 6.1. It is seen that 1964 was a cool dry year relative to a normal year.

b. River Dimensions

Soundings of the Ohio River have been recorded by the Corps of Engineers, most recently in 1964, in order to determine river contour charts for navigational purposes. The charts can be used to construct actual river cross sections from which cross-sectional areas can be calculated or found using a planemeter. This rather time consuming process of computing cross sectional areas had been accomplished previously by the Battelle-Northwest Laboratory which supplied this data to Argonne.

Table 6.1

1964 Average Monthly and Normal* Average Monthly Air Temperatures, Precipitation Amounts, and Wind Speeds for Huntington, West Virginia

Month	Air Temperature, ^0F		Precipitation, In.		Wind Speed, MPH	
	1964	Normal	1964	Normal	1964	Normal
January	34.2	36.6	2.11	3.65	7.7	7.3
February	32.1	37.7	3.07	3.04	7.1	7.4
March	46.4	44.8	4.53	4.20	8.3	8.0
April	58.0	55.7	3.09	3.67	7.8	7.5
May	66.0	64.6	1.25	3.89	5.9	6.2
June	71.7	72.0	1.97	4.10	5.5	5.1
July	76.0	75.2	2.18	4.50	4.4	4.9
August	73.0	74.0	6.21	2.82	4.9	6.3
September	65.7	68.2	4.53	2.54	4.5	5.9
October	52.2	57.3	0.80	1.85	4.7	5.5
November	48.0	45.5	3.37	2.46	5.4	6.7
December	39.4	37.4	3.90	2.81	6.5	7.2

*By normal is meant revised climatological standard normals based on the period 1931-1960. Normals are arithmetic averages that have been adjusted to represent observations at the present location of the weather instruments.

Data Sources: U.S. Department of Commerce, Weather Bureau, "Local Climatological Data - Huntington, West Virginia," 1964.

E. L. Thackston and F. L. Parker, Effect of Geographical Location on Cooling Pond Requirements and Performance, EPA Report 16130 FDQ 03/71, March 1971.

c. Flows

Daily flow values are recorded by the United States Department of the Interior, Geological Survey (USGS) for many locations along the Ohio River and on most of the major tributaries (see Table 6.2). The values are summarized by hydraulic year (October - September) in publications available from the appropriate branch office in the state which has jurisdiction over the waterway.

For the model evaluation phase of this report the flows used were those measured at Sewickly, Pennsylvania and Parkersburg, West Virginia.

d. Water Temperature

Since actual water temperatures are needed to determine the precision of the river temperature prediction models, emphasis was placed on obtaining recorded river temperatures at as many locations as possible. Three sources have been contacted to obtain the required river temperatures:

- U. S. Geological Survey
- Ohio River Valley Water Sanitation Commission
- Municipal Water Works with intakes in the Ohio River

A listing of Ohio River Temperature data for the year 1964 is given in Table 6.3. Originally the measurements from five stations were to be used in the model evaluation phase; these stations being the first five shown in the table, but as is explained later, the South Heights temperatures could not be used.

e. Major Heat Inputs to the River

All the models require the daily discharges from heat sources. The Battelle Northwest Laboratory provided Argonne with power plant daily discharge data that they had obtained for their study.[1] This information included:

- The daily electric demand served by most of the power plants operating in 1964 and discharging into the river,
- The thermal and boiler efficiency of most of these plants.

Table 6.2

Flow Measurement Stations

A. Ohio River

Station	River Mile	Reported Flow	Quality
Sewickley, Pa.	11.8	Daily	good
St. Marys, W. Va.	135.0	Daily	poor
Parkersburg, W. Va.	184.4	Daily	good
Pomeroy, Ohio	265.4	Daily	poor
Point Pleasant, W. Va.	265.4	Daily	poor
Huntington, W. Va.	311.6	Daily	poor
Ashland, Ky.	322.5	Daily	poor
Maysville, Ky.	405.1	Daily	poor
Cincinnati, Ohio	470.5	Daily	poor
Louisville, Ky.	607.3	Daily	good
Evansville, Ind.	792.3	Daily	poor
Golconda, Ill.	903.1	Daily	poor
Metropolis, Ind.	944.0	Daily	fair
B. Major Tributaries			
Monongahela R. (Braddock, Pa.)		Daily	good
Allegheny R. (Natrona, Pa.)		Daily	good
Kanawha R. (Charleston, W. Va.)		Daily	fair
Kentucky R. (Lockport, Ky.)		Daily	fair
Green R. (Calhoun, Ky.)		Daily	fair
Cumberland R. (Smithland, Ky.)		Daily	poor
Tennessee R. (Paducah, Ky.)		Daily	good

Good means that about 95% of the measured daily discharges are within 10% accuracy.

Fair means that about 95% of the measured daily discharges are within 15% accuracy.

Poor means that daily discharges have less than "fair" accuracy.

Table 6.3

Ohio River Temperature Data

Station (Type)	River Mile	Frequency of Measurement
South Heights, Pa. (W)	15	D
Stratton, Ohio (O)	53.8	H
Wheeling, W. Va. (W)	86.8	D
Parkersburg, W. Va. (W)	230.	D
Huntington, W. Va. (O)	304.	H
Ironton, Ohio (W)	325.	D
Cincinnati, Ohio (O)	462.	H
Markland Dam (U)	531.5	D
Madison, Ind. (W)	560.	D
Louisville, Ky. (O)	601.	H
Evansville, Ind. (W)	790.	D

D = Daily H = Hourly

O = ORSANCO U = U.S.G.S. W = Water Works

A list of key individuals who were capable of supplying data to Argonne was obtained from Mr. James Carson, the Chairman of the Power Industry Advisory Committee to the Ohio River Valley Water Sanitation Commission. These individuals were contacted and asked to supply Argonne with data that would complement/supplement the data obtained from Battelle-Northwest Laboratory. Those power plants in the 300 mile river reach used for model evaluation are shown in Table 6.4. The average daily thermal discharge from each of these plants was used in each model's river temperature simulation.

Table 6.4

Power Plants Included in Model Evaluation

Plant*	River Milepoint
J. H. Reed	2.3
F. Phillips	15.6
W. H. Sammis	55.0
Toronto	59.1
Tidd	74.5
Windsor	79.5
R. E. Burger	102.5
Kammer	111.1
Willow Island	160.5
Philip Sporn	241.0
Kyger Creek	260.2

*The Shippingport plant (100 MW generating capacity) is not included in this list because 1) the Battelle Northwest Laboratory did not have data on this plant and 2) Duquesne Power and Light would not supply Argonne with the daily data necessary to compute daily thermal discharges.

Thermal discharges by industrial sources were estimated from the data that each industry files with the United States Environmental Protection Agency in order to obtain a discharge permit. These data were used to represent 1964 industrial thermal discharges and were analyzed for each industry possessing a discharge permit on the Pittsburgh-Huntington reach of the Ohio River. For those industries that discharged large amounts* of heat into the Ohio River a daily heat input was computed and included in the model evaluation phase. The selected industries and their river mile points are given in Table 6.5.

Table 6.5

Industrial Advected Heat Sources Used in Model Evaluation

Industry	River Milepoint
St. Joseph Lead Company	28.5
Crucible Steel	36.5
Wheeling Steel	68.8
Wheeling Steel	71.0
Koppers Company	71.0
Pittsburgh Plate Glass	119.7
Dupont	190.5

Evaluation Strategy

Four criteria were chosen to evaluate each model, namely:

1) How well the computed temperatures replicate observed temperatures;

2) The ease with which a user becomes proficient in model implementation;

3) How difficult it is to obtain the input data needed to implement the model; and

4) How theoretically complete (accurate) each model is.

*By large amounts of heat discharged by industrial sources are meant discharges of at least 750 MWH/day.

The cost of running each model is not selected as an evaluation criteria since this study is concerned with choosing that model which best replicates river temperatures. However, a cost comparison was made during the model evaluation phase resulting in an approximate cost per model per equivalent computer run. These costs were: COLHEAT $4.25; STREAM $2.75; and Edinger-Geyer $4.75.

It is recognized that the four criteria are not independent of one another. For example, a more theoretically complete model usually requires a larger number of input parameters than does a non-rigorous model, hence, 3 and 4 are related.

Since this study is concerned with selecting a model which best replicates observed data, criteria one is weighted more heavily than the other criteria. In fact, criteria 2, 3, and 4 are weighted about equally, with criteria 1 weighted about as heavily as criteria 2, 3, and 4 combined.

a. Application of Criteria 1

Criteria 1 is applied to the model evaluation procedure by comparing the 1964 average daily water temperatures predicted by each model with the actual 1964 average daily water temperatures observed at each of the four water temperature stations. The stations selected and their river mile points are Stratton, Ohio (53.8); Wheeling, West Virginia (86.8); Parkersburg, West Virginia (230.0); and Huntington, West Virginia (304.0). The degree to which the computed and observed water temperatures correlate is determined by evaluating statistically the difference between observed and predicted water temperatures as well as observing how closely the form of the predicted temperature follows that of the observed temperatures.

b. Application of Criteria 2

Criteria 2 is concerned with how quickly can a user learn to implement the model, and once this is learned, how easy is the model to use. This is a rather subjective evaluation and is based on our experience in implementing each of the models.

c. Application of Criteria 3

Criteria 3 is concerned with how difficult it is to obtain the data necessary to run each model. When this study was begun Argonne had no Ohio River data that could be applied to the model evaluation. Hence, the data gathering difficulty could be measured in time, the time needed to assemble the data.

d. Application of Criteria 4

Theoretical completeness is ascertained by analyzing the theoretical development of each model as well as the assumptions inherent in the development.

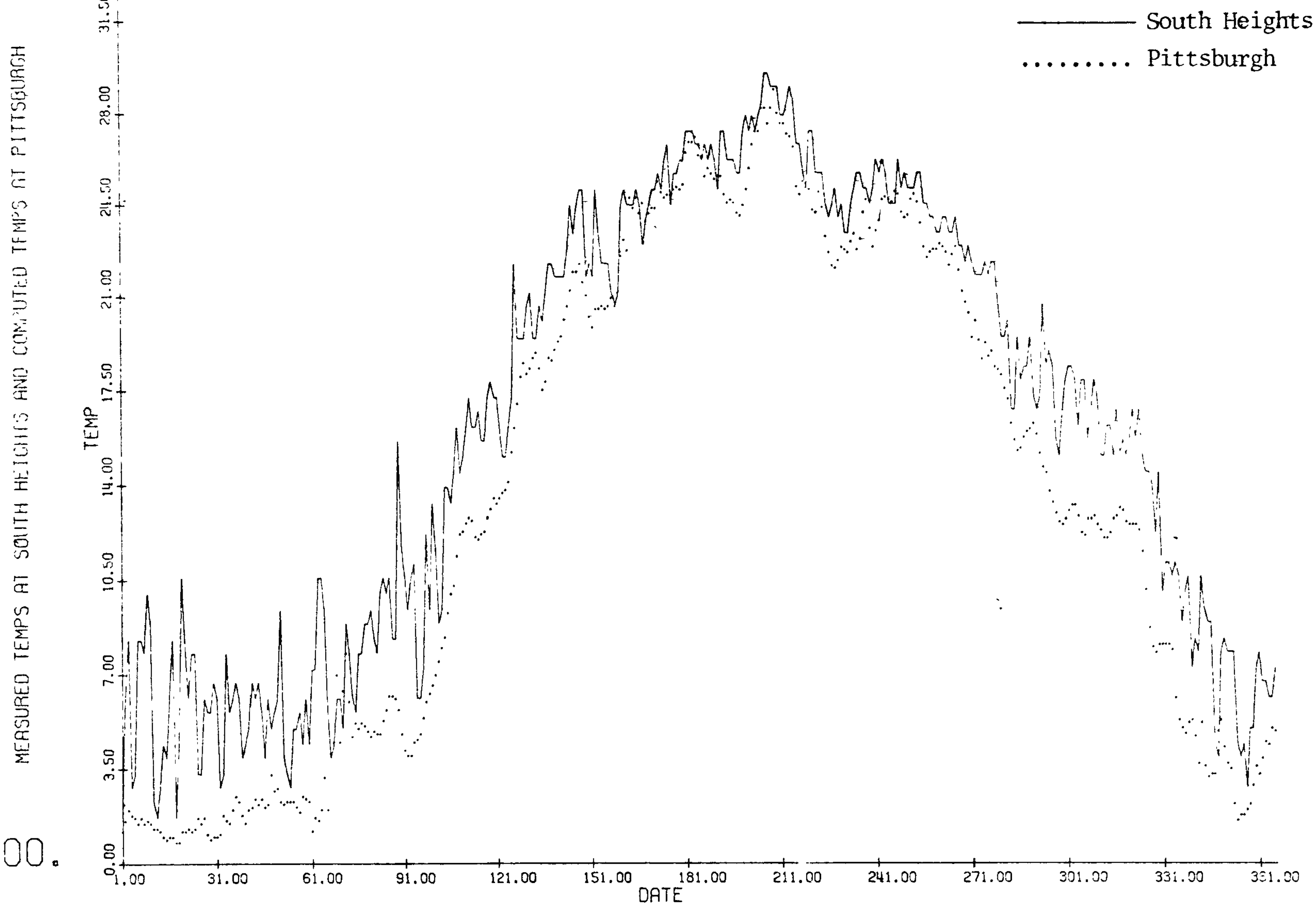
6.2 Evaluation Results

Originally each model was given the daily measured water temperature for 1964 at South Heights, Pennsylvania (milepoint 15) as its initial conditions. However, these recorded temperatures exhibited such large day to day variations (see Fig. 6.2) that they were considered unsuitable for model evaluation. In order to obtain an initial temperature as close as possible to Pittsburgh, Pennsylvania, temperatures recorded at Oakmont, Pennsylvania, near the mouth of the Allegheny River, and Chaleroi, Pennsylvania, near the mouth of the Monongahela River, were weighted by the river flow to obtain a temperature near Pittsburgh, Pennsylvania. The formula used to obtain the Pittsburgh temperature is:

$$T_p = \frac{T_o F_o + T_c F_c}{(F_o + F_c)} \tag{6.1}$$

Figure 6.2

Measured Temperatures at South Heights and
Computed Temperatures at Pittsburgh



where

T_p = Temperature at Pittsburgh

T_o = Temperature at Oakmont

T_c = Temperature at Chaleroi

F_o = Flow at Oakmont

F_c = Flow at Chaleroi

The temperatures used as Pittsburgh temperatures are shown in Fig. 6.2.

Each model used the computed Pittsburgh temperatures as initial conditions to predict temperatures at Stratton, Wheeling, Parkersburg, and Huntington. The results for each model at each temperature station are shown in Figs. 6.3 - 6.26.

6.2.1 Computer Temperature - Observed Temperature Correlation Stratton, Ohio

The water temperatures at Stratton, Ohio, are measured by an ORSANCO robot monitor which is located at the discharge of the raw water pumps of the water treatment plant of Ohio Edison Company's Sammis Power Plant. Water temperatures are measured hourly and are averaged over the day.

As shown in Fig. 6.3, the STREAM Model regularly predicts temperatures which are lower than the actual observed temperatures. This underprediction characteristic is particularly evident from days 181 through 271 (July through October) which constitute the potential low flow periods. STREAM generally follows the form of the observed temperatures except during January when the observed temperatures are about 6° C higher than the predicted temperatures.

The temperatures predicted by COLHEAT are shown with the observed water temperatures in Fig. 6.4. The temperatures predicted by COLHEAT are

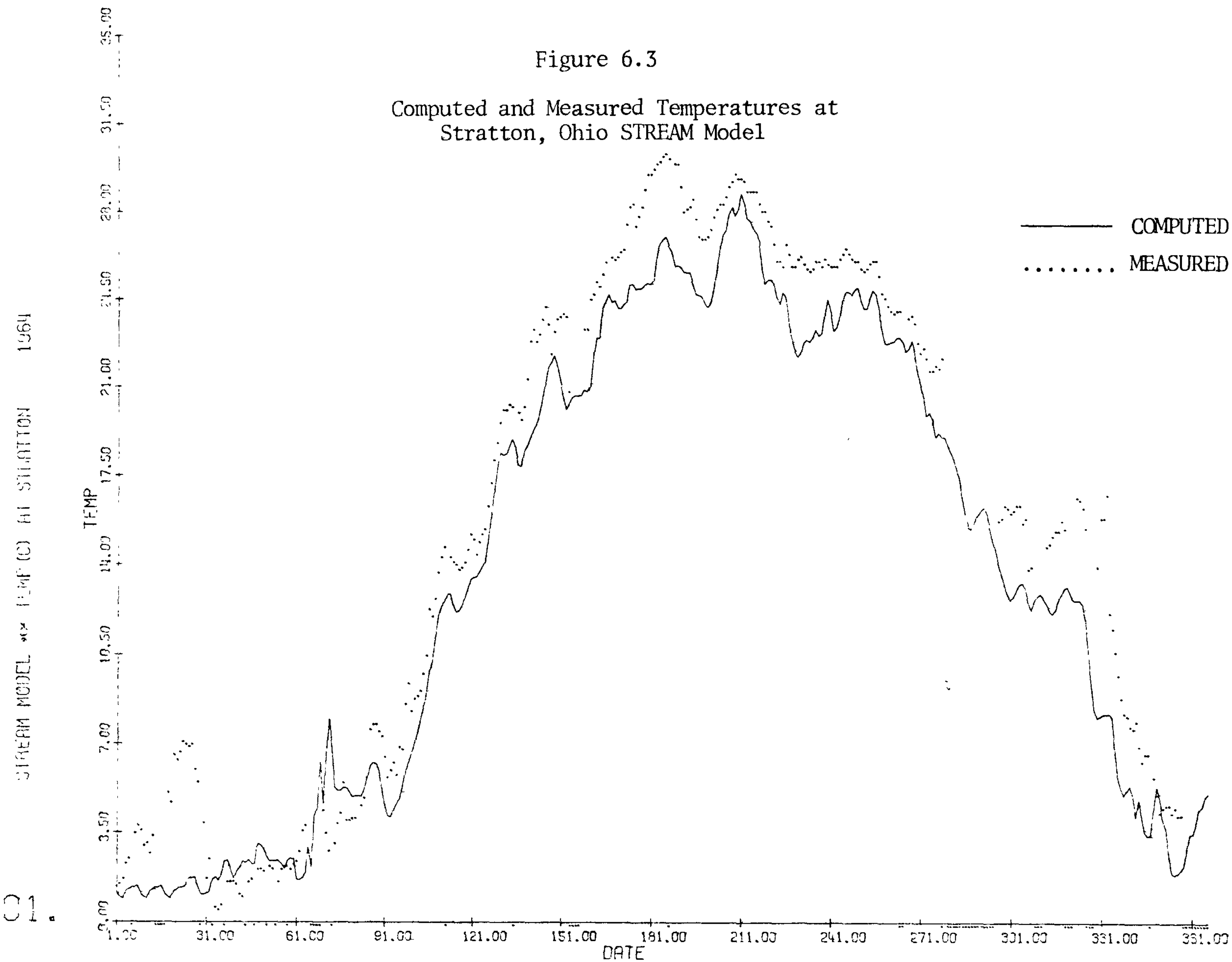


Figure 6.3

Computed and Measured Temperatures at Stratton, Ohio STREAM Model

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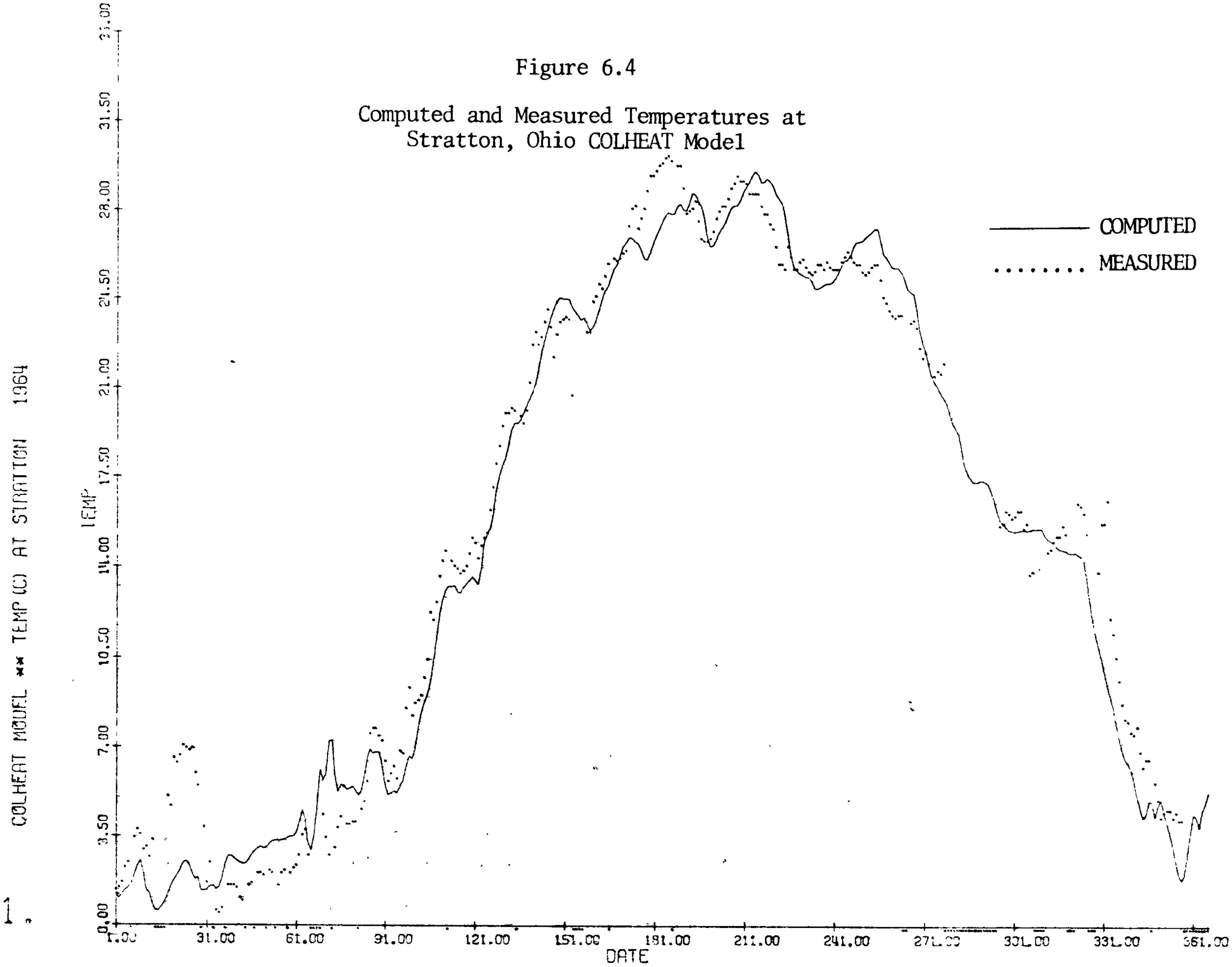
Figure 6.4

Computed and Measured Temperatures at
Stratton, Ohio COLHEAT Model



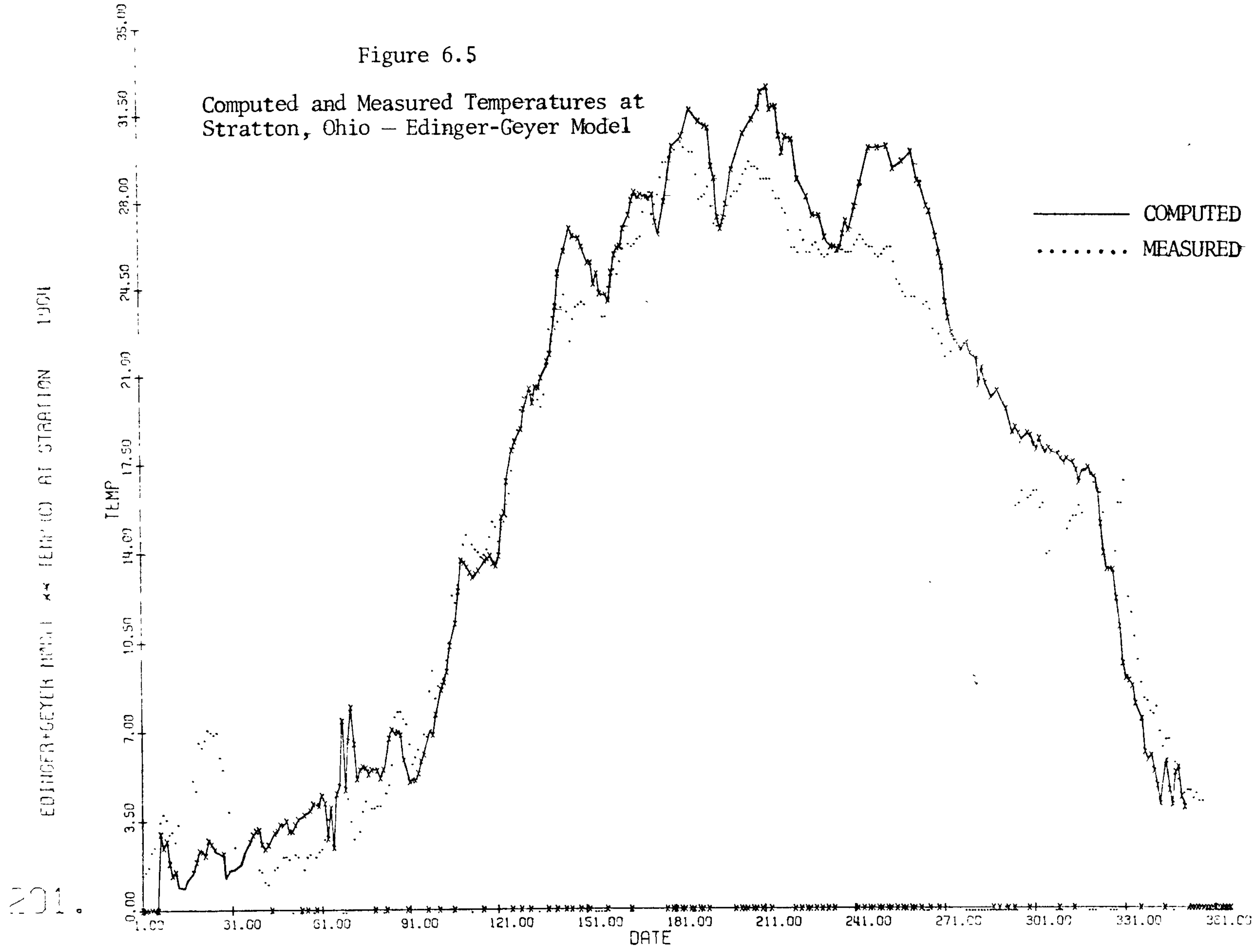


Figure 6.5

Computed and Measured Temperatures at Stratton, Ohio — Edinger-Geyer Model

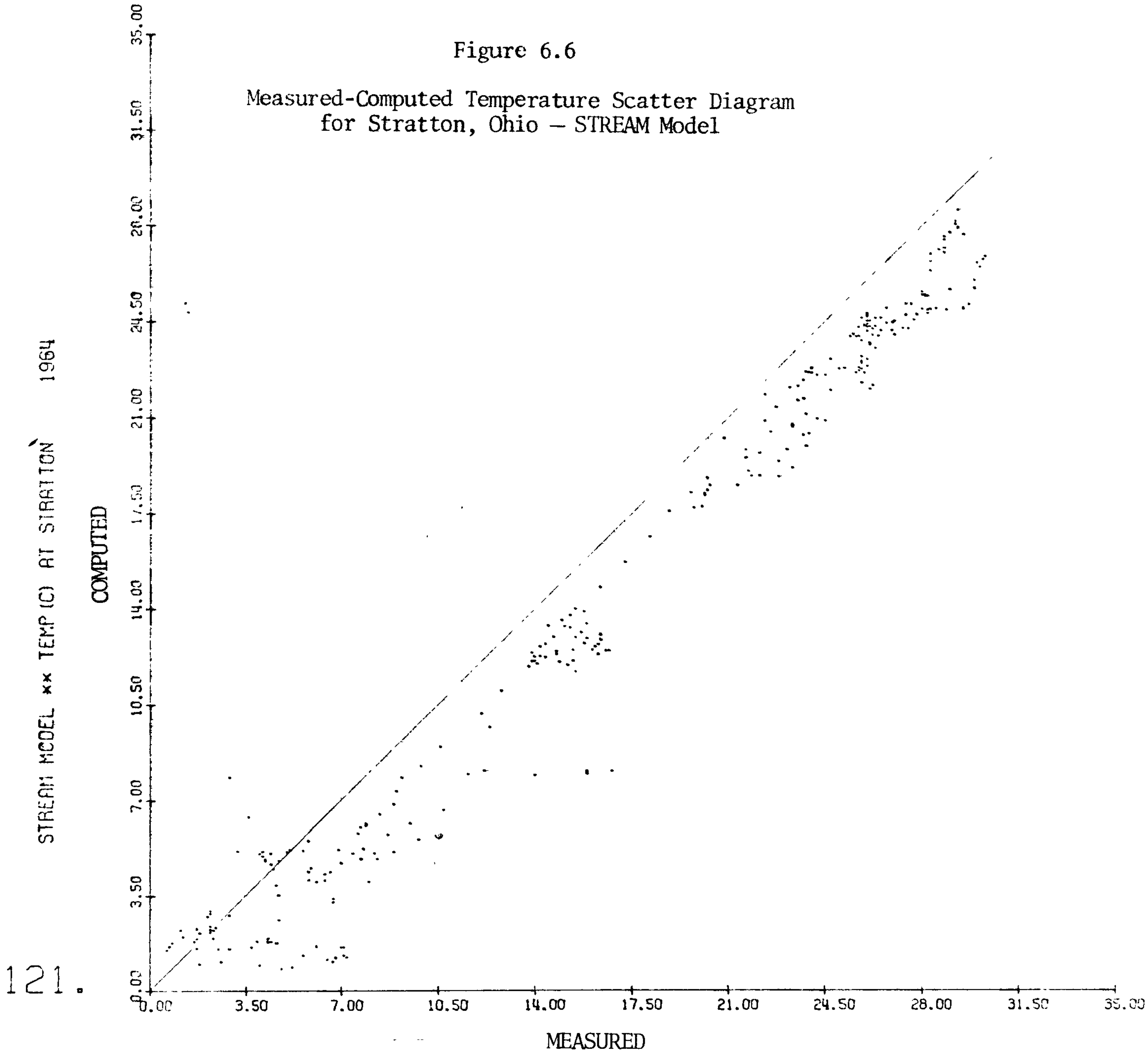


Figure 6.6

Measured-Computed Temperature Scatter Diagram for Stratton, Ohio – STREAM Model

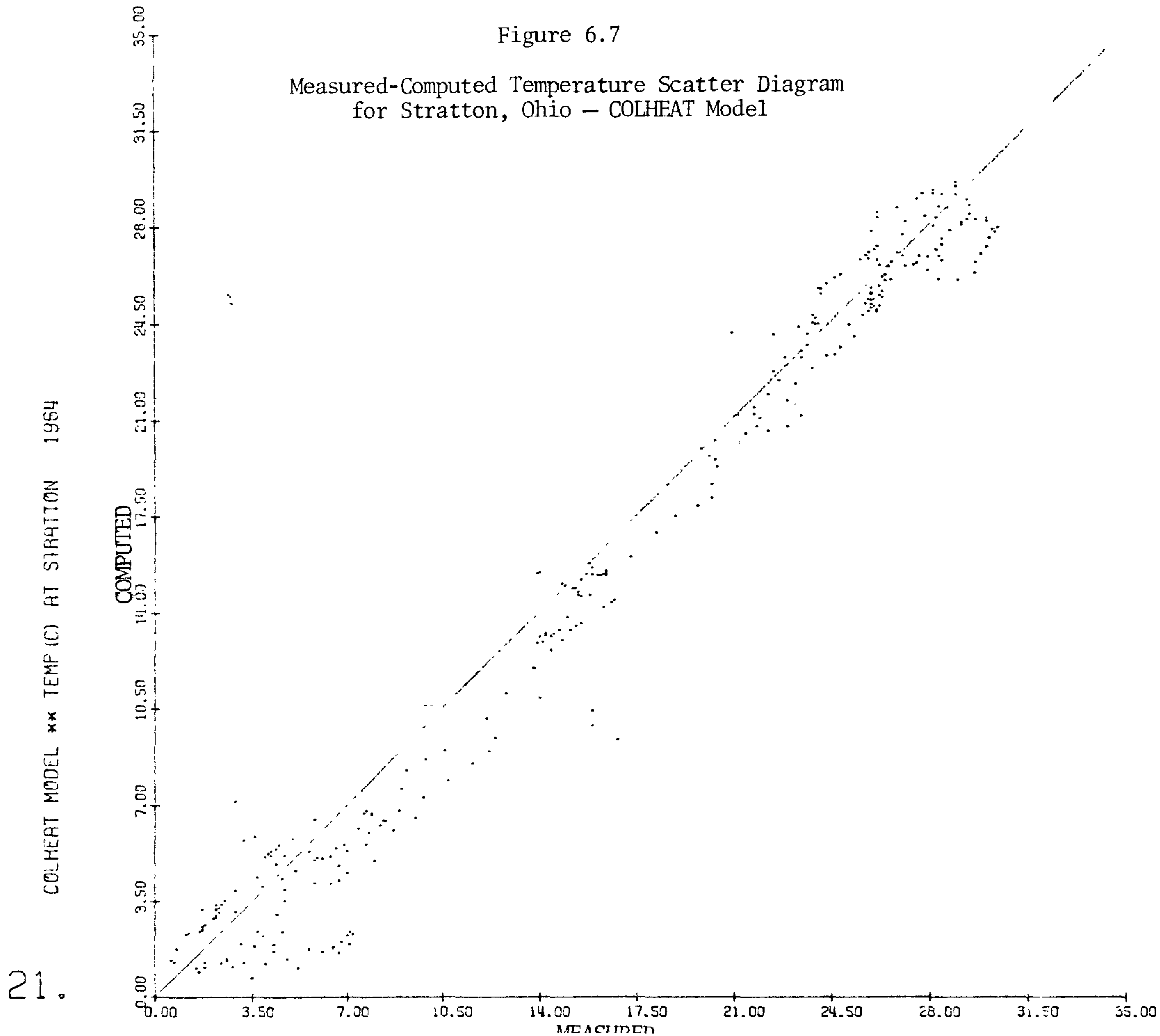


Figure 6.7

Measured-Computed Temperature Scatter Diagram
for Stratton, Ohio — COLHEAT Model

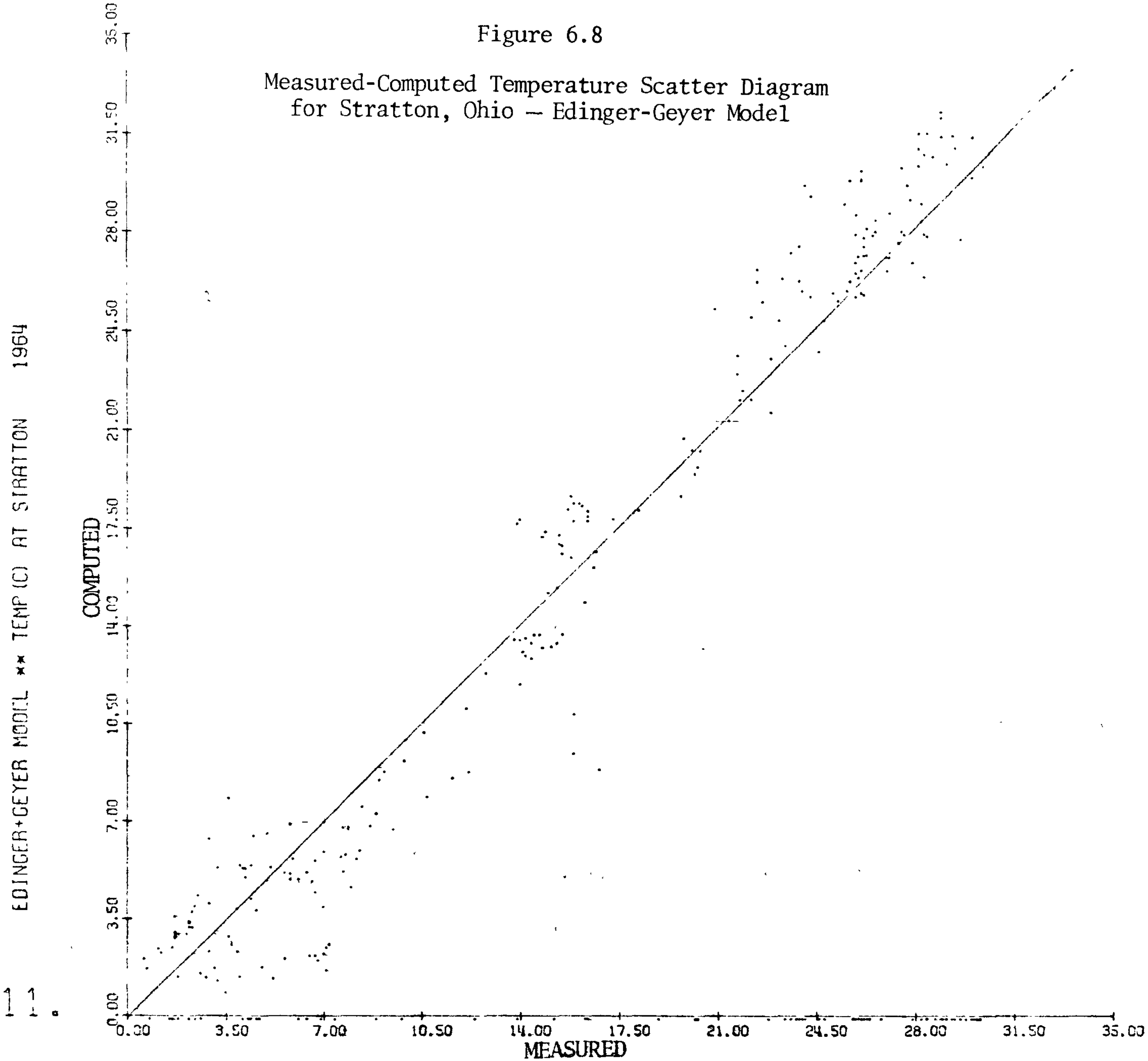


Figure 6.8

Measured-Computed Temperature Scatter Diagram
for Stratton, Ohio — Edinger-Geyer Model

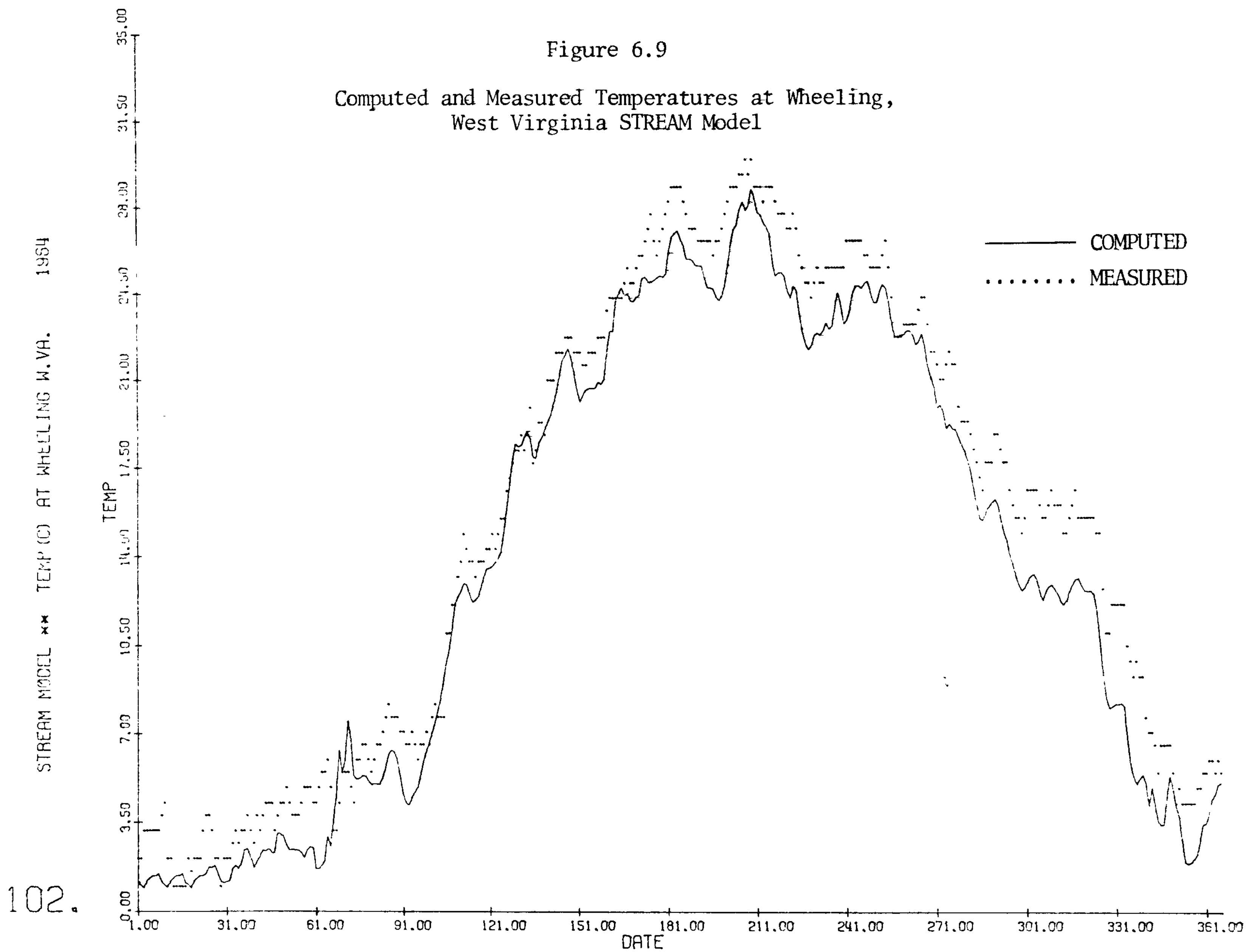


Figure 6.9

Computed and Measured Temperatures at Wheeling, West Virginia STREAM Model

Figure 6.10

Computed and Measured Temperatures at Wheeling, West Virginia — COLHEAT Model

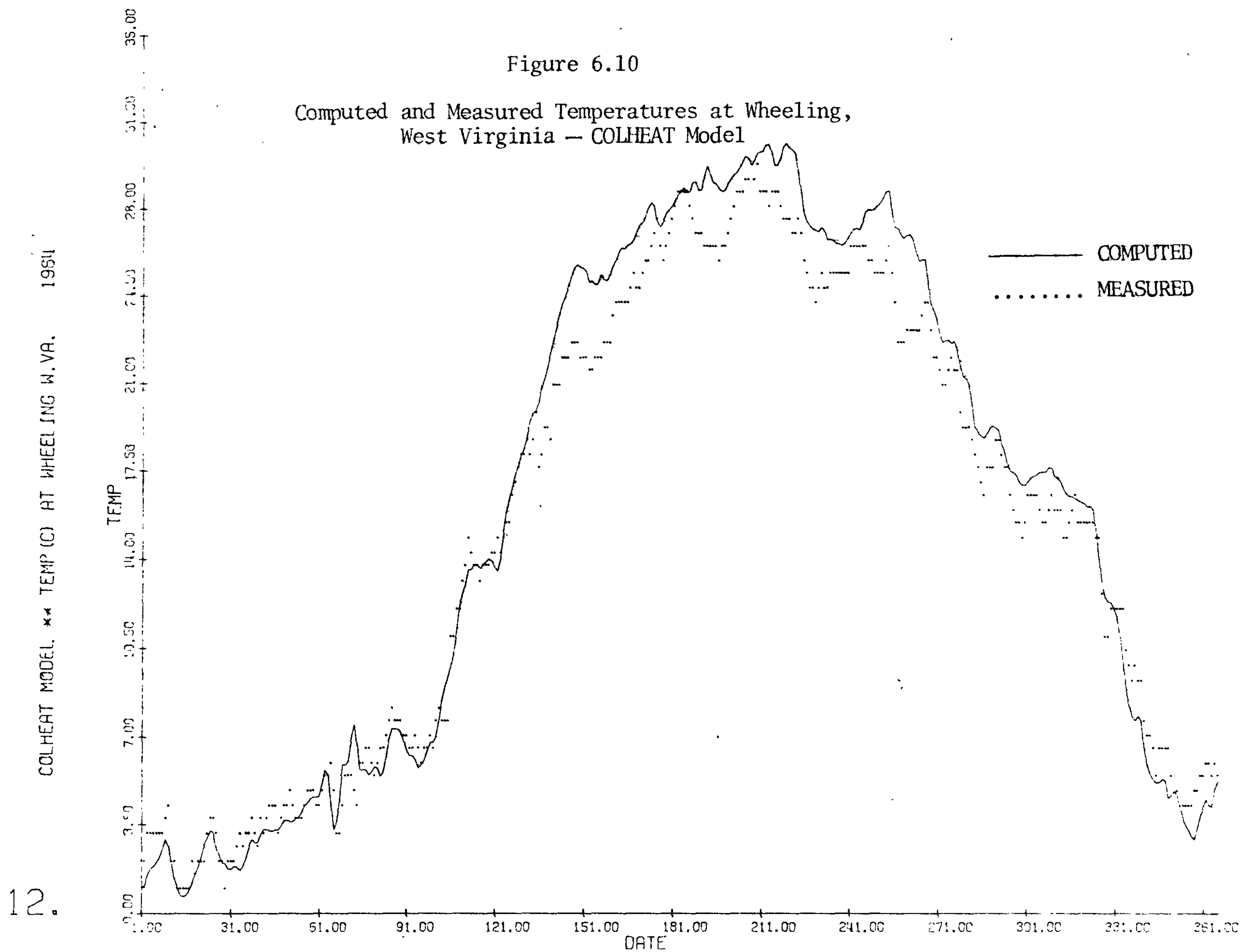


Figure 6.11

Computed and Measured Temperatures at Wheeling, West Virginia — Edinger-Geyer Model

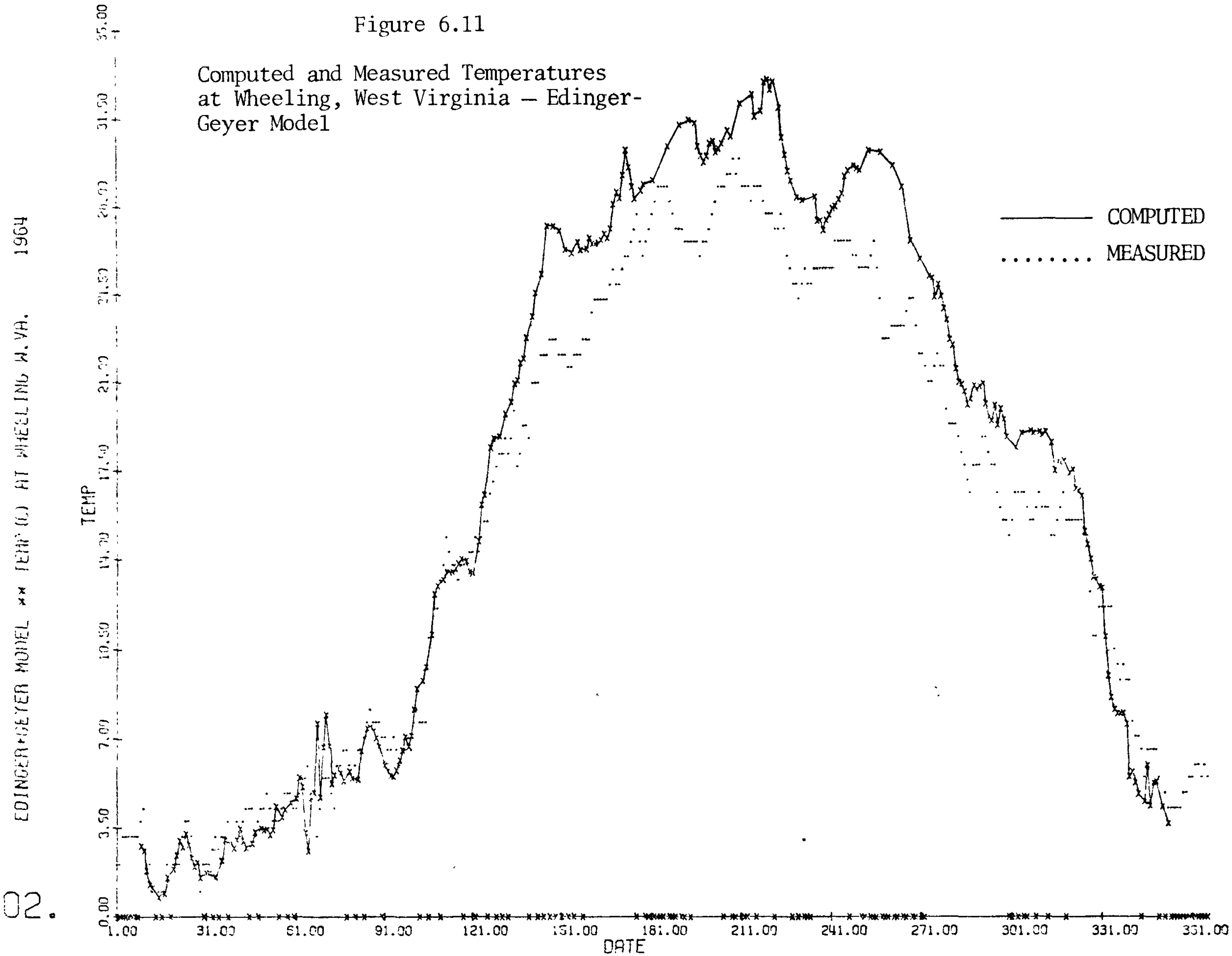


Figure 6.12

Measured-Computed Temperature Scatter Diagram
for Wheeling, West Virginia – STREAM Model

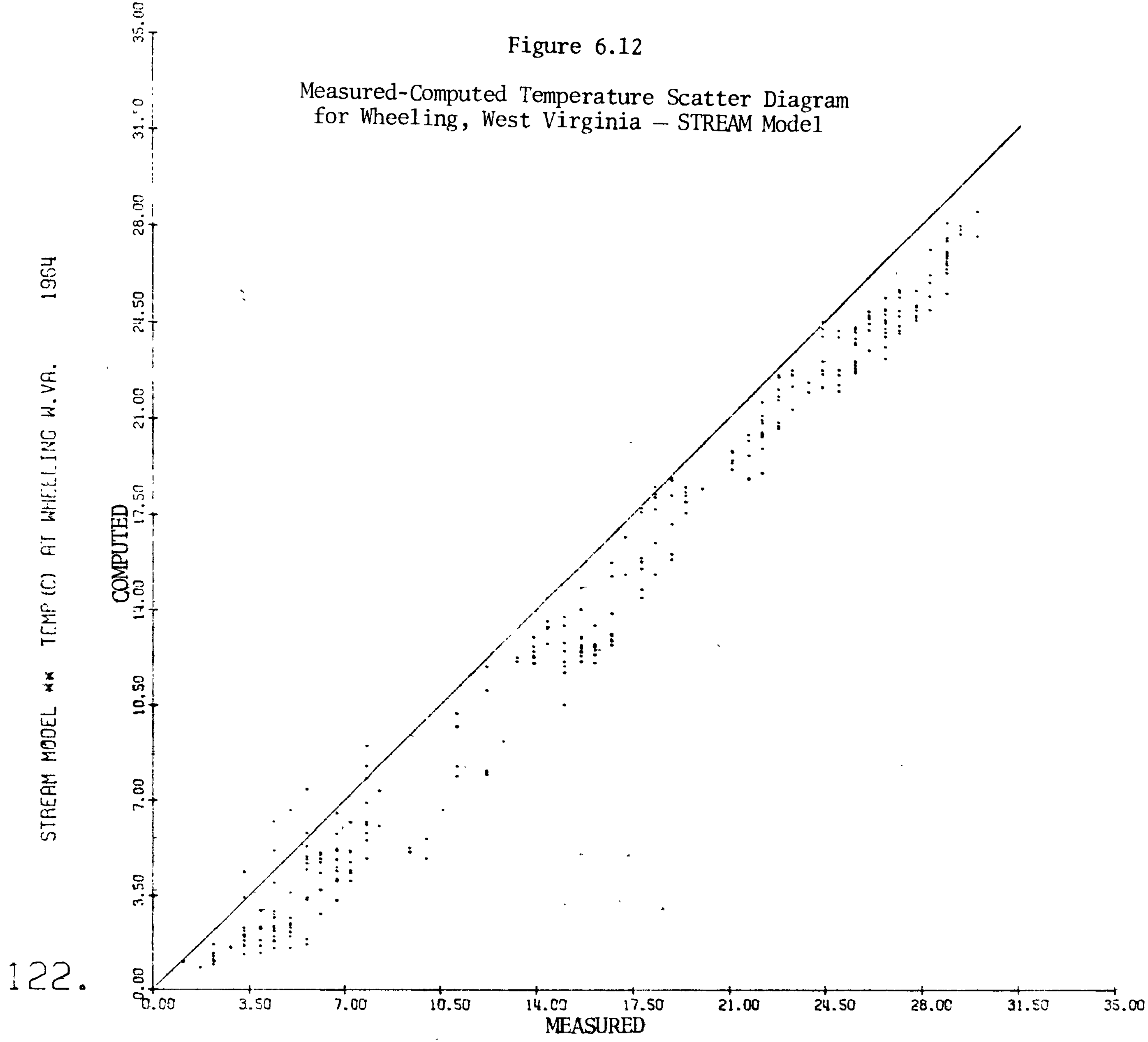


Figure 6.13

Measured-Computed Temperature Scoatter Diagram
for Wheeling, West Virginia — COLHEAT Model

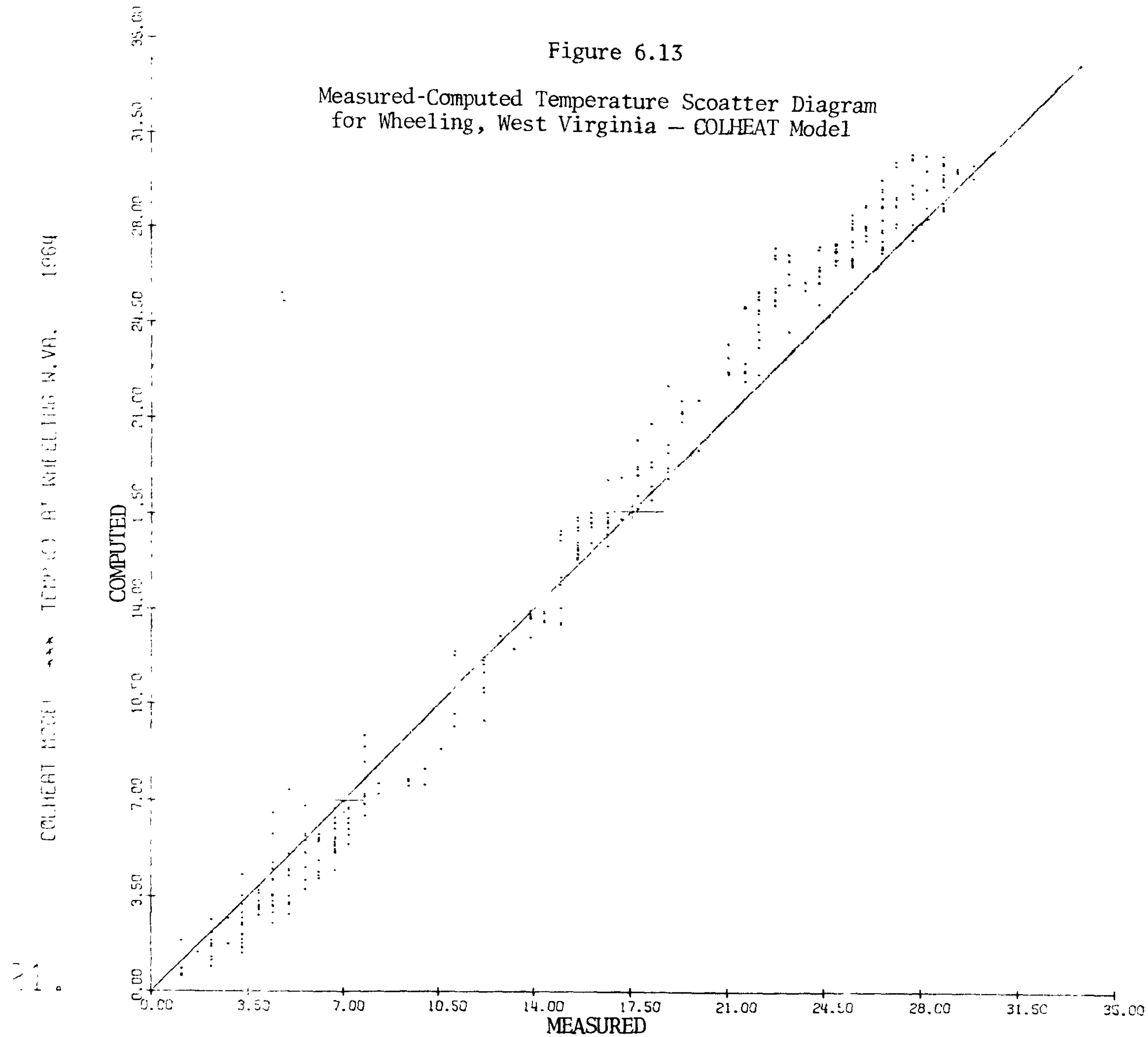
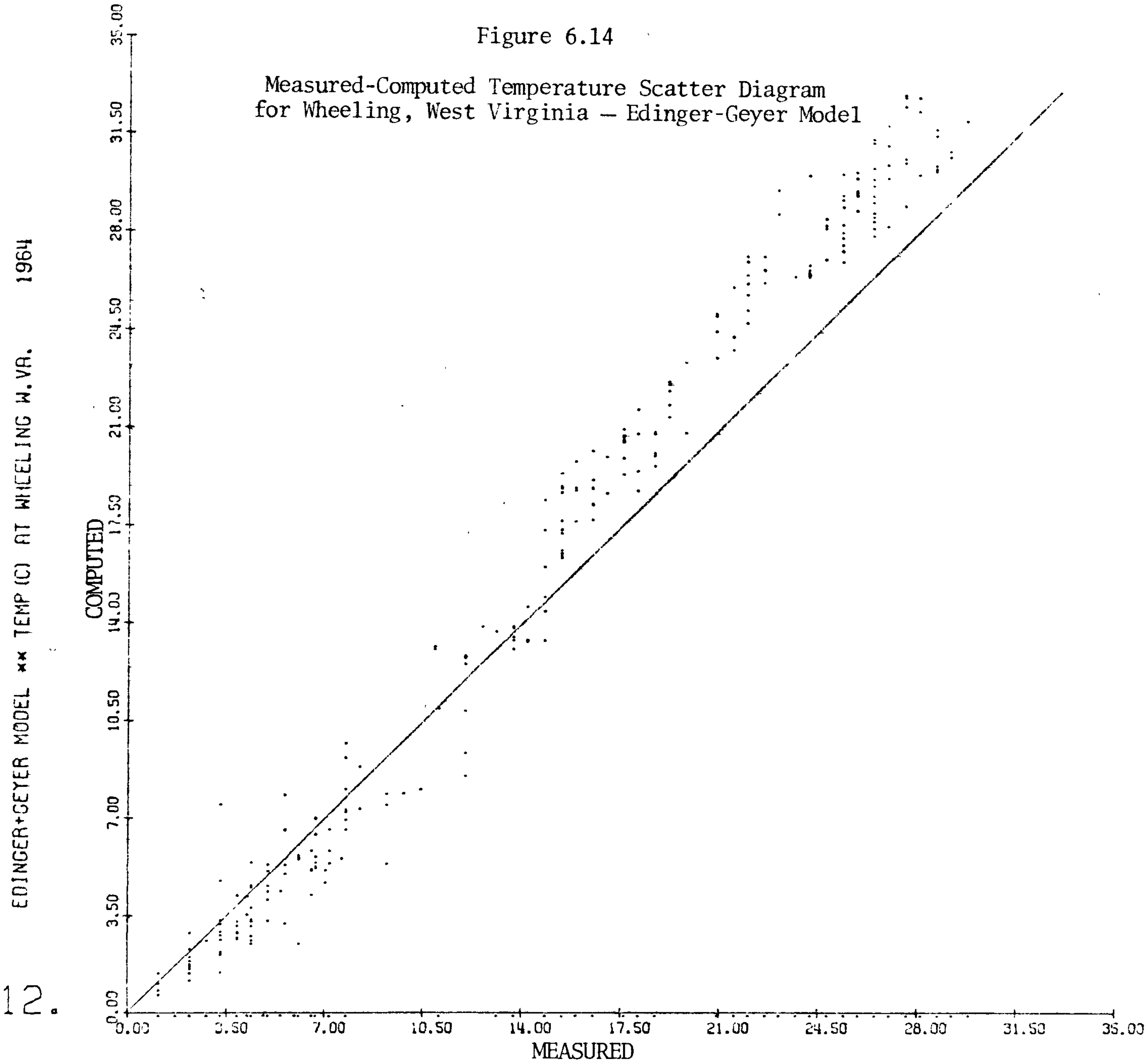


Figure 6.14

Measured-Computed Temperature Scatter Diagram
for Wheeling, West Virginia — Edinger-Geyer Model



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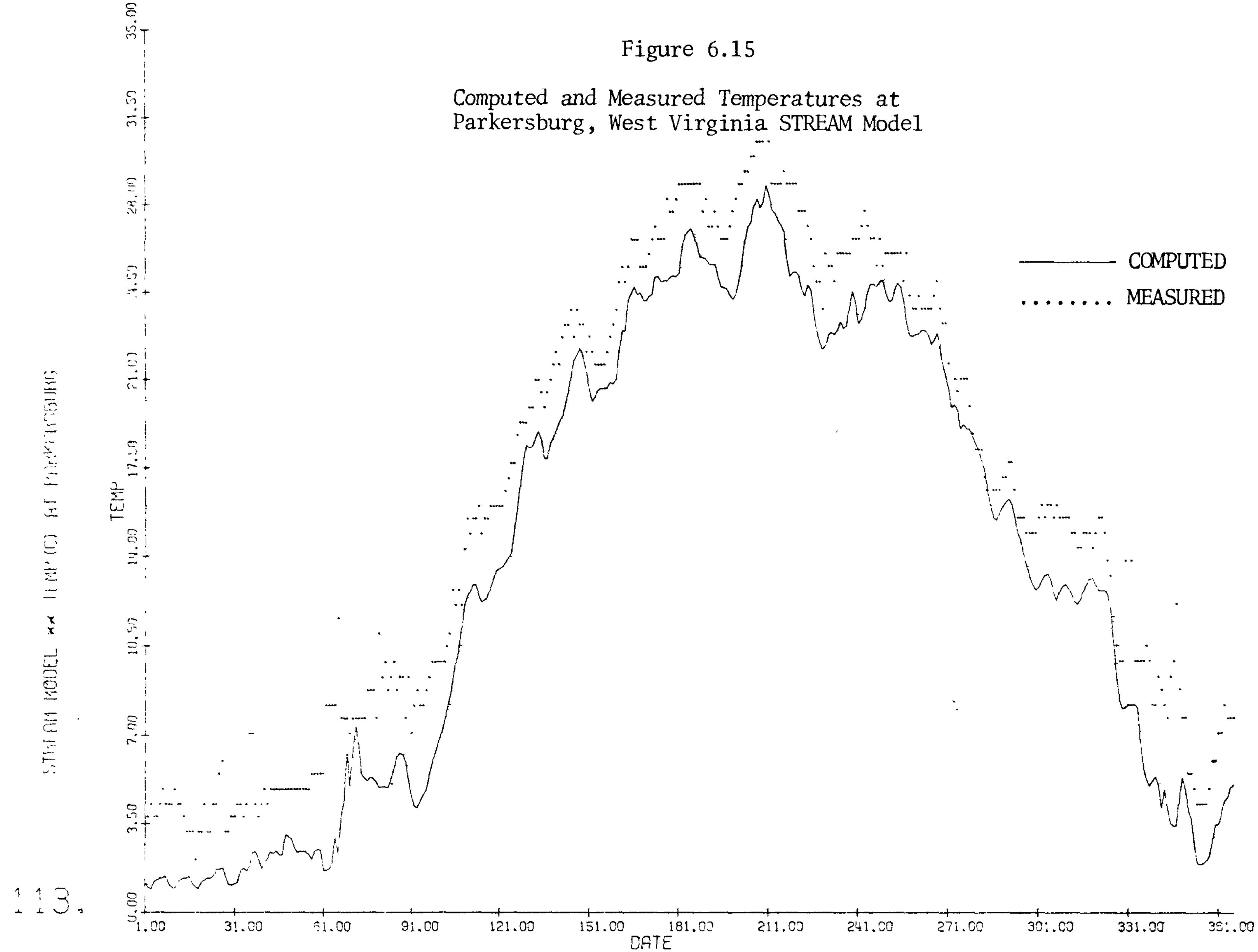
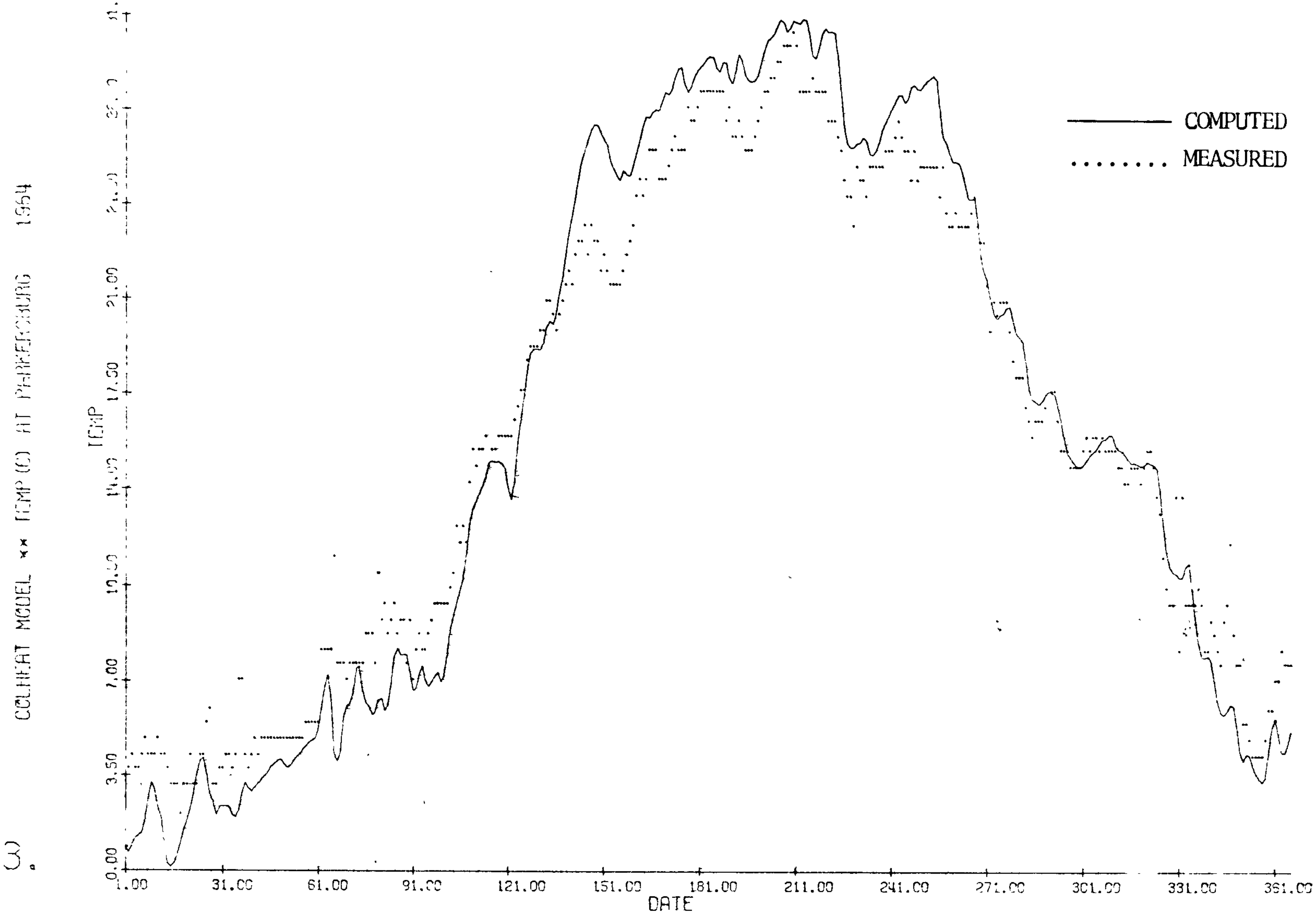


Figure 6.15

Computed and Measured Temperatures at
Parkersburg, West Virginia STREAM Model

Figure 6.16

Computed and Measured Temperatures at Parkersburg, West Virginia COLHEAT Model



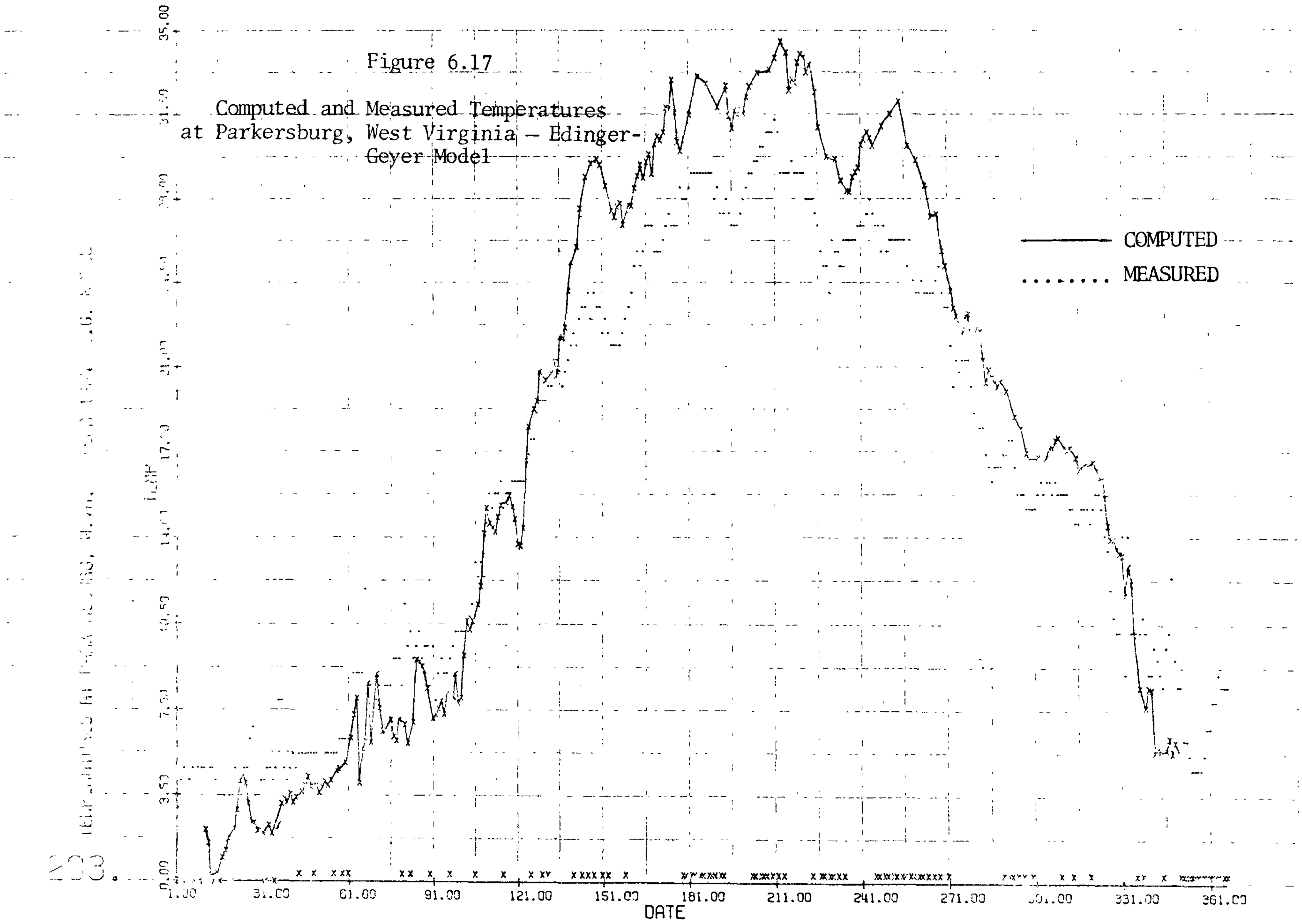
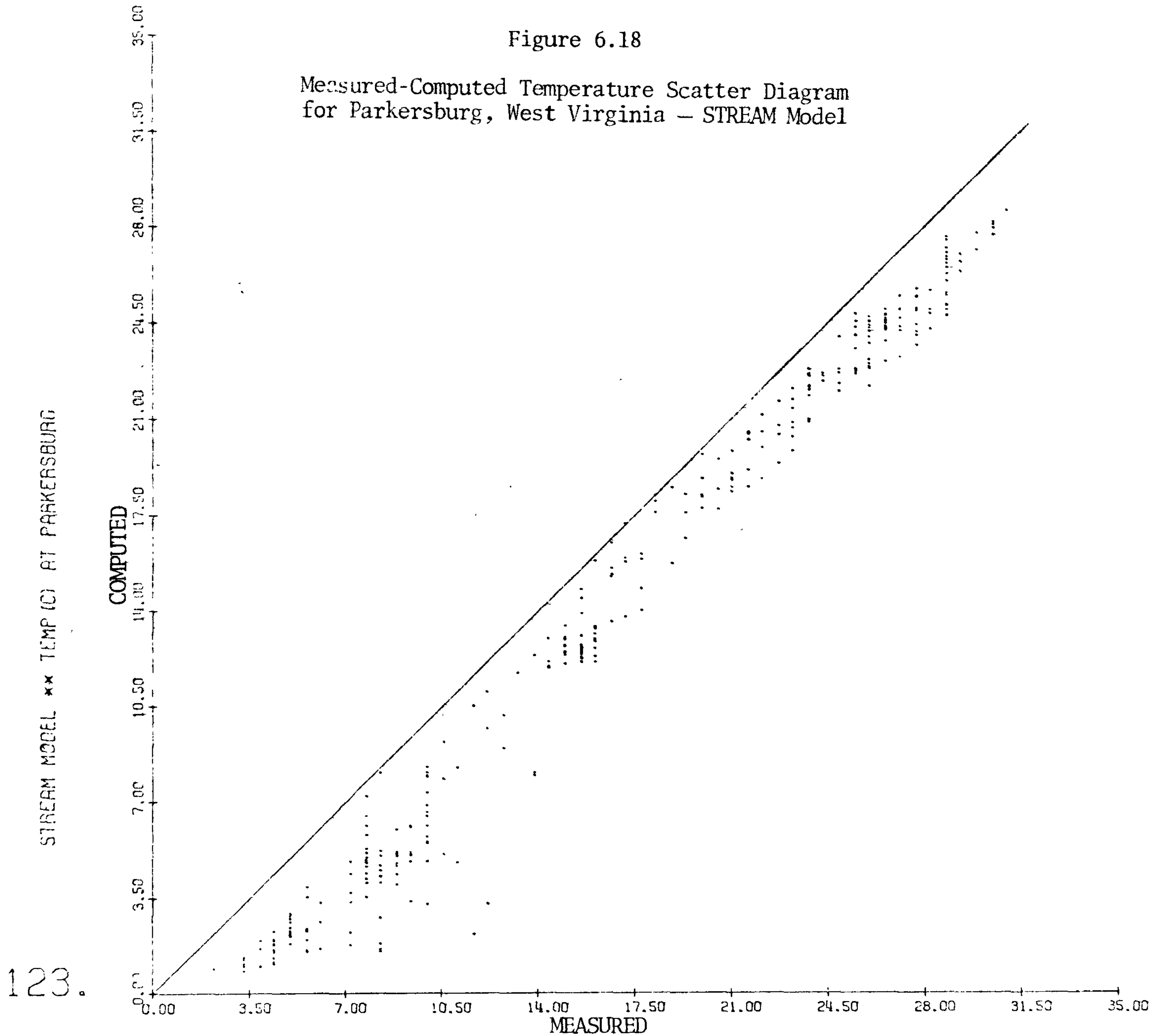


Figure 6.17

Computed and Measured Temperatures at Parkersburg, West Virginia – Edinger-Geyer Model

Figure 6.18

Measured-Computed Temperature Scatter Diagram for Parkersburg, West Virginia — STREAM Model



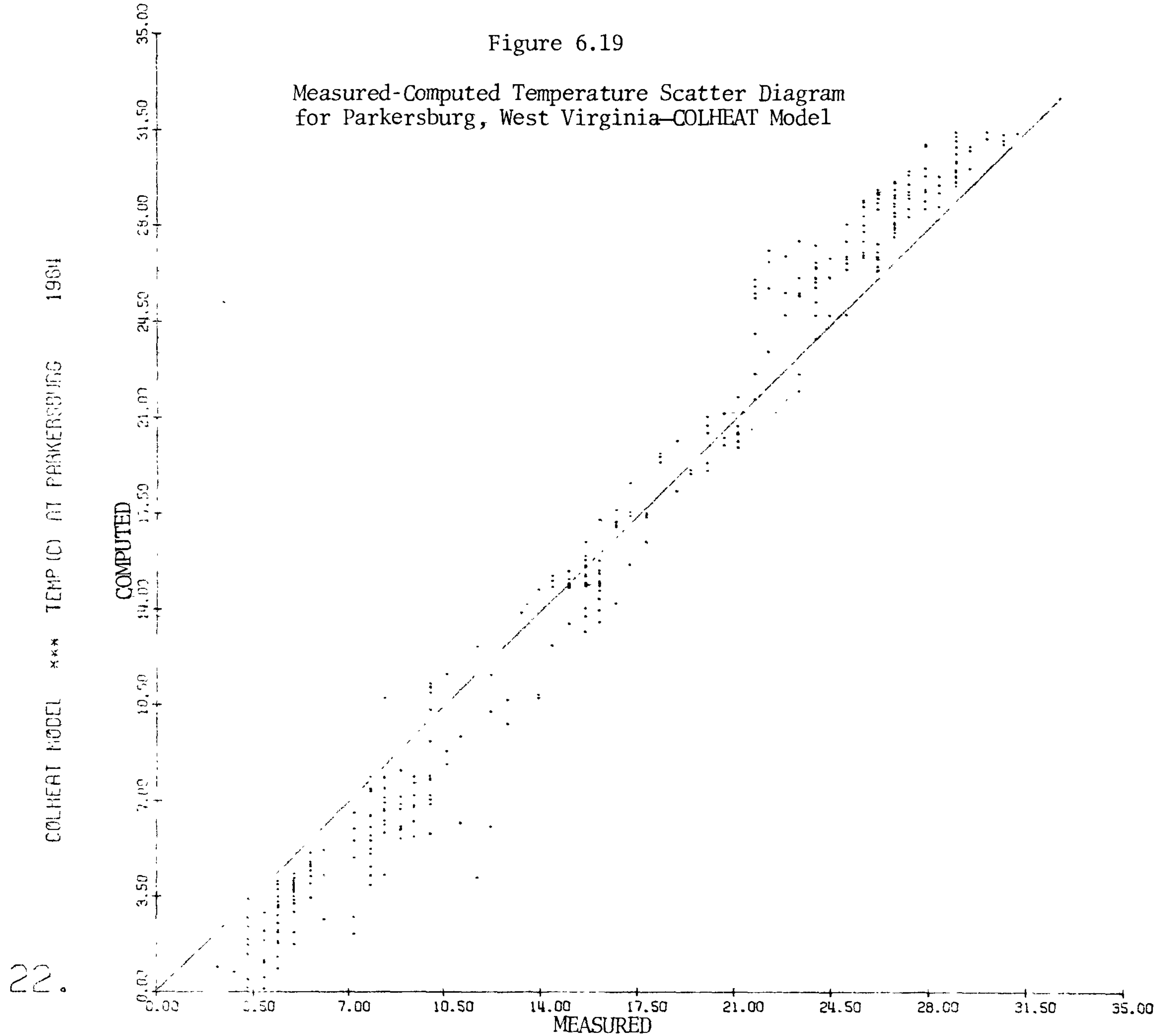
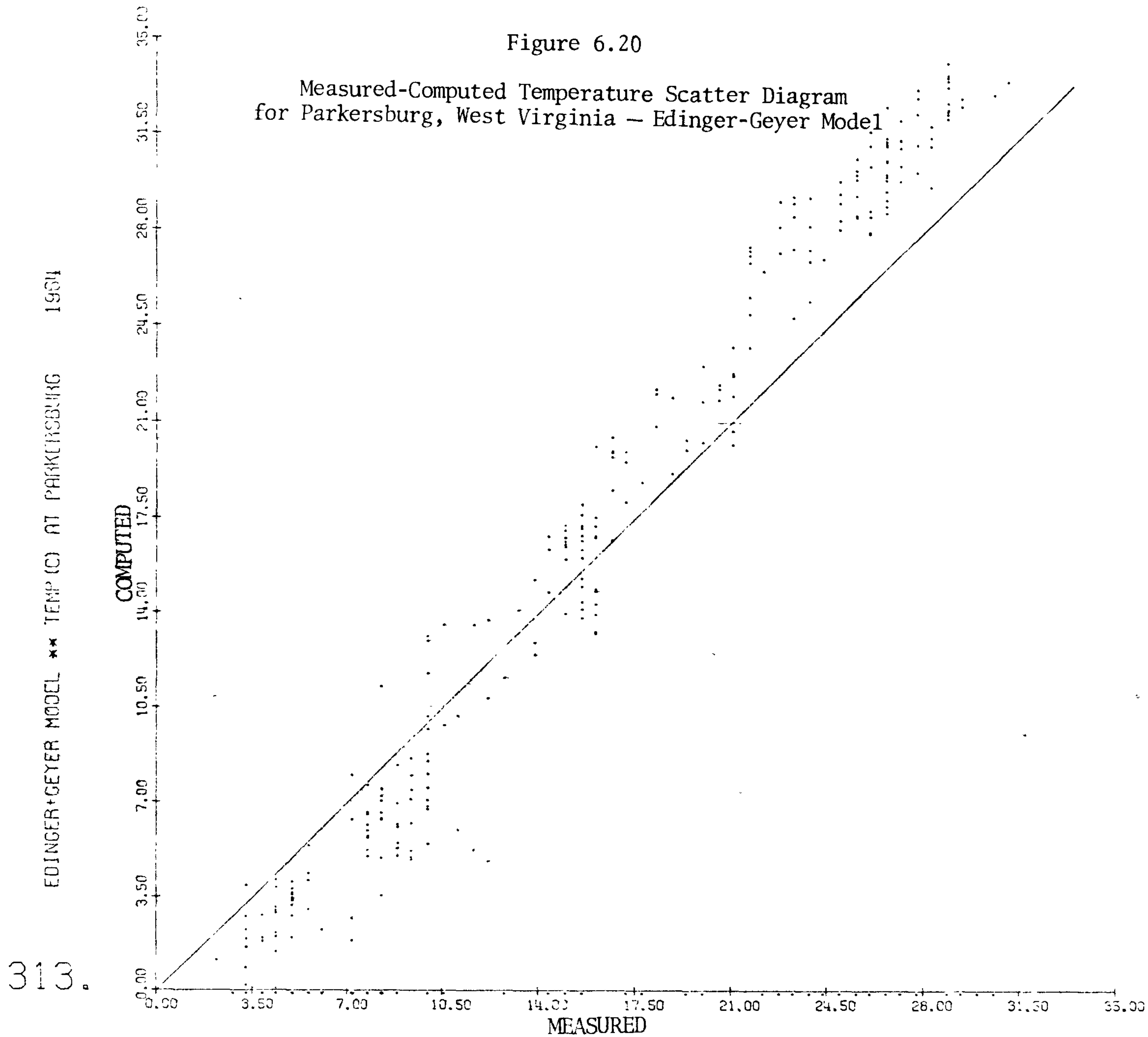


Figure 6.19

Measured-Computed Temperature Scatter Diagram
for Parkersburg, West Virginia—COLHEAT Model

Figure 6.20

Measured-Computed Temperature Scatter Diagram
for Parkersburg, West Virginia — Edinger-Geyer Model



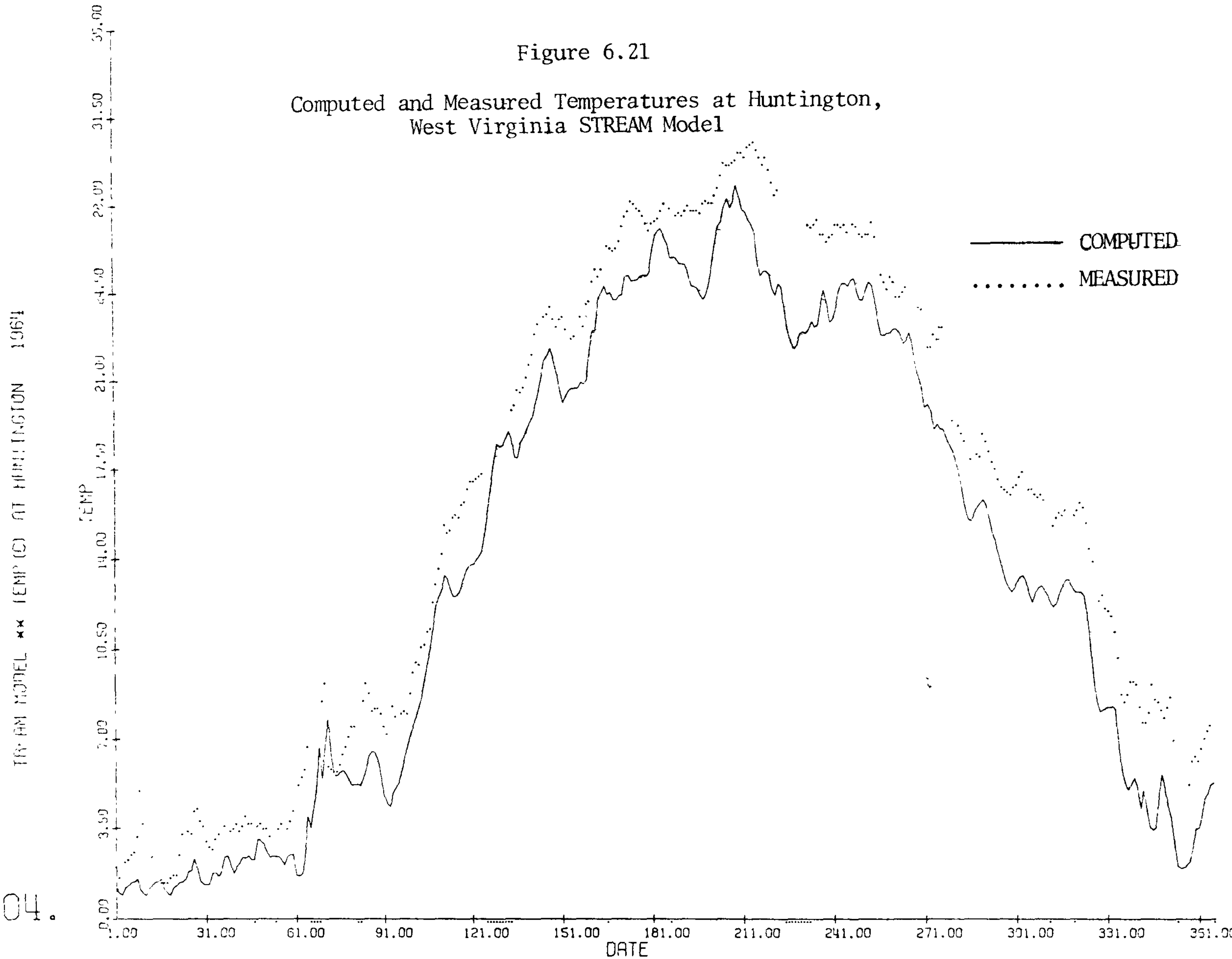


Figure 6.21

Computed and Measured Temperatures at Huntington, West Virginia STREAM Model

Figure 6.22

Computed and Measured Temperatures at Huntington,
West Virginia COLHEAT Model

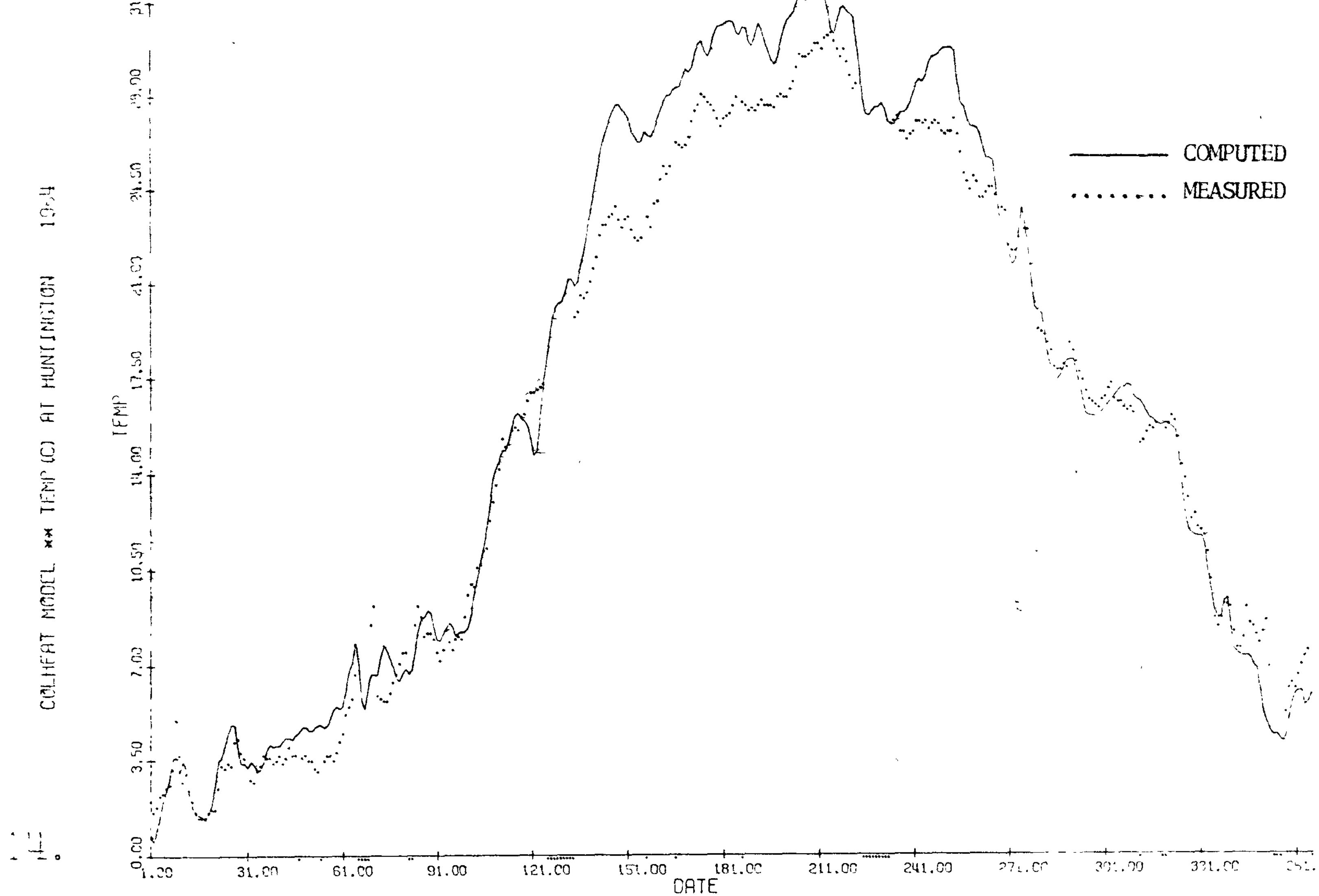


Figure 6.23

Computed and Measured Temperatures
at Huntington, West Virginia
Edinger-Geyer Model

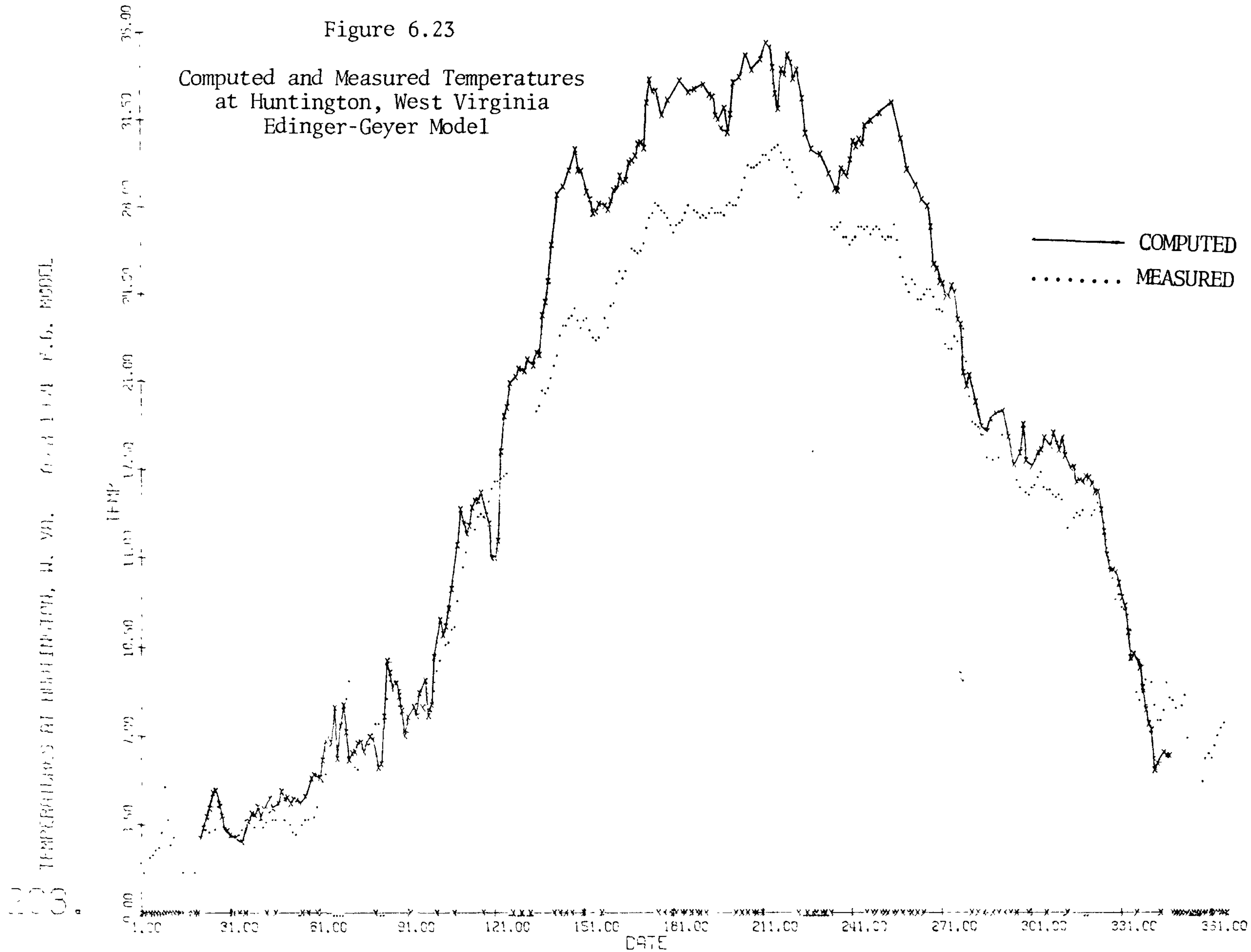
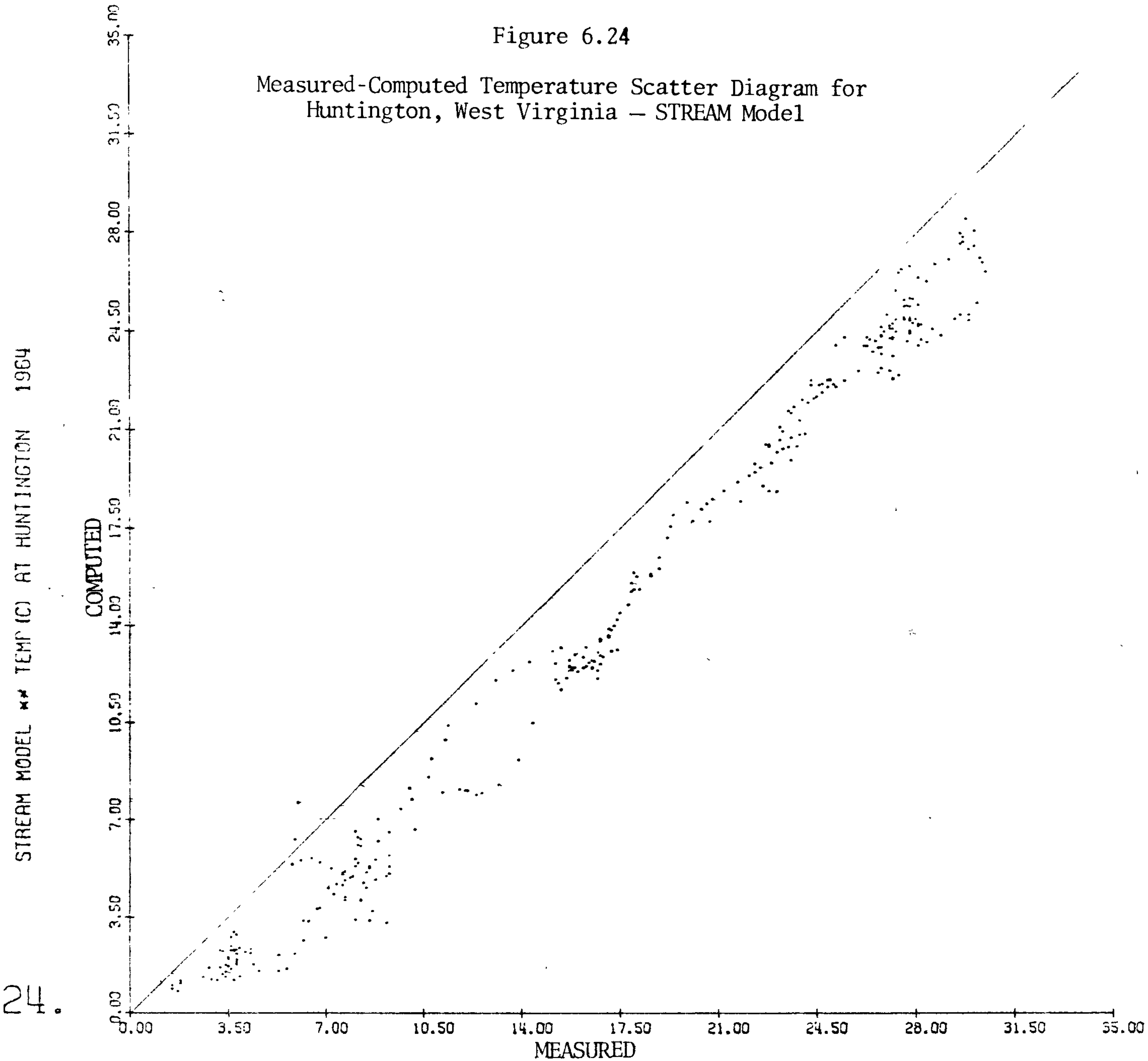


Figure 6.24

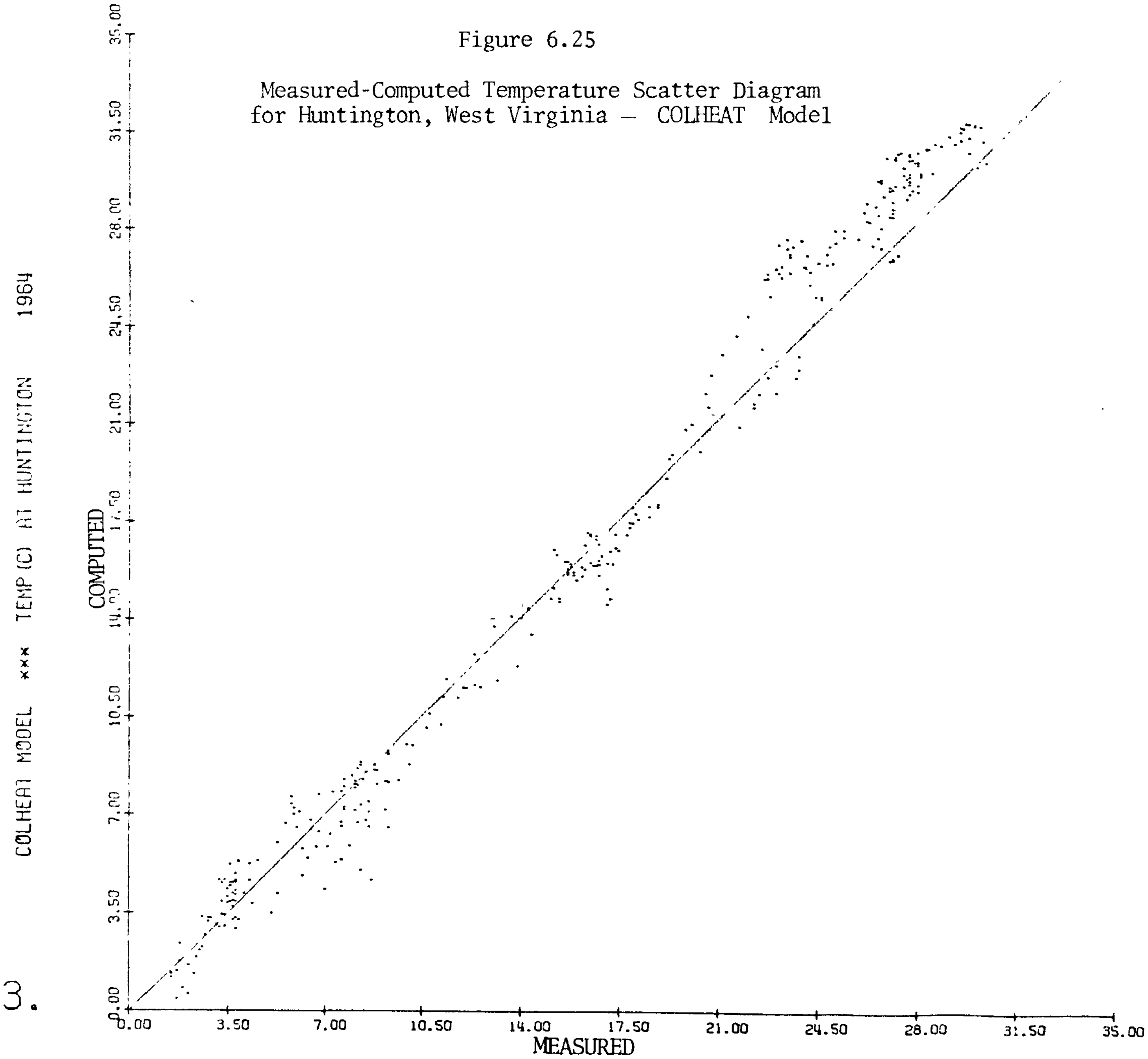
Measured-Computed Temperature Scatter Diagram for
Huntington, West Virginia — STREAM Model



124.

Figure 6.25

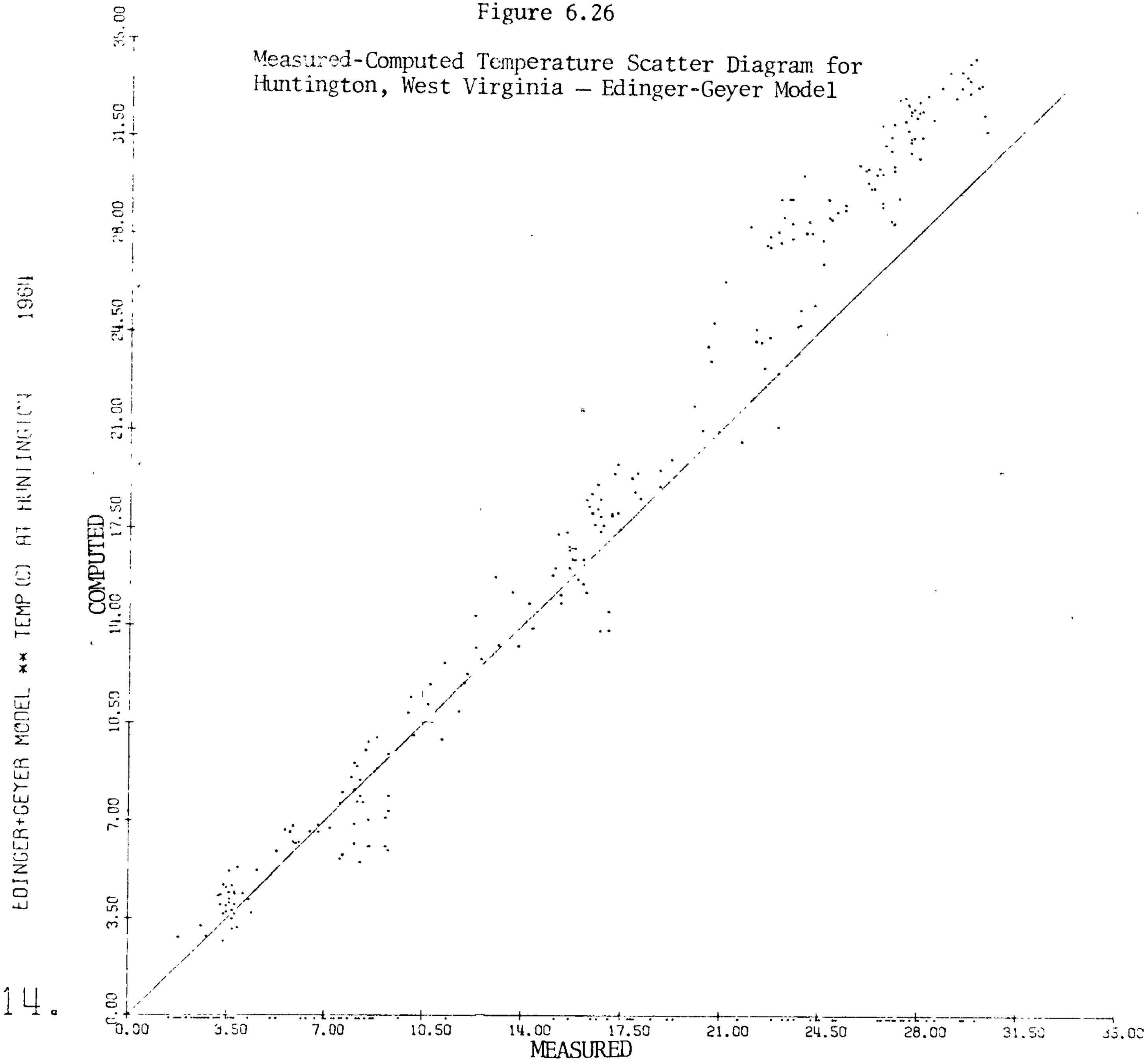
Measured-Computed Temperature Scatter Diagram
for Huntington, West Virginia — COLHEAT Model



23.

Figure 6.26

Measured-Computed Temperature Scatter Diagram for
Huntington, West Virginia — Edinger-Geyer Model



314.

more consistent with the observed temperatures than were STREAM's temperatures. COLHEAT predicts high in September by about 1.5° C and low in July by about 2.5° C. Elsewhere, except January, COLHEAT replicates the observed temperatures to a high degree of precision. COLHEAT follows the form of the observed data rather well except for January when the observed temperatures are about 6° C higher than the predicted temperatures.

The Edinger-Geyer Model, shown in Fig. 6.5, predicts rather high in the months of July, August, September, and October, particularly in September when it differs by approximately 6° C from the measured water temperature. The form of the observed temperatures is not followed as well by Edinger-Geyer as by the other two models though its predicted January temperatures are as low as those predicted by the other models.

Scatter diagrams, which compare computed and observed values, are often useful aids in judging the precision of a model. Figures 6.6 through 6.8 show the scatter diagrams for the STREAM, COLHEAT, and Edinger-Geyer Models, respectively, at Stratton, Ohio. The line drawn at an angle of 45° with the horizontal signifies where the points would lie if there was a perfect match between observed and computed values. Points below the line indicate that the model predicts low while points above the line indicate that the model predicts high. The scatter diagrams indicate that STREAM predicts low regularly; COLHEAT predicts temperatures that are close to the observed values; and Edinger-Geyer predicts well at the middle temperatures (7°-21° C) but predicts high at high temperatures and low at low temperatures.

Other statistical parameters have been determined for each model at each temperature measurement station. Regression lines were computed and drawn for each model, the difference between each observed temperature and its corresponding computed temperature was calculated, and the temperature difference distribution was constructed for each of the models. These data are presented in Appendix A.

Wheeling, West Virginia

The water temperatures at Wheeling, West Virginia, are measured daily by the City of Wheeling and reported to ORSANCO. The City of Wheeling has provided the following description of the 1964 water temperature measurement procedure:

> "The raw water temperatures recorded during these years were taken from the raw water main extending underground from the intake pier in the Ohio River through the pumping station and then underground to the sedimentation basins. This line to the sedimentation basins is tapped and runs into our filtration plant raw water testing tap. Here the stream is continuously running into a pail with the thermometer in it and the temperature usually recorded at 8 AM. This is done except when the plant is shut down."[2]

The STREAM Model, shown in Fig. 6.9, once again regularly predicts temperatures that are lower than the observed river temperatures. However, the form of the predicted temperature curve follows quite closely the form exhibited by the observed temperature curve. The COLHEAT Model, Fig. 6.10, is more precise than the STREAM Model at Wheeling, but its form following characteristic is not quite as good. The Edinger-Geyer Model, Fig. 6.11, again, predicts higher temperatures during the warm months than actually occur. Also the curve traced by Edinger-Geyer's predicted temperature does not follow the observed temperature curve as well as the other two models do.

The scatter diagrams contained in Figs. 6.12 through 6.14 show that STREAM predicts consistently low, sometimes as much as 3.5° C, while COLHEAT more nearly replicates observed temperatures. The Edinger-Geyer Model begins predicting too high at about 14° C and as observed temperature increases so does the amount of Edinger-Geyer's overpredictions.

Parkersburg, West Virginia

The water temperature at Parkersburg is measured daily and is reported to ORSANCO who incorporates the temperature into their Ohio River data base. The observed and computed river temperatures for each of the models are shown in Figs. 6.15 through 6.17. Again the STREAM Model predicts temperatures that are consistently lower than the observed water temperatures. The COLHEAT Model predicts temperatures that are consistent with observed temperatures (Fig. 6.16) for most of the year except for May and August when the COLHEAT predicted temperature is significantly higher (about 5° C) than the observed temperature. Both STREAM and COLHEAT's curve of computed temperatures closely approximates the curve of observed temperature. The overpredictive characteristic of the Edinger-Geyer Model (Fig. 6.17) becomes more pronounced at Parkersburg. The model predicts temperatures 3°-5° C higher than observed for the months of July, August, September, October and most of November.

The scatter diagrams shown in Figs. 6.18 through 6.20 serve to amplify the statements made in the preceding paragraph. STREAM constantly predicts low; COLHEAT predicts low at low temperatures and high at high temperatures but is closer to the observed values than the other two models. Edinger-Geyer predicts low at low temperatures, quite high at high temperatures and is more widely scattered about the 45° line than are the other two models.

Huntington, West Virginia

The water temperatures at Huntington, West Virginia, are measured by an ORSANCO robot monitor that is located at the raw water intake pump discharge of the Huntington Water Company's 40th Street pumping station. Water temperatures are measured hourly and are averaged over the day.

Figures 6.21, 6.22, and 6.23 show the observed daily temperatures at Huntington for 1964 plotted along with the daily water temperatures computed by the STREAM, COLHEAT, and Edinger-Geyer Models, respectively. The comments regarding the two temperature plots for each model are the same as for the other stations. STREAM (Fig. 6.21) predicts lower temperatures than observed, while COLHEAT (Fig. 6.22) predicts temperatures more in line with observed temperatures than does STREAM. However, COLHEAT does predict temperatures that average about 2° C higher than observed in May, June, and July. The Edinger-Geyer Model (Fig. 6.23) again predicts about 4° C high for the months of May, June, July, August, and September. Each model's predicted temperature curve seems to follow the form of the observed temperature curve equally well. The scatter diagrams, shown in Figs. 6.24 through 6.26 serve to reinforce the statements made above.

Conclusions - Criteria 1

The temperatures predicted by the COLHEAT model at the four river temperature measurement stations considered in this study agree more favorably with the actual measurements taken at these stations than do the temperatures computed by the other two models. This conclusion is based on an analysis of the temperature-time plots and the scatter diagrams presented earlier in this section as well as on the statistical analysis presented in Appendix A.

As shown above, the STREAM Model constantly predicts lower temperatures than those actually observed. STREAM's tendency to underpredict temperatures could be troublesome when the model is used to predict river temperatures during times of low flow or when using the model to predict the effect of new heat sources. The temperatures predicted by the Edinger-Geyer Model are not consistent with observed river temperatures. The Edinger-Geyer Model predicts too low at the lower river temperatures and too high at the higher river temperatures. Moreover, the prediction error of the model seems to get worse the further downstream the model is used.

One criticism that might be made of the COLHEAT Model is that it tends to predict higher temperatures than are actually measured when the river is at its warmest. This is an interesting criticism because COLHEAT might be expected to underpredict temperatures during the warm months since it computes the bulk temperature of a river section rather than that section's surface temperature (By bulk temperature is meant the temperature of the thoroughly mixed volume of water comprising the river section in question. In the evaluation phase of this study the river sections used by COLHEAT were 1-5 miles in length and had a volume on the order of 100 million cubic feet). It might be expected that, during the warmer months, the bulk or average temperature might be slightly cooler than the temperature at the river's surface.

One explanation of this apparent discrepancy might be the river temperature measurement stations themselves. It may be that the water, whose temperature is measured, is being pumped from a deeper cooler portion of the river during the warm months. Another explanation is that the Lake Hefner evaporation formula used by COLHEAT has limitations when applied to the Ohio River.

6.2.2 Criteria 2 - Ease of Use

Ease of use means how quickly can a user learn to implement the model, and once the implementation procedure is mastered, how easy is the model to use. As stated previously this is the most subjective test used in the evaluation procedure and is based on our experience in implementing each of the models. Based on our experience, STREAM is the easiest model to use of the three.

6.2.3 Criteria 3 - Input Data Acquisition

Criteria 3 is concerned with how difficult it is to obtain the data necessary to run each model. COLHEAT and Edinger-Geyer require meteorological data because they employ a heat budget, whereas STREAM requires no meteorological data. It has been our experience that meteorological data is relatively easy to get and can be obtained in a rather short amount of time. All three models require advected heat inputs and this parameter is the most difficult* to obtain. Consequently, we conclude that there is essentially no more difficulty involved in obtaining input data for one model than the other two.

6.2.4 Criteria 4 - Theoretical Completeness

The theoretical formulation of STREAM is quite different from that of COLHEAT and Edinger-Geyer since STREAM does not utilize a heat budget. Instead, STREAM postulates an exponential decay of the added heat as one moves downstream from the heat source. Expressed in equation form, this is

$$T = T_n + (\Delta T)\ 10^{-Kt} \tag{6.2}$$

where

T = temperature of the river downstream from the heat source, °F

T_n = normal (ambient) temperature of the river, °F

ΔT = temperature differential $(T_o - T_n)$, °F

K = decay constant, day^{-1}

t = travel time, days

T_o = temperature at heat discharge point, °F

Equation (6.2) is similar to several [3,4] simplified river temperature prediction models, except for one major difference: The exchange coefficient K is not usually held constant but is a function of meteorological conditions.

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*All three models also require cross-sectional areas (Even though it has been stated that STREAM does not require cross-sectional areas, they were needed for velocity computations) which are nearly as difficult to obtain as the advected heat inputs.

The exchange coefficient, K, is set equal to 1.0 in the STREAM Model. The explanation for this choice is:

> "The verification of 1.0 as the default value for the Dunvillain (K) constant was accomplished during the following year after its postulation. Several hundred modeling activities utilizing the temperature module were tried with existing monitoring data and thermal generating statistics supplied by local power plants. The results were beyond expectation! Not one time did a temperature fall outside the two-degree F. acceptance level!"[5]

Care must be taken in the verification of any model. During this study, STREAM was run in the PROFILE mode between Pittsburgh, Pennsylvania and Wheeling, West Virginia. Temperatures were input to the model daily at Pittsburgh and the profile for September 15, 1964, is shown in Fig. 6.27. (September 15 was chosen because this day had the lowest flow of 1964, 3200 cfs.) Note that the temperature increase caused by the Phillips Plant dissipates in about six miles, while the temperature increments due to the other heat sources take less distance to die away. To the best of our knowledge,[5,6,7,8] the closest downstream placement of a monitor to a power plant cooling water discharge during STREAM's verification runs was 6.4 miles. The monitor was located at Aurora, Indiana, 6.4 miles downstream of the Miami Fort Plant.* Hence, one reason that the Dunvillain constant

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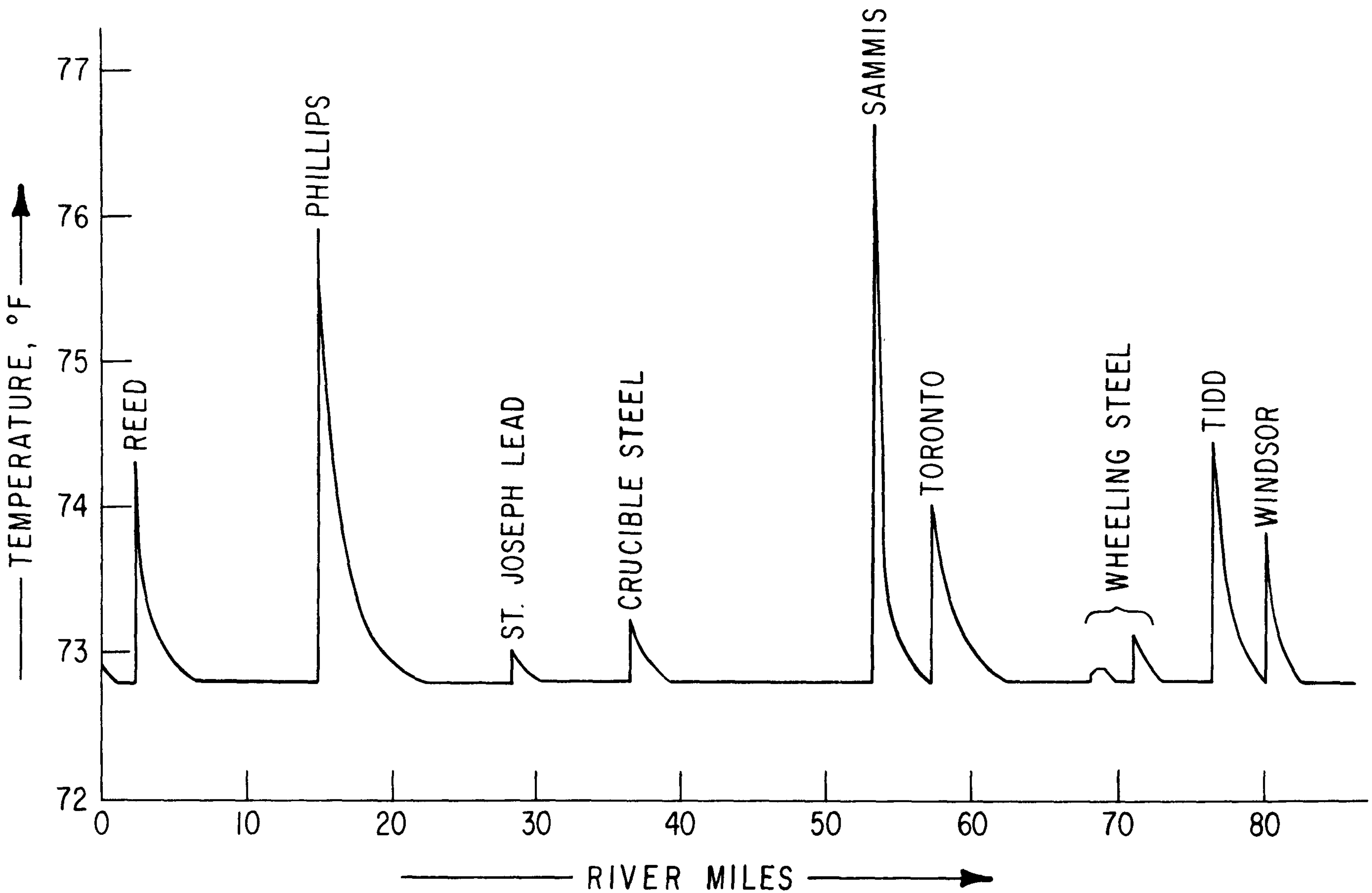
*At the Miami Fort Plant the flows are considerably higher than at Phillips. In fact, in 1964, a seven-day average flow of 3200 cfs would be expected only once every 100 years. (Reference: Corps of Engineers, "Frequency Charts for Low Flows on the Ohio River," June 1970.)

Figure 6.27

Temperature Profile September 15, 1964, STREAM Model



has checked so well against observed data is that the observed data has always occurred at the flat portion of the exponential die-away curve, five or more time constants removed from its origin. This explains why success has also been achieved with K values of 0.5 and 1.5.[5]

It has been stated that:

> "With regard to changing the heat decay rate to reflect changes in meteorological conditions, it should be recognized, first of all, that with dynamic modeling, river temperatures at the starting point of a model run are varied day by day, and thus compensation is automatically provided for variations in such factors as air, temperature, humidity, cloud cover, and wind direction."[7]

This procedure was followed in the model evaluation phase of this study, and STREAM regularly predicted lower temperatures than observed for 1964.

A problem was encountered with STREAM's travel modules during the model evaluation phase. As stated in Section 5, an assumption basic to the travel time module is that the velocity at a constant flow can always be defined as a linear function of river mile point. Hence, for constant flow

$$V = a + b\,x \qquad \text{(mile/day)} \qquad (6.3)$$

where

a is the V intercept, mile/day

b is the slope, (day^{-1})

x is the mile point, miles

The coefficient a and b can be determined if the flow, Q, and the cross-sectional area, A, at two discontinuity points are known. Then at point x_1, $V_1 = Q_1/A_1$ and at point x_2, $V_2 = \frac{Q_2}{A_2}$; the solution of the resulting set of simultaneous equations yields the proper value of a and b. Using these coefficients in the STREAM travel modules will result in both travel times between points as well as distances traveled during designated time periods.

We found for several sets of coefficients, a and b, the river velocity became "negative" with the result that a water parcel moves upstream instead of downstream. The difficulty was traced to the distance and time calculations made in Subroutines BACK and TRAVL of the STREAM Model. We modified these subroutines, and the model worked satisfactorily. Our modification procedure was as follows: Assume the river is numbered mile point 981 at Pittsburgh and mile point 0 at Cairo. Then the time of travel downstream between any two discontinuities is

$$t = \int_{x_1}^{x_2} \frac{dx}{a + b\,x} \tag{6.4}$$

where x_2 is downstream of x_1 so that

$$|x_1| > |x_2|$$

then

$$t = \frac{1}{b} \ln\left(\frac{a + b\,x_2}{a + b\,x_1}\right) \tag{6.5}$$

If the time of travel is known and no discontinuities are encountered between x_1 and x_2, the mile point of the point reached downstream from x_1 can be determined from

$$x_2 = \frac{-a + (a + b\,x_1)\,e^{bt}}{b} \qquad (6.6)$$

Similarly, traveling back upstream to calculate the point at which the parcel of water was released t units previously, the result is

$$x_1 = \frac{-a + (a + b\,x_2)\,e^{-bt}}{b} \qquad (6.7)$$

Some difficulty was also encountered in the initial runs of the Edinger-Geyer Model. The fluctuations of the equilibrium temperature, as calculated by the model, were excessive, and the calculated equilibrium temperature itself was very high during the summer months. This difficulty seemed to arise because of the model's linearization of several of the inherent nonlinear relations involved in the heat budget formulation. Specifically, the procedure to calculate long-wave radiation seemed especially vulnerable to linearization and was replaced by the techniques used in the COLHEAT Model to simulate long-wave radiation. Another cause of these difficulties arises from the fact that the original[3] Edinger-Geyer formulation is not really amenable to large day-to-day changes in meteorological parameters. As Koberg[9] states, more agreement between measured temperatures and computed temperatures is obtained when the computations are made with long-wave radiation averaged over a month or longer.

No difficulties of a theoretical nature were encountered when utilizing the COLHEAT Model.

We conclude that of the three models evaluated the COLHEAT Model is the most theoretically complete.

6.2.5 Model Selection

Based on the criteria outlined above, we conclude that the COLHEAT Model is the most appropriate model of the three evaluated to use for river temperature prediction on the Ohio River at the present time.

It must be understood that criteria one (computed - observed temperature correlation) depends heavily on the river temperatures measured at the four river stations. These temperatures are regarded as "truth" and the computed temperature from each model is compared to this "true" temperature. Now whether temperatures measured in a bucket at Wheeling, West Virginia, faithfully reproduce the actual water temperature of the Ohio at Wheeling is questionable, but these temperatures were measured and were available.

The value of the measured river temperature data used in this study brings into focus the problems involved in honestly validating a model. To confidently evaluate the three models used in this study, more reliable measured temperatures are required. ORSANCO, through their monitoring program, is progressing toward this end, but more should be done if a model is to be used with complete confidence. Some suggestions are as follows:

1) Pick a river reach for validation (e.g., Pittsburgh-Huntington reach).

2) Place sufficient monitors along the river or monitor manually such that temperatures are recorded at mile increments downstream from major heat sources (e.g., the ones used in the Pittsburgh-Huntington reach) until there is no evidence of residual thermal die away.

3) Take measurements at other strategic locations in the reach of interest (e.g., mouths of tributaries).

4) Take these measurements hourly if a robot monitor is used and daily if done manually. If done manually, make certain the measurements are made at the same point and the same time each day.

5) Make the validation measurements over a sufficient period of time so that seasonal river temperature variations are included.

A great deal of money and time has been spent in designing a large number of river temperature models. The time is at hand to make vigorous attempts to obtain good data from problem rivers so that the proper model may be used with confidence in each case.

Section 6 References

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7. OHIO RIVER TEMPERATURE PREDICTION STUDY

In this section the COLHEAT river temperature simulation model is used to predict river temperature profiles along the Ohio River from its origin at Pittsburgh, Pennsylvania to below Louisville, Kentucky. The purpose of these simulations is to determine the natural temperature along the Ohio River under certain conditions and to compare the natural temperature with that occurring when man-made heat inputs are added to the river. This comparison, along with a knowledge of the various state* temperature standards, may be used to detect anticipated water temperature violations and to pinpoint when and where they may occur.

This portion of the report is divided into two parts. Section 7.1 gives a brief description of both the state* standards and the Ohio River Valley Water Sanitation Commission (ORSANCO) standards as they apply to water temperature while Section 7.2 is devoted to the Ohio River temperature simulations.

7.1 Water Temperature Standards

A. State Standards

The water temperature standards adopted by each of the six states contiguous to the Ohio River are similar in nature. Each state has three general types of water temperature criteria that must be met.
are: 1) monthly maximum allowable temperatures, 2) a maximum allowable temperature increase above a defined base temperature, and 3) an allowable mixing zone at the edge of which, temperature criteria must be met.

Monthly Maximum Allowable Temperatures

The monthly maximum allowable temperature along the Ohio River by each state is given in Table 7.1. In addition to its monthly maximum

*For the purposes of this report the term "states" means the following ORSANCO signatory states: Illinois, Indiana, Kentucky, Ohio, Pennsylvania, and West Virginia.

Table 7.1

Monthly Maximum Allowable Temperature
Along the Ohio River

Month \ State	Illinois		Indiana		Kentucky		Ohio		Pennsylvania		West Virginia (Tentative)	
January	50°F	(10.0°C)	50°F	(10.0°C)	50°F	(10.0°C)	50°F	(10.0°C)	87°F	(30.6°C)	50°F	(10.0°C)
February	50	(10.0)	50	(10.0)	50	(10.0)	50	(10.0)	87	(30.6)	50	(10.0)
March	60	(15.6)	60	(15.6)	60	(15.6)	60	(15.6)	87	(30.6)	60	(15.6)
April	70	(21.1)	70	(21.1)	70	(21.1)	70	(21.1)	87	(30.6)	70	(21.1)
May	80	(26.7)	80	(26.7)	80	(26.7)	80	(26.7)	87	(30.6)	80	(26.7)
June	87	(30.6)	87	(30.6)	87	(30.6)	87	(30.6)	87	(30.6)	87	(30.6)
July	89	(31.7)	89	(31.7)	89	(31.7)	89	(31.7)	87	(30.6)	89	(31.7)
August	89	(31.7)	89	(31.7)	89	(31.7)	89	(31.7)	87	(30.6)	89	(31.7)
September	87	(30.6)	87	(30.6)	87	(30.6)	87	(30.6)	87	(30.6)	87	(30.6)
October	78	(25.6)	78	(25.6)	78	(25.6)	78	(25.6)	87	(30.6)	78	(25.6)
November	70	(21.1)	70	(21.1)	70	(21.1)	70	(21.1)	87	(30.6)	70	(21.1)
December	57	(13.9)	57	(13.9)	57	(13.9)	57	(13.9)	87	(30.6)	57	(13.9)

allowable temperatures the State of Illinois requires that:

> "The water temperature at representative locations in the main river shall not exceed the maximum limits (shown in Table 7.1) during more than one percent of the hours in the 12-month period ending with any month. Moreover, at no time shall the water temperature at such locations exceed the maximum limits (shown in Table 7.1) by more than 3°F."[1]

The Commonwealth of Pennsylvania has no allowable monthly maximum temperature as such, but instead has the requirement that the Ohio River experience:

> "Not more than a 5°F rise above ambient temperature, or a maximum of 87°F, whichever is less; not to be changed by more than 2°F during any one hour period."[2]

Maximum Allowable Temperature Increase

Most of the states limit the maximum temperature rise to 5°F above natural temperature where natural temperature is defined as:

> "The normal daily and seasonal temperature fluctuations that existed before the addition of heat due to other than natural causes."[3]

Of course, if the monthly maximum allowable temperature is less than a 5°F increment above natural temperature, the full incremental 5°F rise is not allowed.

Pennsylvania also allows a 5°F rise, but the base temperature used is ambient temperature which is defined as:

> "The temperature of the water body upstream of a heated waste discharge or waste discharge complex. The ambient temperature sampling point should be unaffected by any sources of waste heat."[2]

Perhaps the key statement here is that the sampling point should be "unaffected by any source of waste heat." Taken literally, this statement means that the ambient temperature is, in actuality, the natural temperature because only at the natural temperature is it a certainty that the sample point is "unaffected by any source of waste heat."

Mixing Zones

Each state has its own definition of what constitutes a mixing zone. Since all of the models evaluated in this study are far-field models, mixing zones shall not be considered in this report. Moreover, it should be pointed out that none of the models evaluated in this report should be used for stimulations involving mixing zones. Near-field or the so-called thermal plume models should be used for this type of simulation.

B. Ohio River Valley Water Sanitation Commission (ORSANCO) Standard[4]

The ORSANCO standard regarding heat input into the Ohio River requires that the aggregate heat-discharge rate not be of such magnitude that an increase in river temperature of more than 5°F results. The allowable heat discharge rate is given by:

$$HR = 62.4\ Q\ (T_A - T_R)\ (0.9)$$

where

HR = allowable heat-discharge rate (Btu/sec)

T_A = allowable maximum temperature as specified as follows:

	T_A		T_A
January	50	July	89
February	50	August	89
March	60	September	87
April	70	October	78
May	80	November	70
June	87	December	57

T_R = River temperature (daily average in °F) upstream from the discharge

Q = River flow, measured flow but not less than critical flow values specified below:

River Reach		Critical flow in cfs*
From	To	
Pittsburgh, Pa. (mi.0.0)	Willow Is. Dam (161.7)	6,500
Willow Is. Dam (161.7)	Gallipolis Dam (279.2)	7,400
Gallipolis Dam (279.2)	Meldahl Dam (436.2)	9,700
Meldahl Dam (436.2)	McAlpine Dam (605.8)	11,900
McAlpine Dam (605.8	Uniontown Dam (846.0)	14,200
Uniontown Dam (846.0)	Smithland Dam (918.5)	19,500
Smithland Dam (918.5)	Cairo Point (981.0)	48,100

*Minimum daily flow once in ten years.

7.2 Ohio River Temperature Simulations

7.2.1 Data

Water temperatures along the Ohio River from Pittsburgh, Pennsylania to river mile 705, about one hundred miles below Louisville, Kentucky were simulated under various conditions. A river temperature profile was determined for each day from May 24 through November 10 for a year in the mid-to-late 1970's. Thirty year average, once in ten years low flows were applied to the river in the months of July, August, and September. The magnitude of these flows and their points of entrance into the model are shown in Table 7.2. Regular flows (those actually measured on a daily basis in 1964) were applied to the river on the other dates.

The meteorological parameters used were those measured on a daily basis in 1964. Three weather stations were used:

1. Huntington, West Virginia - the data from this station were used to simulate meteorological conditions from Pittsburgh, Pennsylvania to Maysville, Kentucky (see Fig. 7.1).

2. Cincinnati, Ohio - the data from this station were used to simulate meteorological conditions from Maysville, Kentucky to Madison, Indiana.

3. Louisville, Kentucky - the data from this station were used to simulate meteorological conditions from Madison, Indiana to milepoint 705.

Solar radiation measurements were taken from State College, Pennsylvania and Indianapolis, Indiana. Water temperature of the river at Pittsburgh was initialized daily using the 1964 calculated water temperatures at Pittsburgh as described in Section 6.

The advected heat input to the river due to once-through cooling steam-electric power plants is given in Table 7.3. These figures were obtained by using the latest yearly average data available for each power plant and calculating the advected heat input in MWH/day from this data. It was assumed that the daily average advected heat input from an individual plant remained constant each day.

Table 7.2
Thirty Day Average, Once in Ten Years Low Flows and the Mile Point Where these Flows Enter the Simulation

City	Flow (cfs)*	Milepoint Initiated
Pittsburgh, Pa.	6,800	0.0
Wheeling, W. Va.	7,600	87.2
Parkersburg, W. Va.	9,000	185.1
Huntington, W. Va.	10,800	261.0
Maysville, Ky.	12,200	410.0
Louisville, Ky.	14,700	550.0

*Source: Corps of Engineers, "Frequency Charts for Low Flows on the Ohio River," June 1970. Due to delays in the reservoir construction upon which these charts are based, the flow figures given are higher than actually occurring.

7.2.2 Results

The results shown in this section are for 30-day average once in ten year low flows. Low flow profiles were obtained for each day from July 1

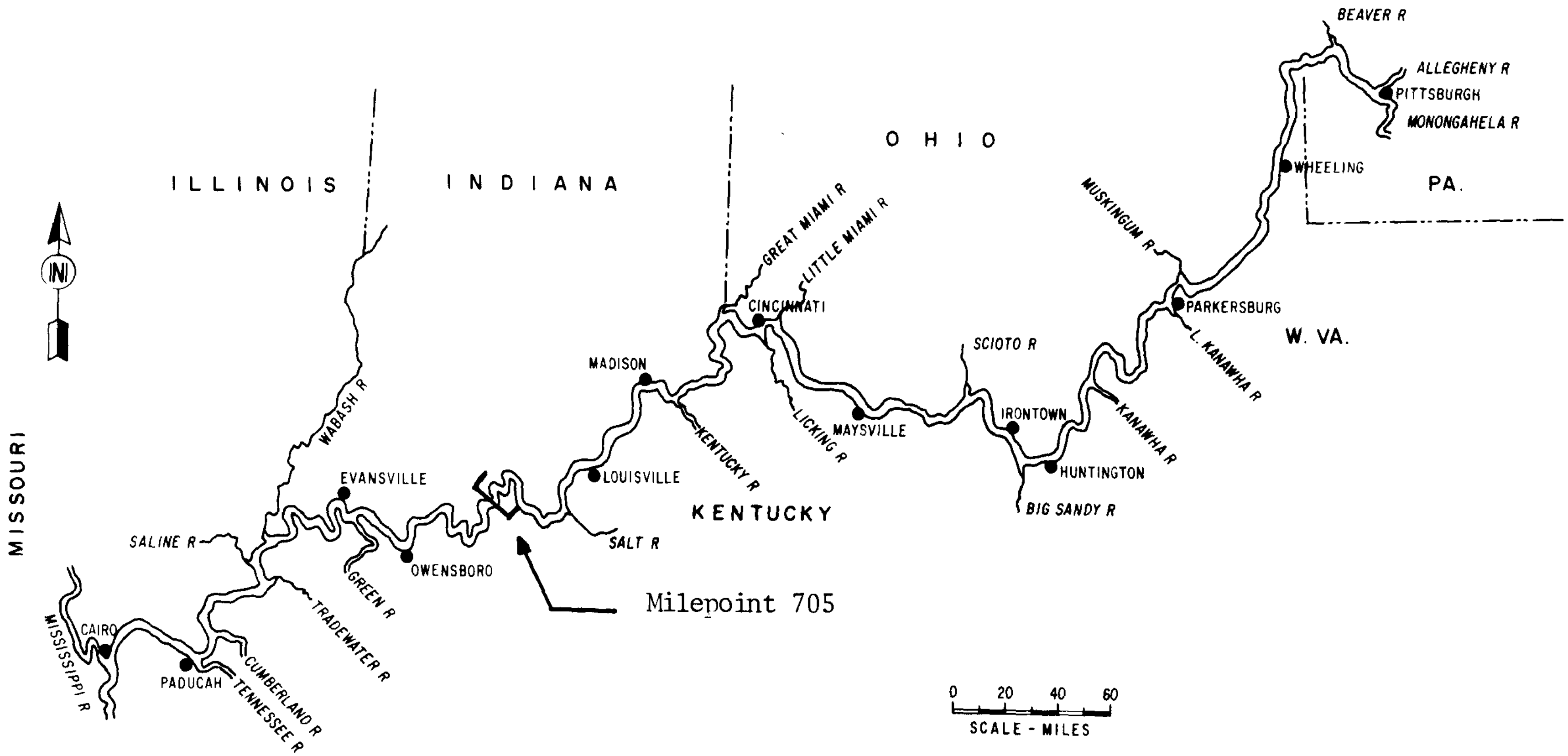


Figure 7.1

The Ohio River

Table 7.3

Factors Used to Determine Daily Advected Heat Input
Due to Each Steam-Electric Power Plant
Using Once-Through Cooling

Milepoint	Plant	Generating[1] Capacity (MW)	Heat Rate[2] (BTU/KWH)	Plant Factor[5] (%)	Advected Heat Rate (MWH/Day)
2.3	J. H. Reed	180.0	18,814	35	5,568
15.6	F. Phillips	411.2	11,829	58.4	11,213
33.8	Shippingport	100.0	10,340[3]	21.2	801
55.0	W. H. Sammis	2303.5	9,290	60.9	44,233
59.1	Toronto	175.8	14,089	44.1	4,668
74.5	Tidd	226.3	12,022	60	6,503
75.0	Cardinal	1230.5	9,067[3]	80	28,868
102.5	R. E. Burger	544.0	10,603	64	13,708
111.1	Kammer	712.5	9,998	63.3	16,134
160.5	Willow Island	215.0	10,687	78.1	6,700
241.0	Philip Sporn	1105.5	9,238	69	23,818
260.2	Kyger Creek	1086.3	9,309	76	26,123
405.7	J. M. Stuart	1830.6	9,180	77	43,768
453.5	W. C. Beckjord	1220.3	9,575[3]	65	25,898
471.4	West End	219.3	15,116	26	3,775
490.3	Miami Fort	393.2	10,753	55.8	8,837
494.5	Tanners Creek	1100.3	9,513	74	26,756
558.5	Clifty Creek	1303.6	9,407	82	34,447
604.0	Paddy's Run	337.5	13,829	18	3,567
616.6	Cane Run	1016.7	10,111	57	21,118
618.0	Gallager	637	10,000[4]	70	15,951

Notes:
1. Source: National Coal Association, Steam Electric Plant Factors - 1972 Edition, December 1972.

2. Source: Federal Power Commission, Steam Electric Plant Construction Costs and Annual Production Expenses - 24th Annual Supplement 1971, February 1973, except where noted.

3. Heat Rate figure is for 1969. Data supplied by the Ohio River Valley Water Sanitation Commission.

4. Estimate

5. Source: Engineering estimate based on plant factors obtained from Federal Power Commission

through September 30, and three of these profiles are presented in this report for three typical days during the low flow period - July 25, August 18, and September 11. No attempt was made to pick the "worst" day, that is, a day which would cause a maximum temperature increment near any power plant. Thirty-day average flows were selected rather than 7-day average flows in order to be more conservative.

It should be mentioned that 30-day average once in ten year low flows are not expected to persist over a 3-month period as modeled in this section. It might be argued that the assumption of such a lengthy low flow period permits the effect of an upstream power plant to be felt downstream, further than a distance equal to that traveled by a slug of water during 30 days of low flow. For the lowest flow shown in Table 7.2 (6800 cfs), a slug of water travels approximately 120 miles in 30 days. It is seen from the results in this section that the temperature increase from any power plant is negligible at this distance downstream from its discharge point.

The strategies shown in this section were selected by the staff of the United States Environmental Protection Agency Region V and are meant to provide answers to "what if" questions. Hence, these strategies should not be construed to be conclusions or recommendations resulting from this study.

Figures 7.2 and 7.4 depict the temperature profile along the Ohio River on July 25 for both average power plant loads and for no loads.* Figures 7.3 and 7.5 show the difference between natural river temperatures

*"No loads" means no man caused heat sources are put into the river. Thus, the "no load" case approximates the natural temperature of the river.

Figure 7.2

Ohio River Temperature Profile,
July 25 - Part 1

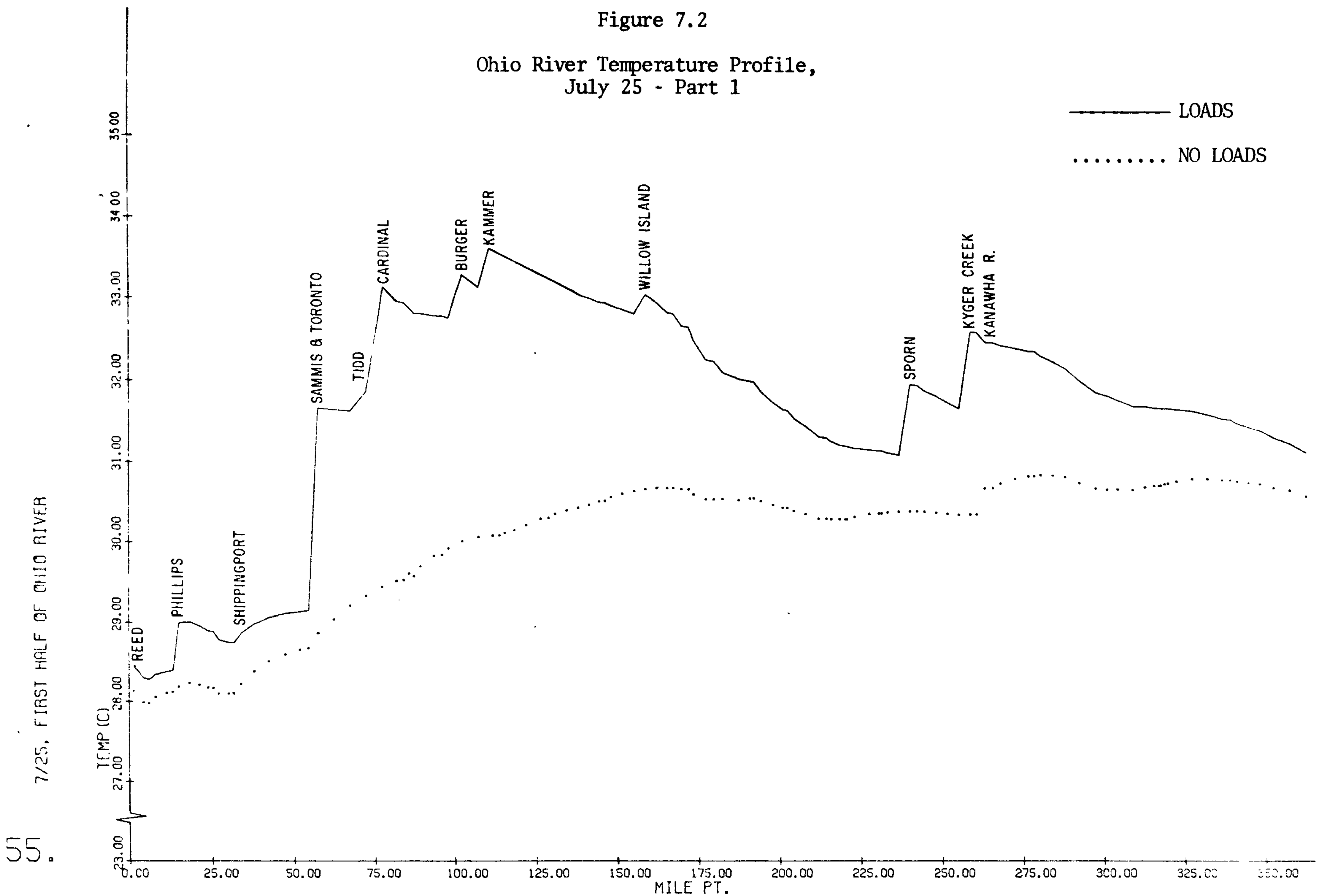
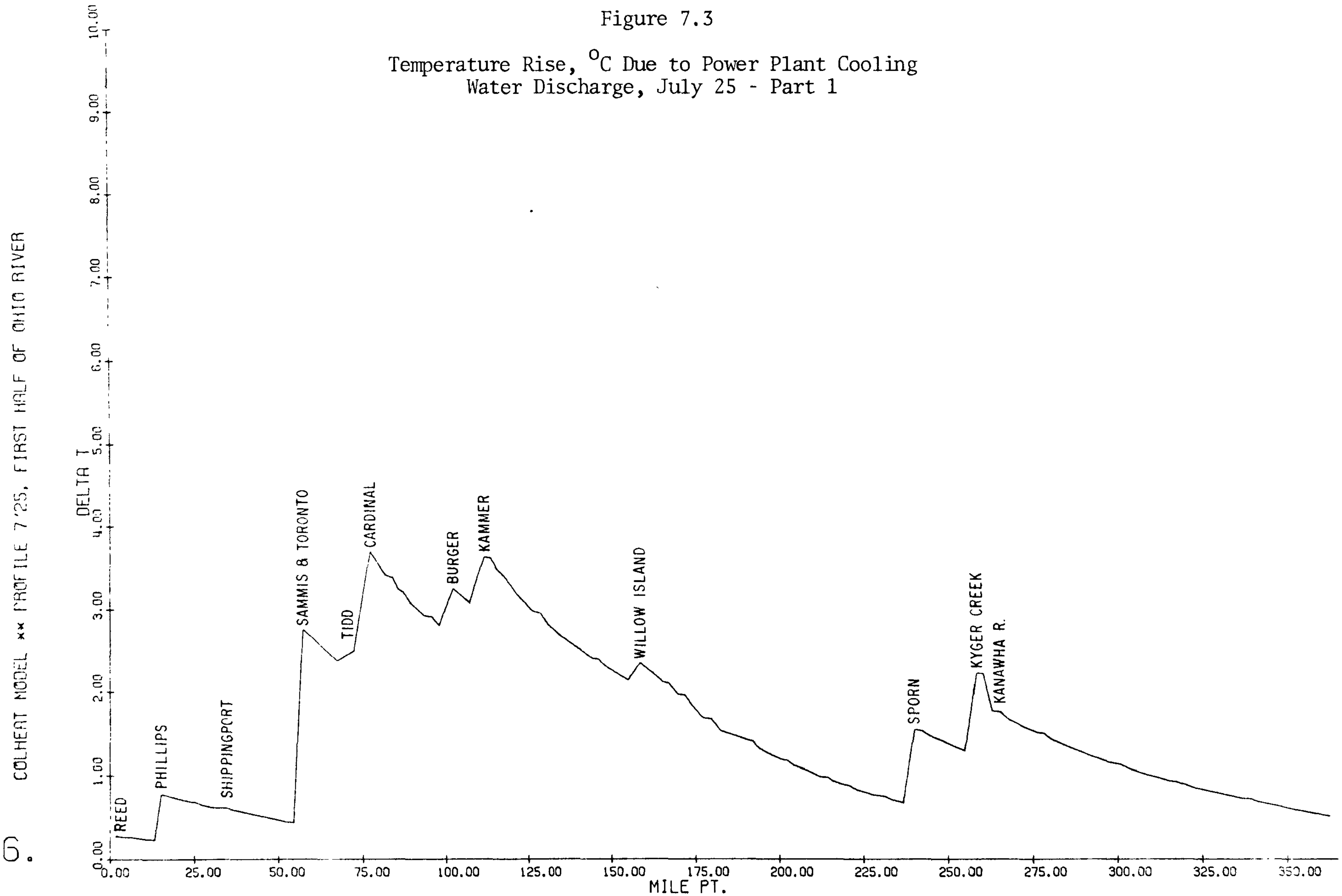


Figure 7.3

Temperature Rise, °C Due to Power Plant Cooling
Water Discharge, July 25 - Part 1



6.

Figure 7.4

Ohio River Temperature Profile, July 25 - Part 2

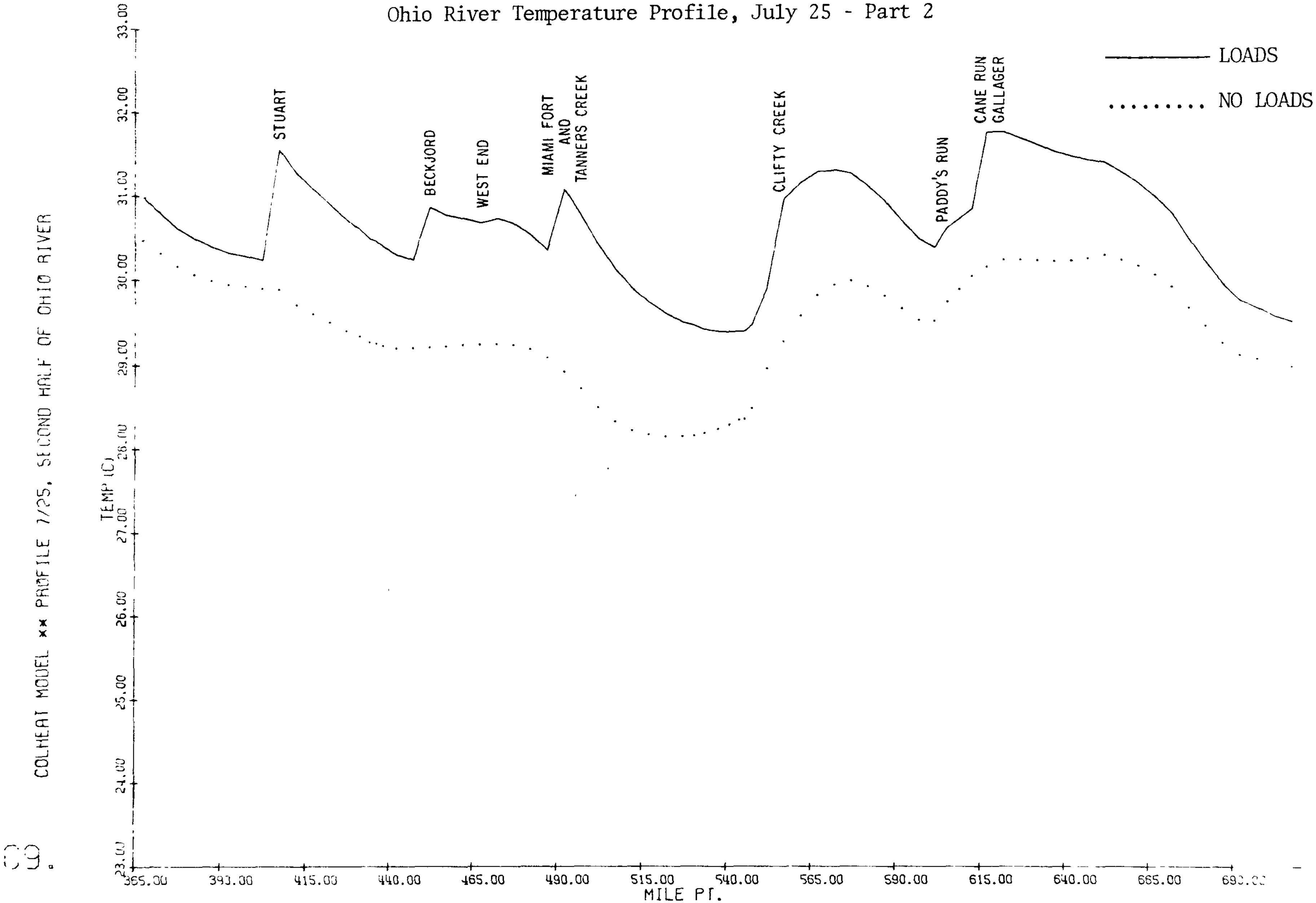
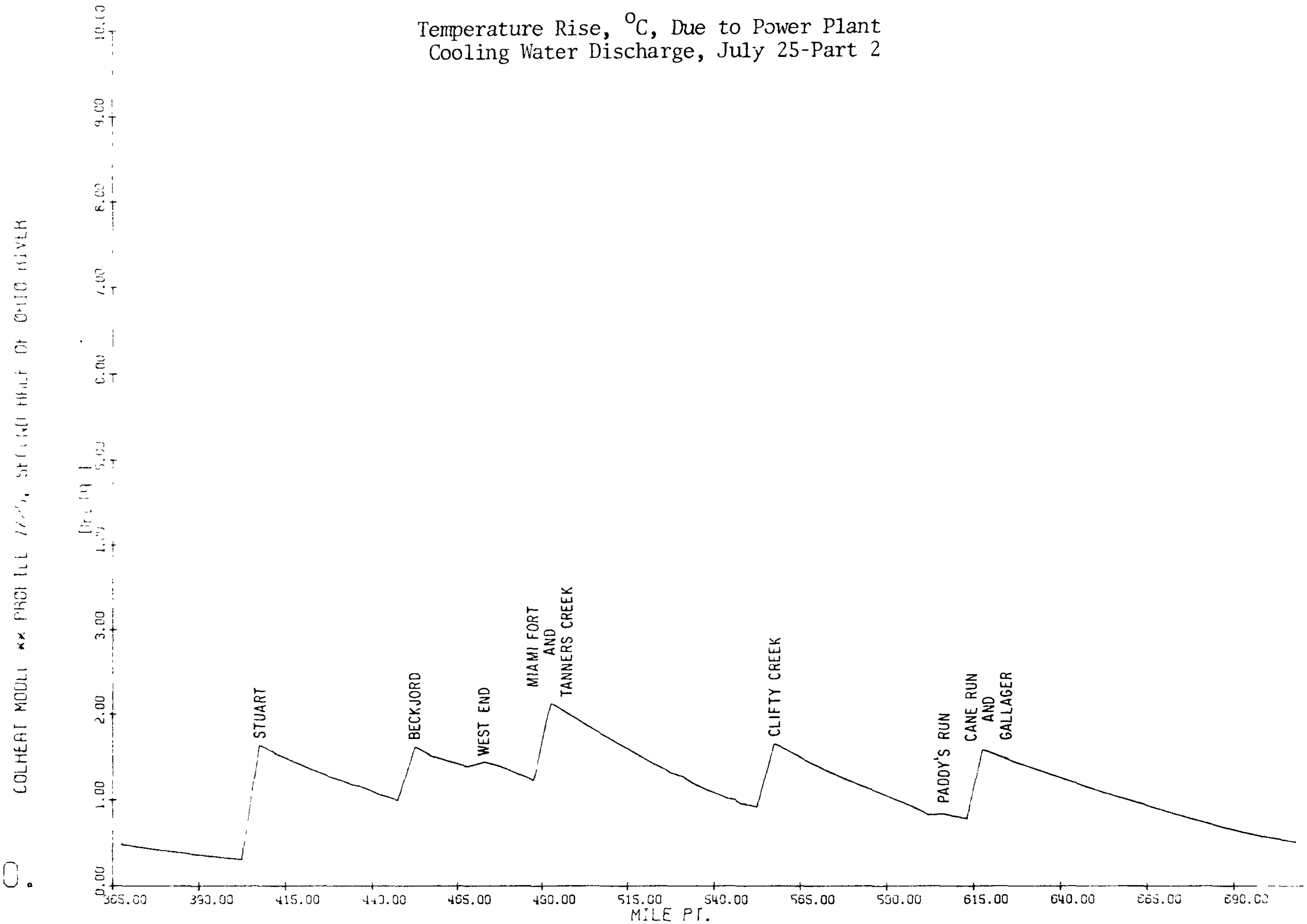


Figure 7.5

Temperature Rise, °C, Due to Power Plant Cooling Water Discharge, July 25-Part 2



and those resulting when loads are applied to the river. It can be seen from Figs. 7.2 and 7.3 that the Sammis, Toronto, Tidd, and Cardinal plant complex violates both the maximum allowable monthly temperature (31.7°C) standard and the 2.8°C (5.0°F) temperature increment standard.

Figures 7.6 and 7.8 show the temperature profile along the river for August 18. There is no monthly maximum temperature violation, but Fig. 7.7 shows that the Cardinal and Kammer plant cause the incremental temperature to rise greater than 2.8°C.

The river temperature profile for September 11 is given in Figs. 7.10 and 7.12. The maximum allowable monthly temperature for September is 30.6°C. Figure 7.10 clearly shows that this temperature is exceeded near the Cardinal, Burger and Kammer plants as is the 2.8°C maximum temperature rise (see Fig. 7.11).

Strategy 1

Since violations occurred near the Cardinal and Sammis plants, one strategy applied was to take Cardinal and Sammis completely off line. The results of this strategy are shown in Figs. 7.14 through 7.16. The top line represents operation as usual, the lower solid line represents the strategy (Sammis and Cardinal off line), and the dotted line represents natural temperatures. It is seen that water temperature standards are met if Cardinal and Sammis are taken off line.

Strategy 2

A second strategy was applied to the river, namely: what would the result be if the advected heat discharged from the Kyger Creek and Stuart plants were cut by 50% and 67%, respectively (Cardinal and Sammis remain off line). Again, the top line represents normal heat loads, the lower solid line represents the strategy and the dotted line represents the natural river temperature (figs. 7.17 through 7.19).

Figure 7.6

Ohio River Temperature Profile,
August 18 - Part 1

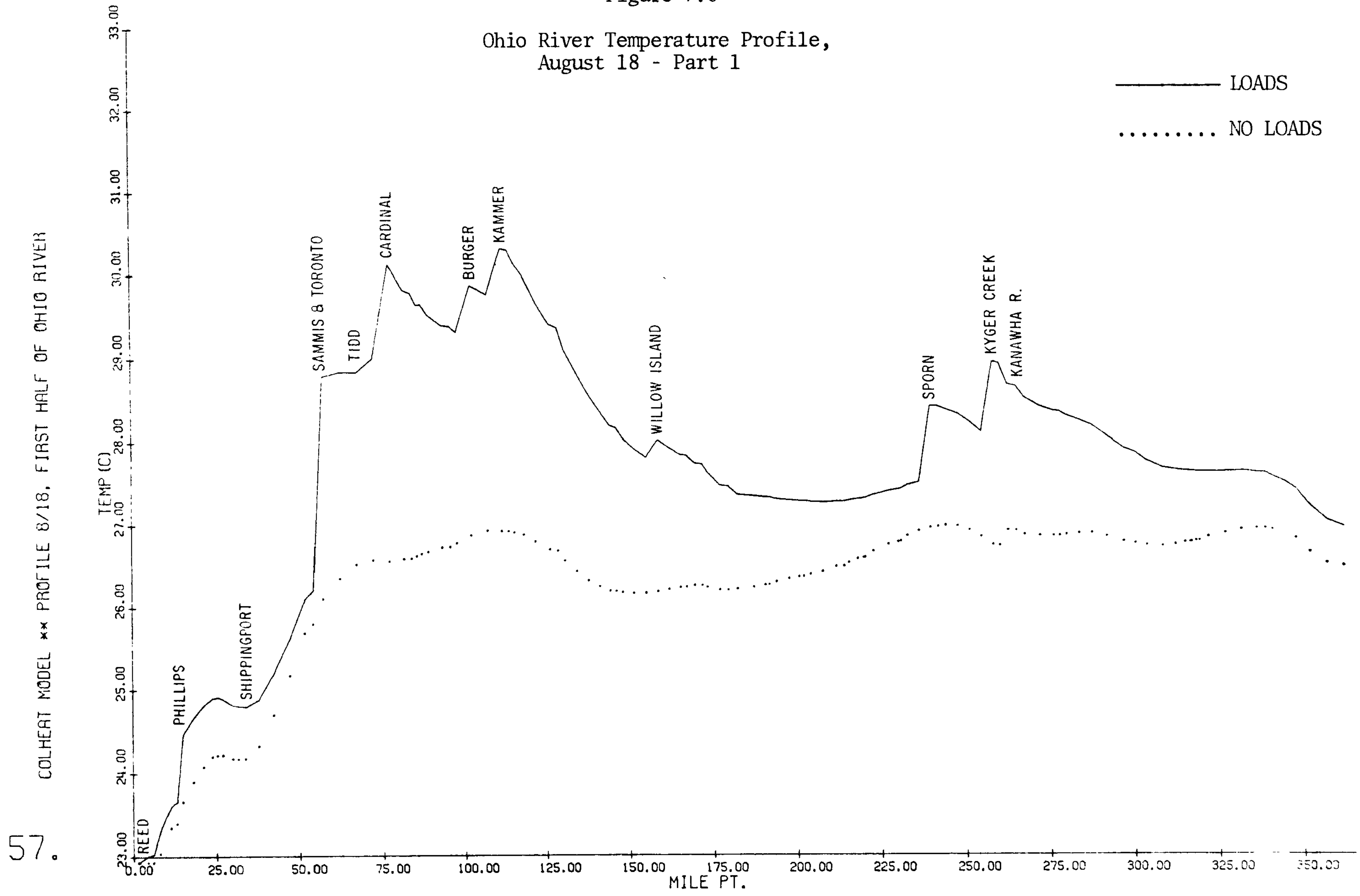


Figure 7.7

Temperature Rise, °C, Due to Power Plant Cooling Water Discharge, August 18 - Part 1

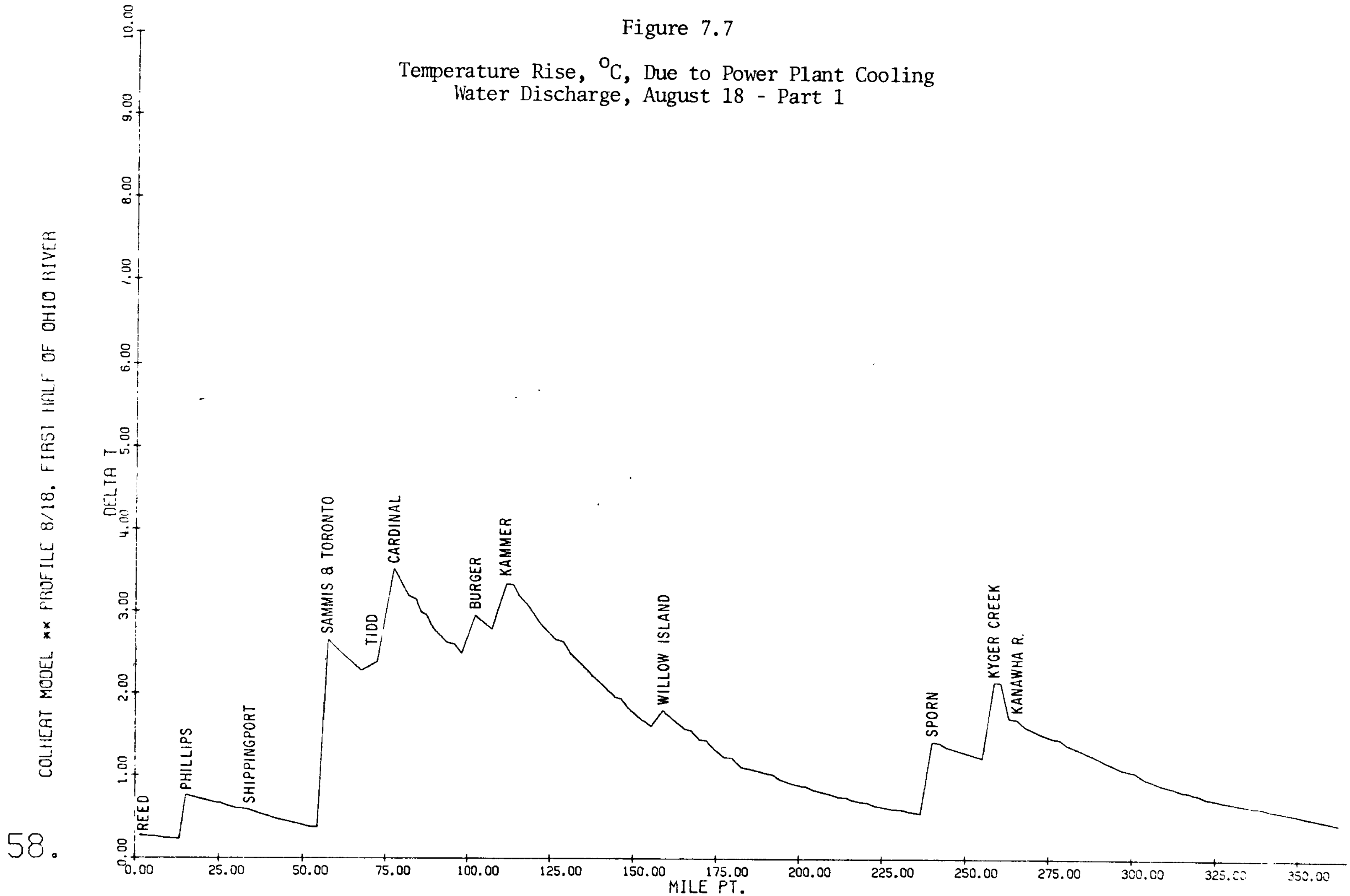
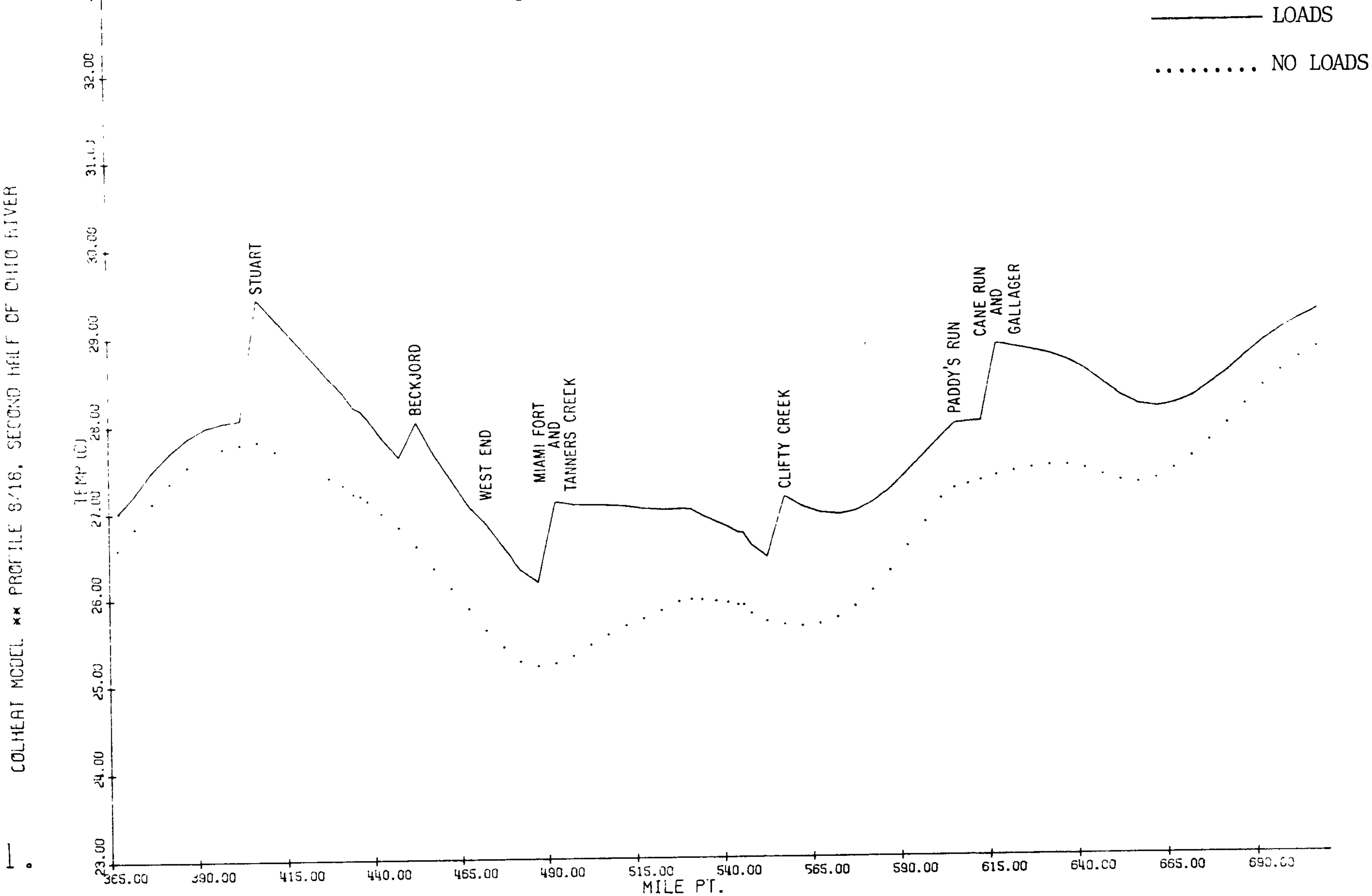


Figure 7.8

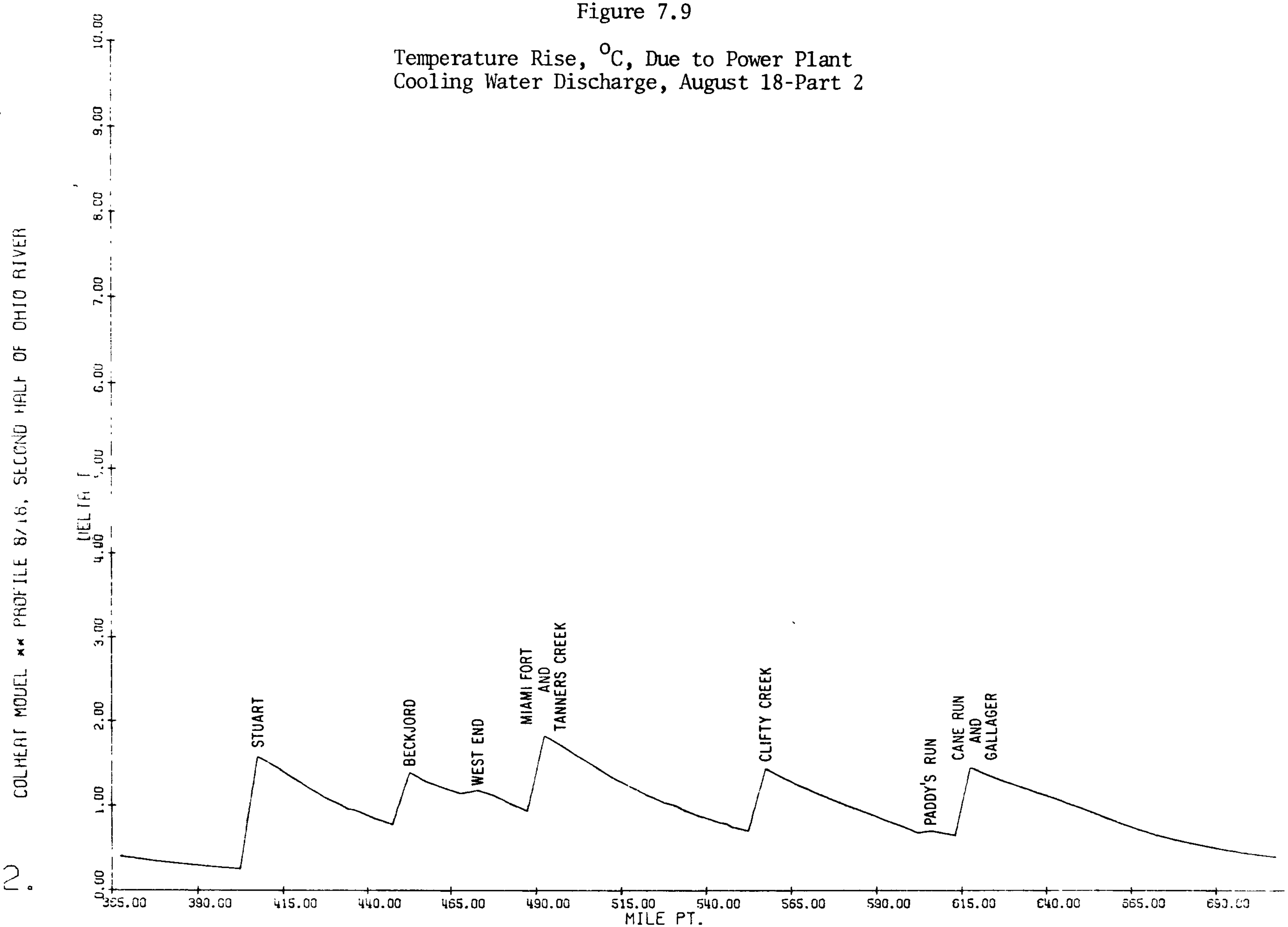
Ohio River Temperature Profile, August 18 - Part 2



71.

Figure 7.9

Temperature Rise, ^{o}C, Due to Power Plant Cooling Water Discharge, August 18-Part 2



72.

Figure 7.10

Ohio River Temperature Profile, September 11 - Part 1

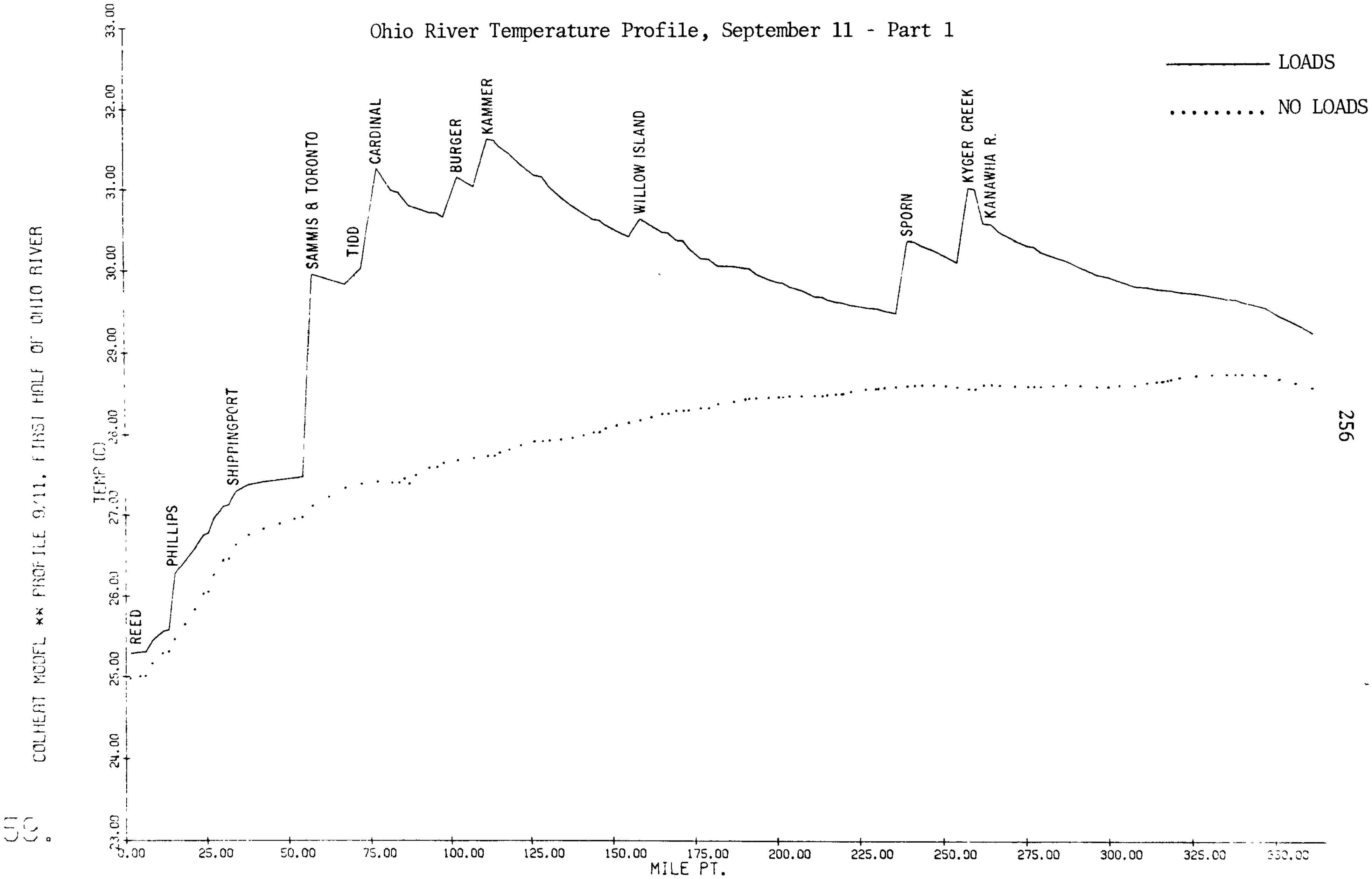


Figure 7.11

Temperature Rise, °C, Due to Power Plant Cooling Water Discharge, September 11 - Part 1

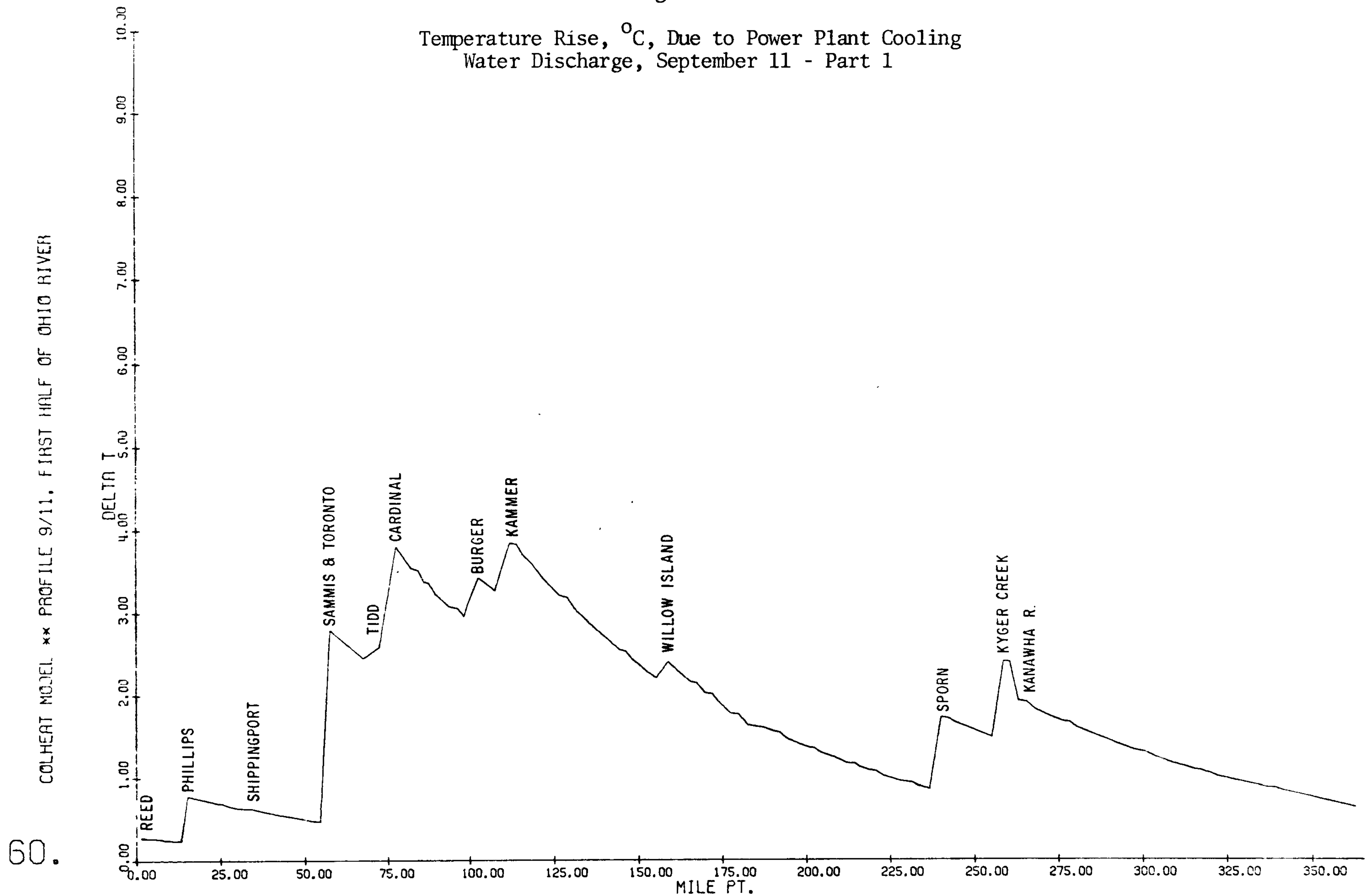


Figure 7.12

Ohio River Temperature Profile, September 11 - Part 2

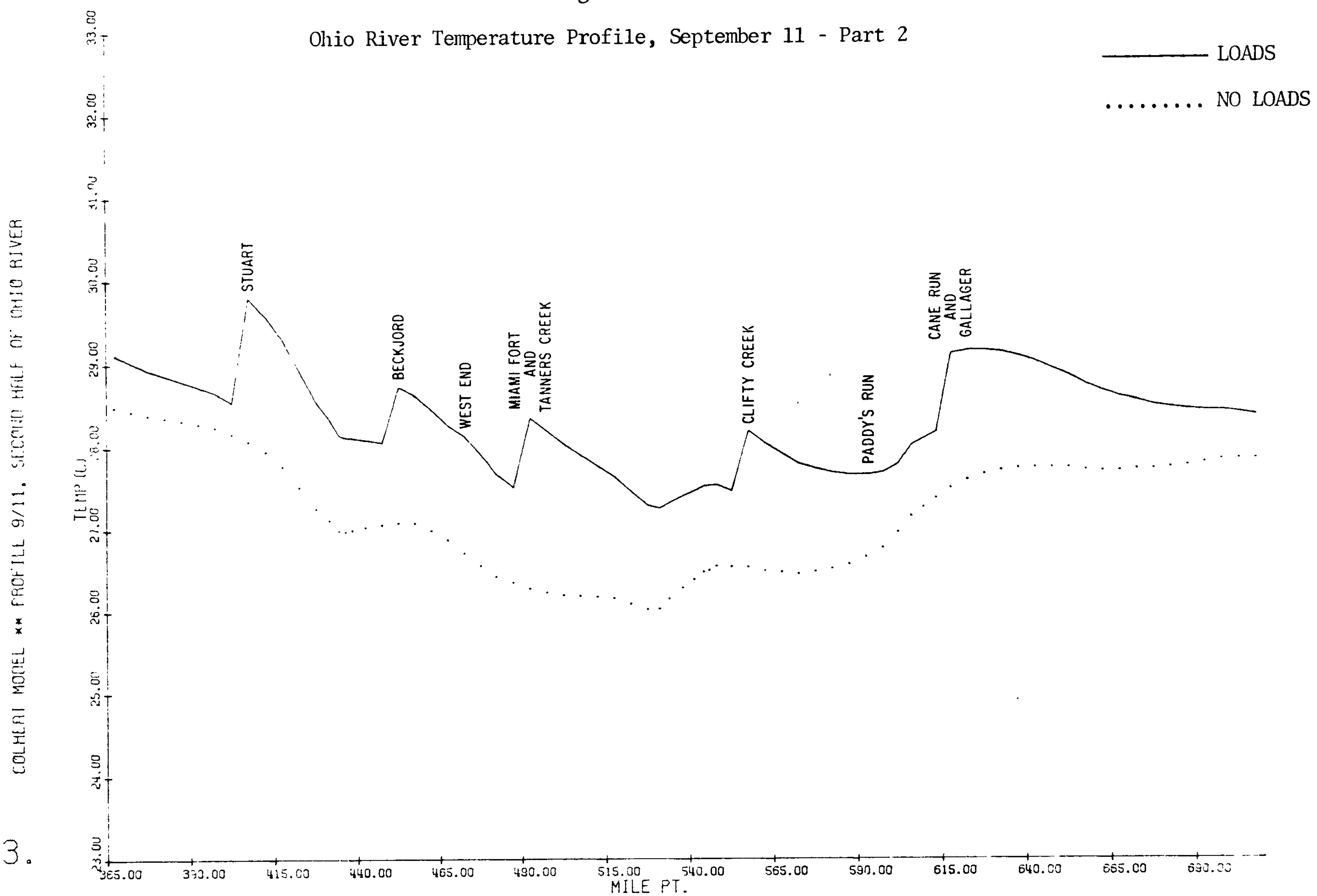


Figure 7.13

Temperature Rise, ^{O}C, Due to Power Plant Cooling Water Discharge, September 11 - Part 2

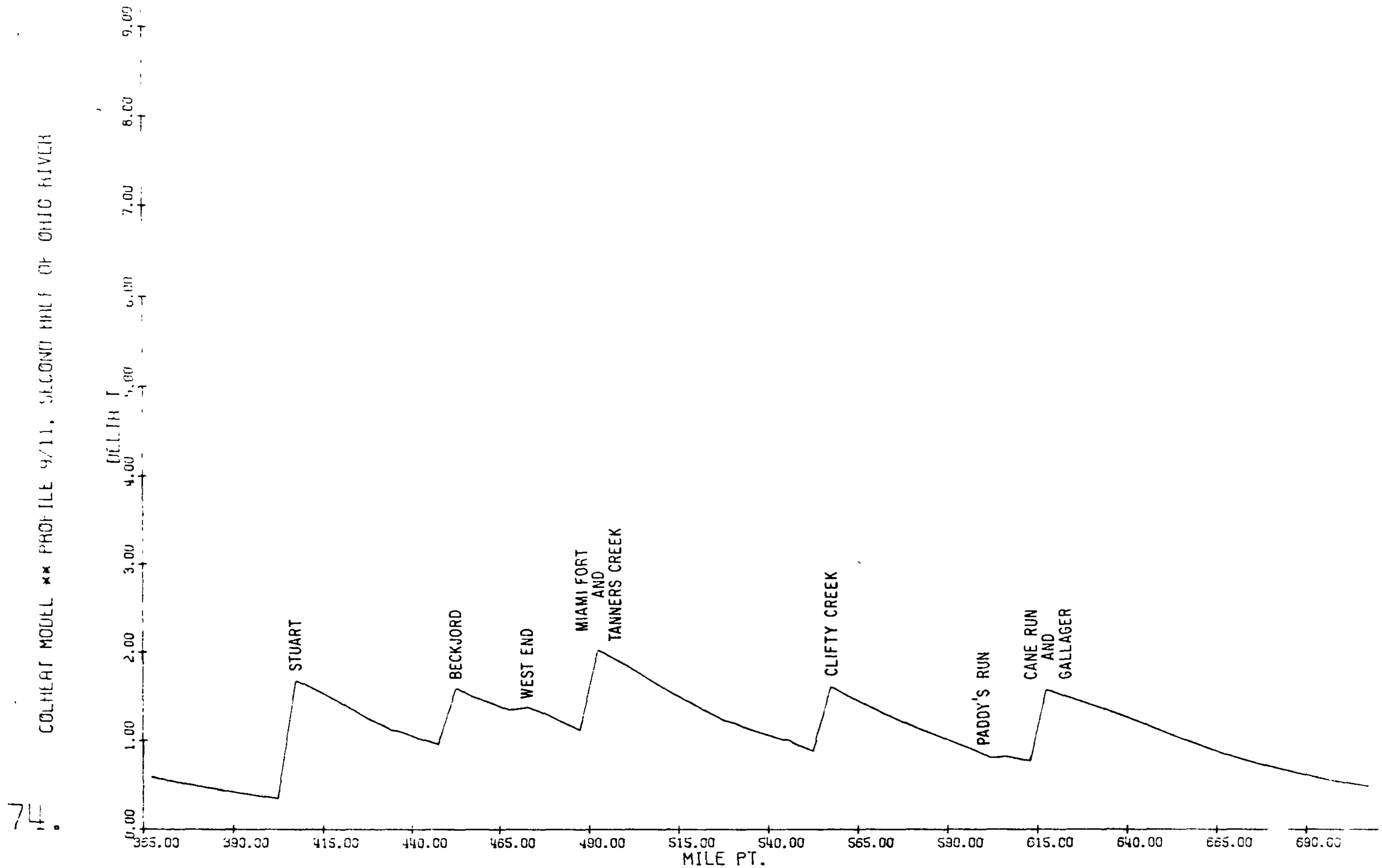
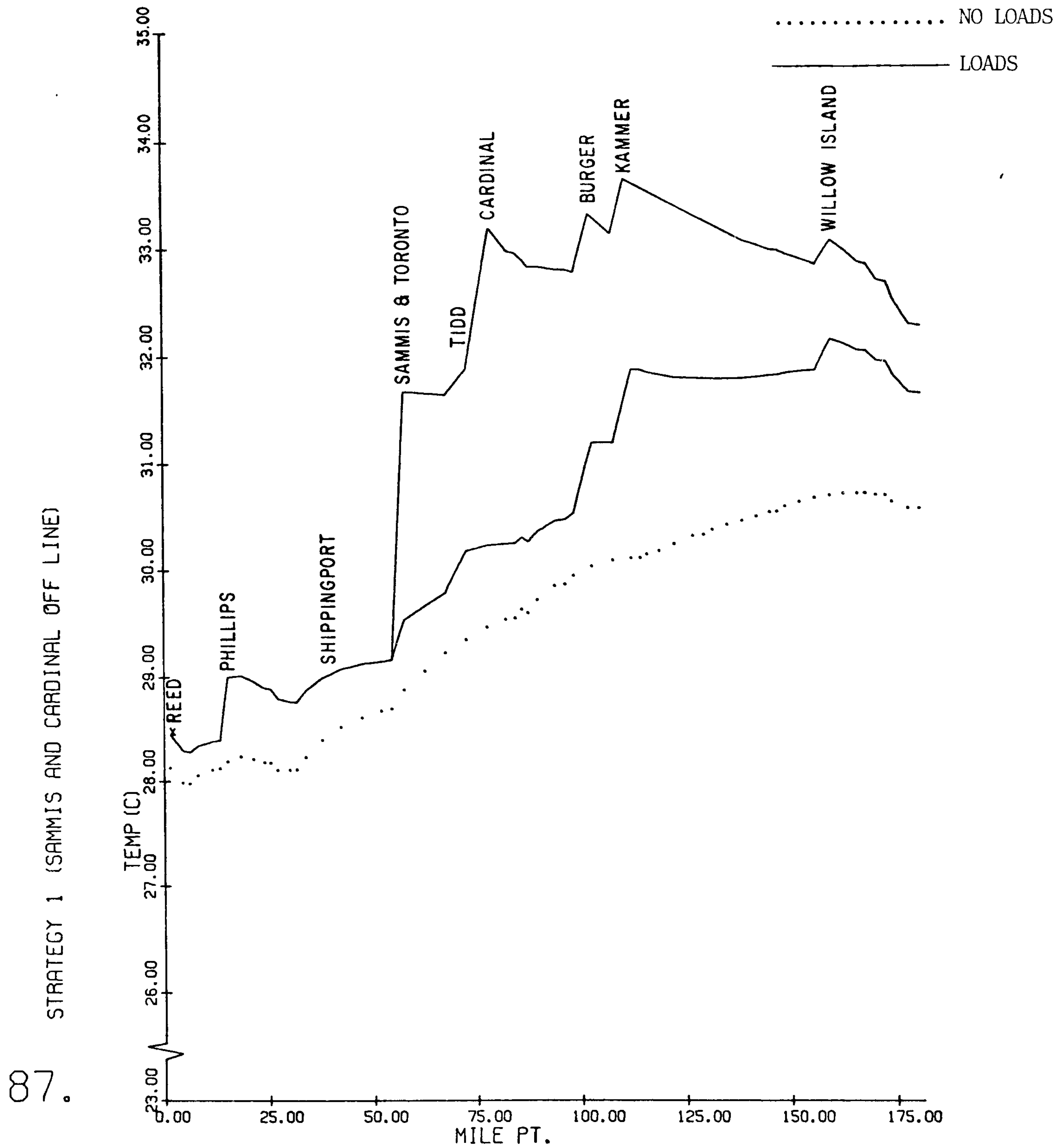


Figure 7.14

Temperature Profile for Strategy 1 - July 25



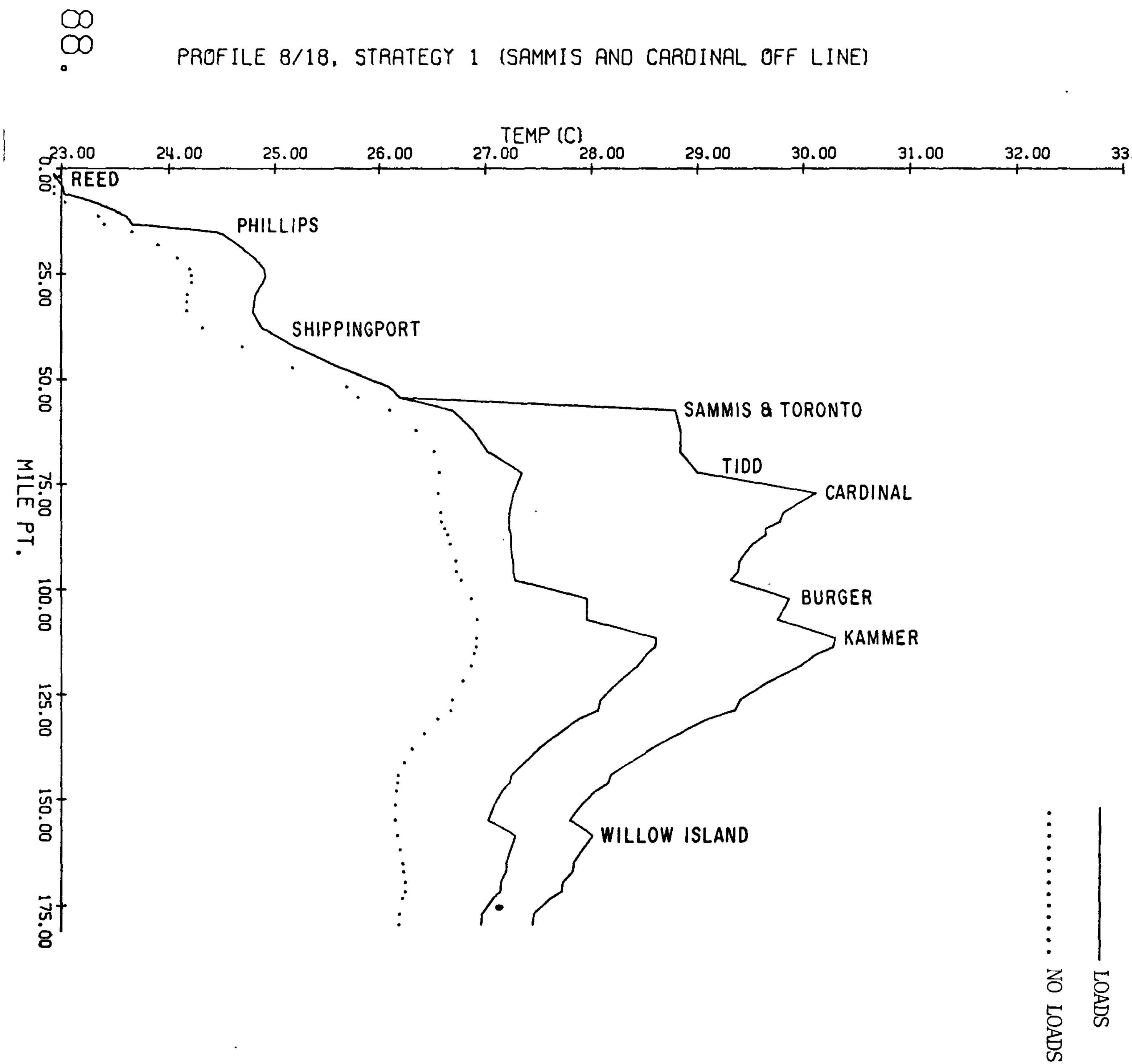
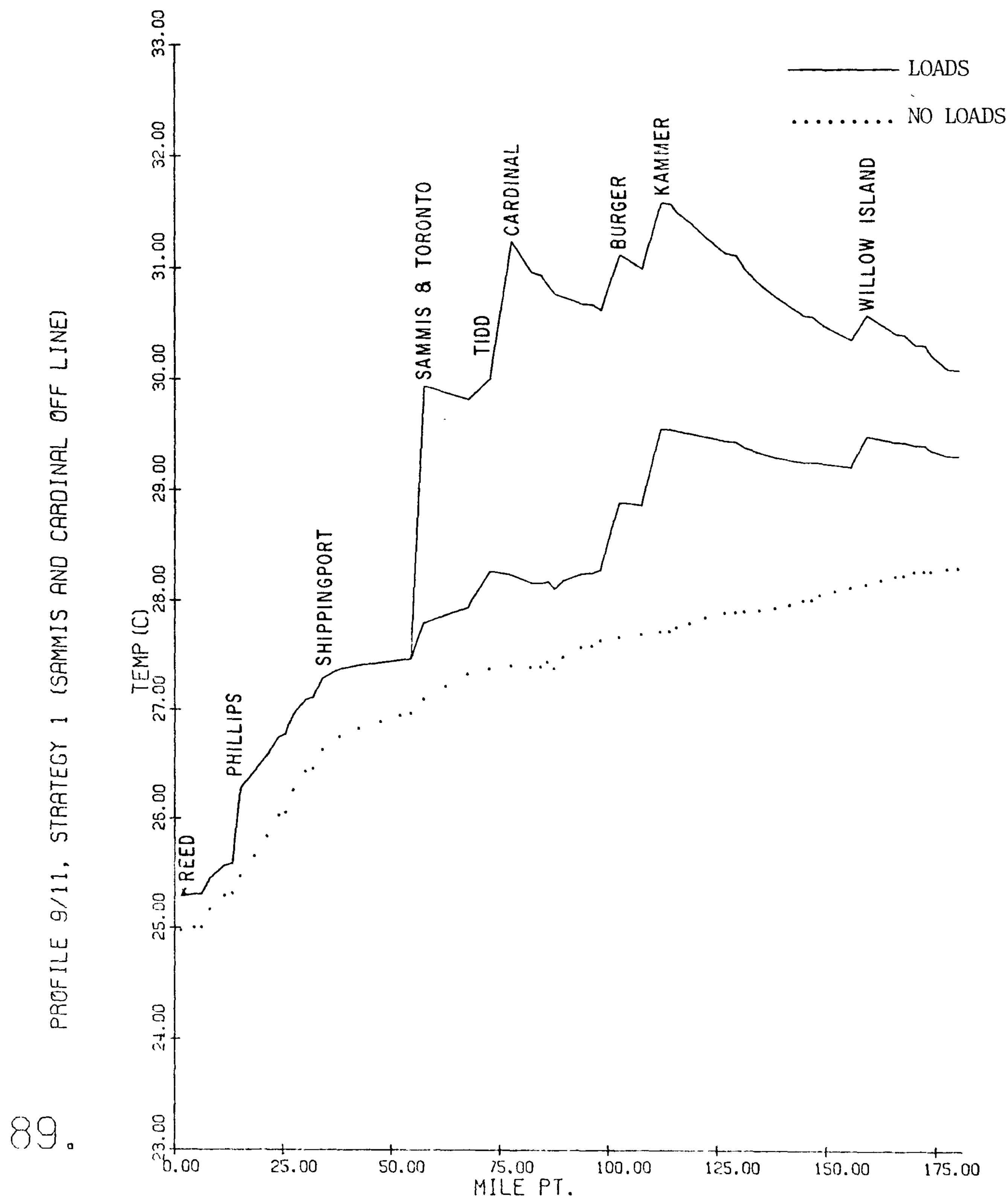


Figure 7.15
Temperature Profile for Strategy 1 - August 18

Figure 7.16

Temperature Profile for Strategy 1 - September 11



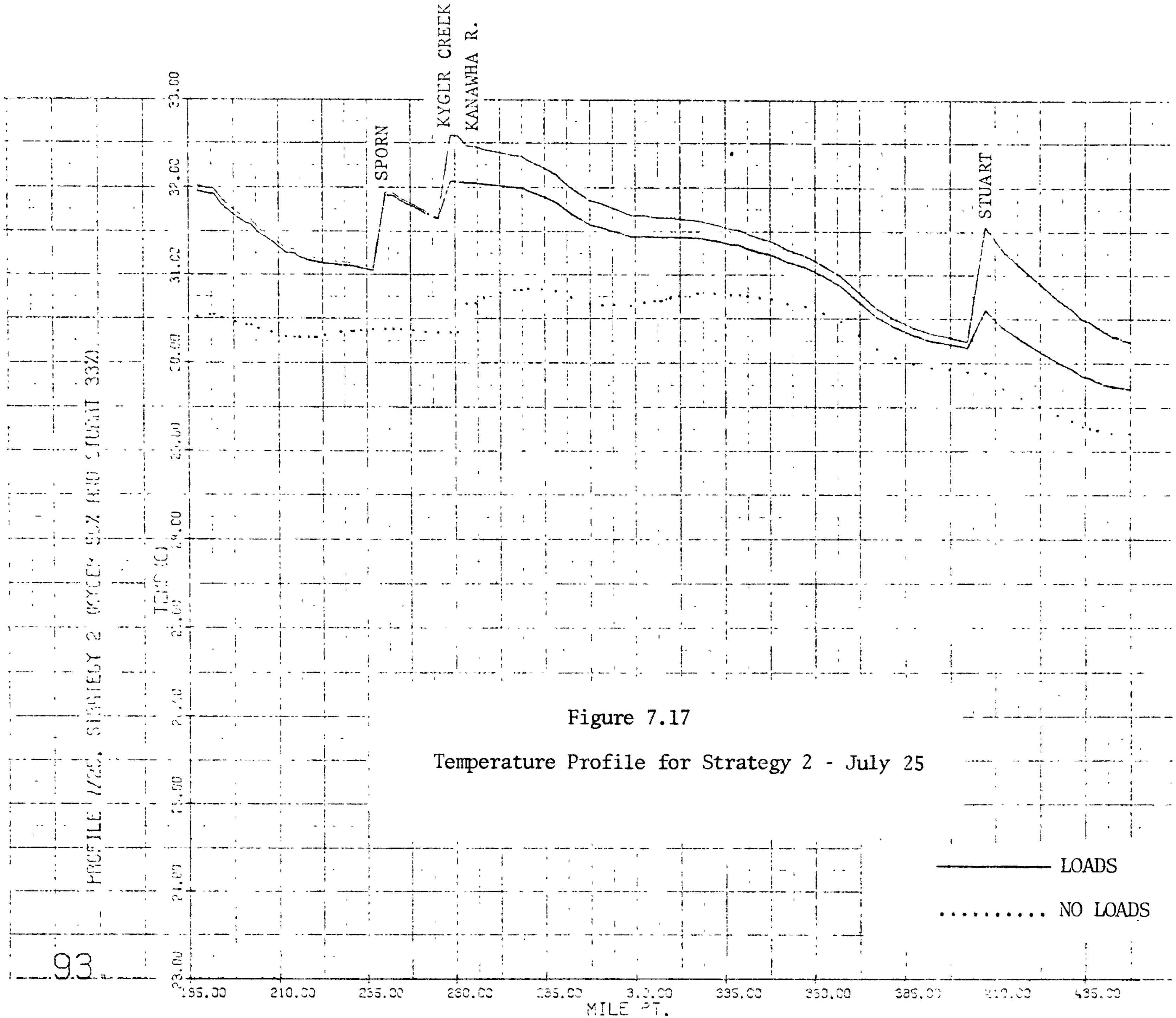


Figure 7.17

Temperature Profile for Strategy 2 - July 25

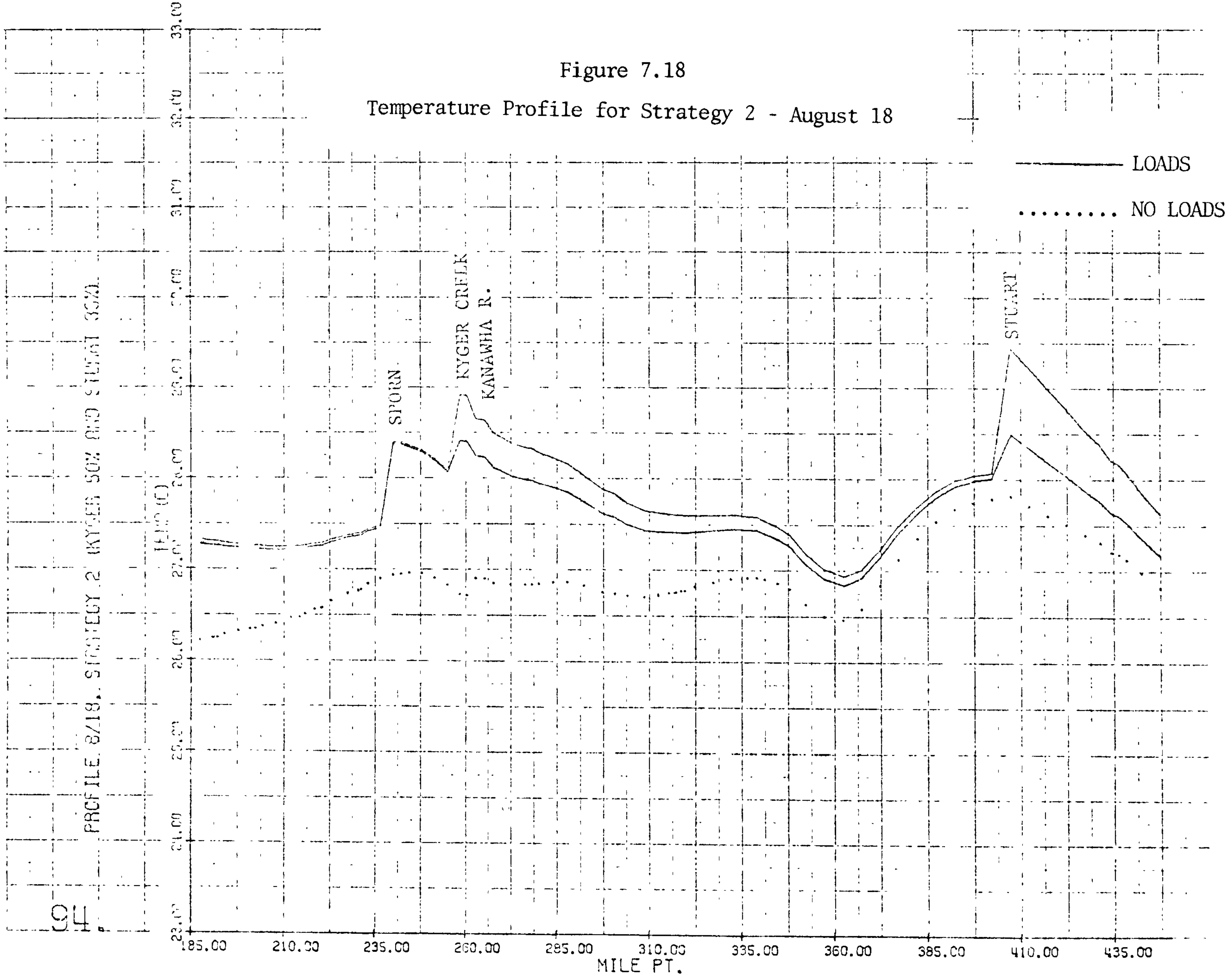


Figure 7.18

Temperature Profile for Strategy 2 - August 18

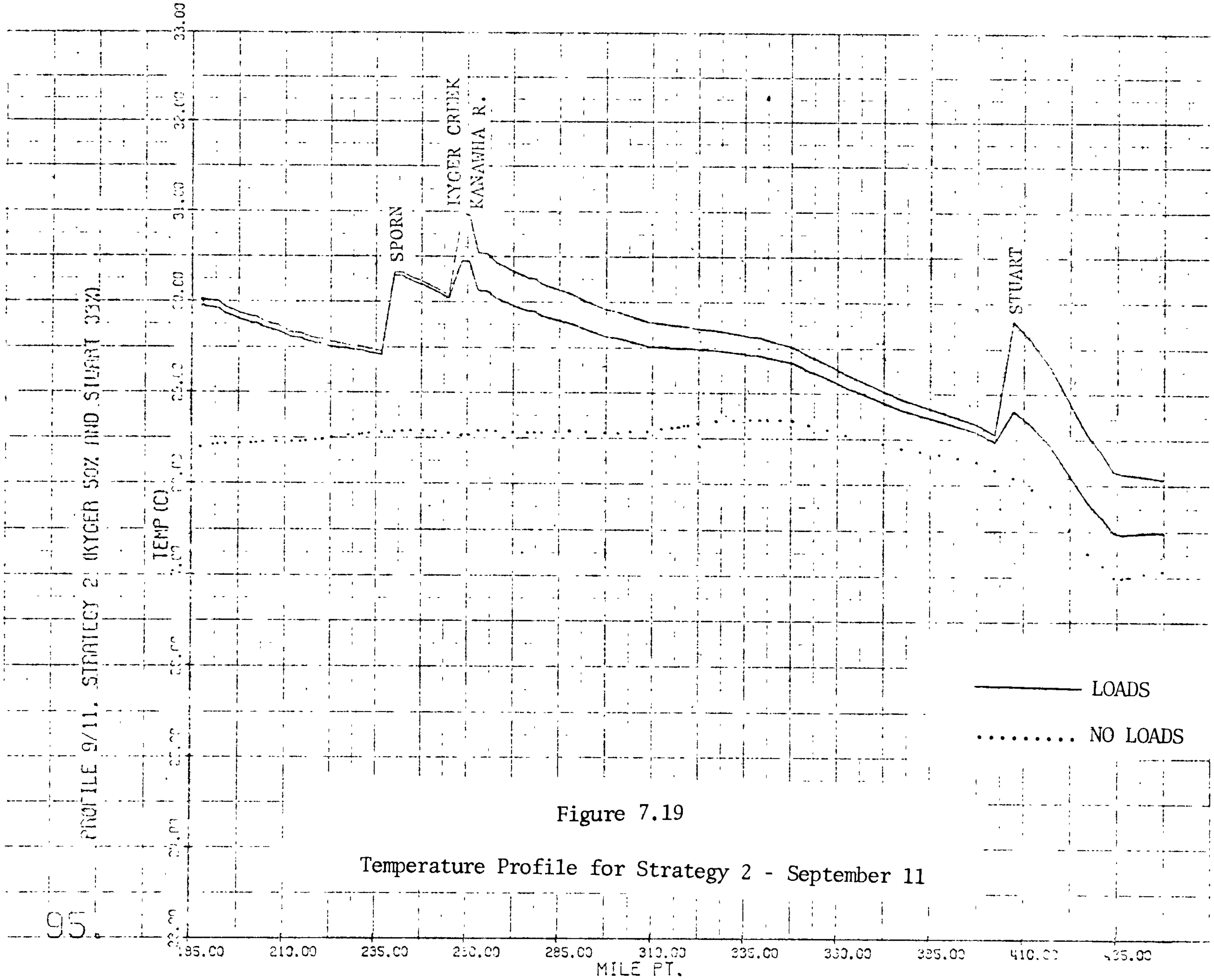


Figure 7.19

Temperature Profile for Strategy 2 - September 11

Strategy 3

A third strategy applied was as follows: let all power plants discharge at their regular rates* except for Stuart, Tanners Creek and Cane Run. Stuart's discharge rate is cut to 33% of its normal discharge rate as it was in strategy two, while Tanners Creek and Cane Run are cut to 50% of their normal discharge rate. The results are shown in Figs. 7.20 through 7.22. The top line represents the normal situation, i.e., no strategy, the lower solid line represents the strategy and the dotted line represents the natural river temperature.

Several other strategies could have been tried, but were not due to time limitations. However, it is seen that the COLHEAT model is quite capable of being used to develop strategies for enforcement agencies.

*By regular rates are meant those advected heat rates shown in Table 7.3.

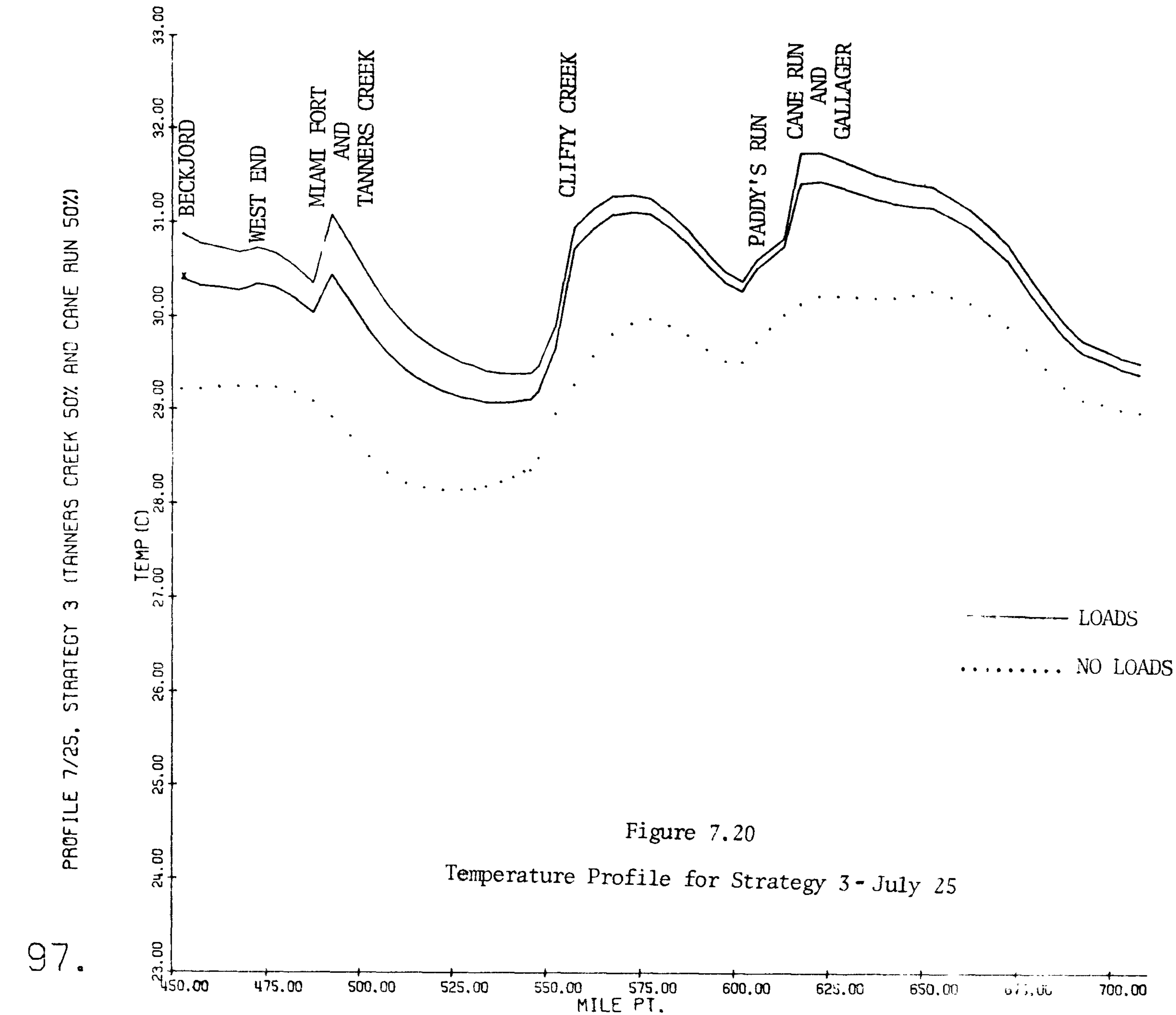
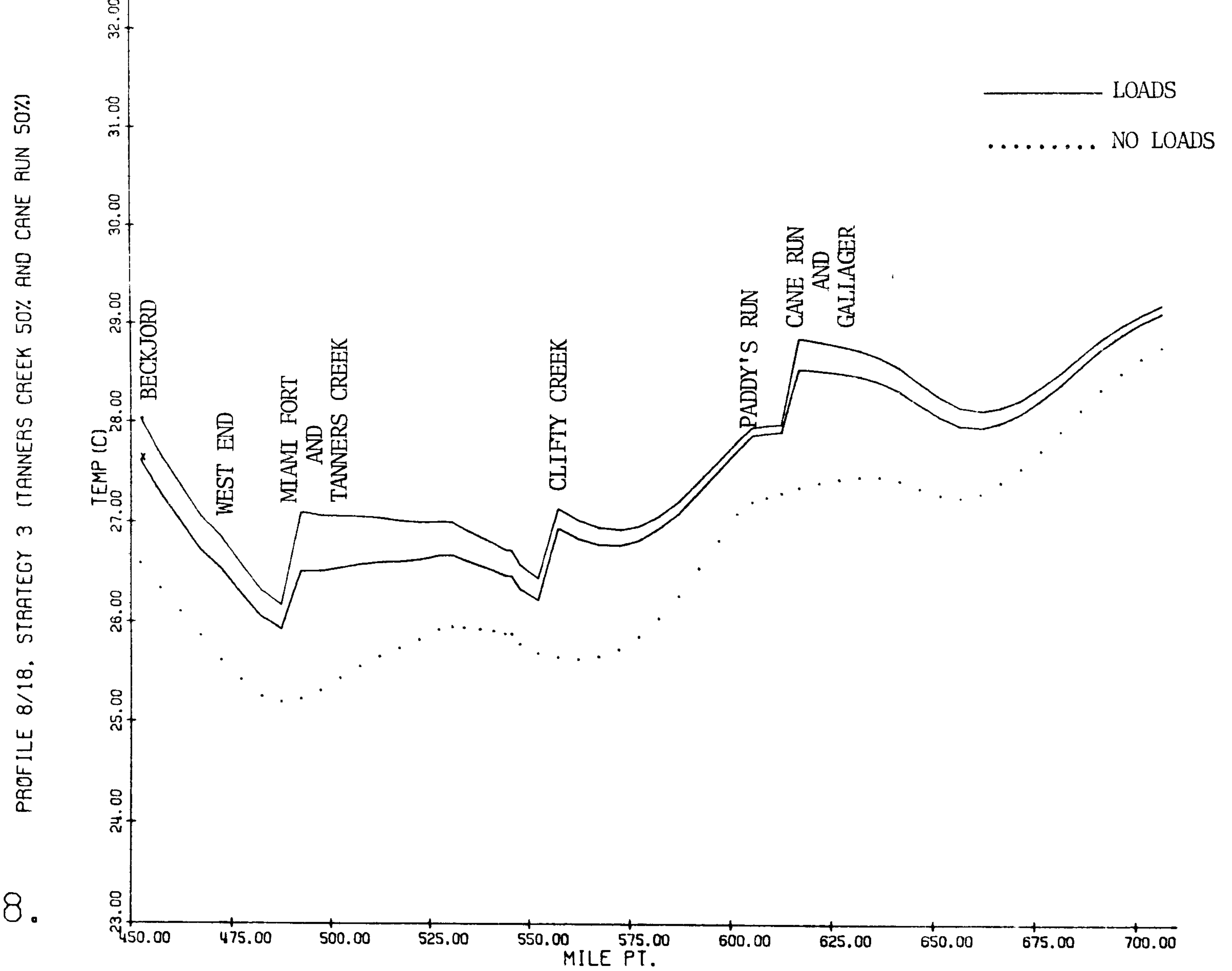


Figure 7.20

Temperature Profile for Strategy 3 - July 25

Figure 7.21

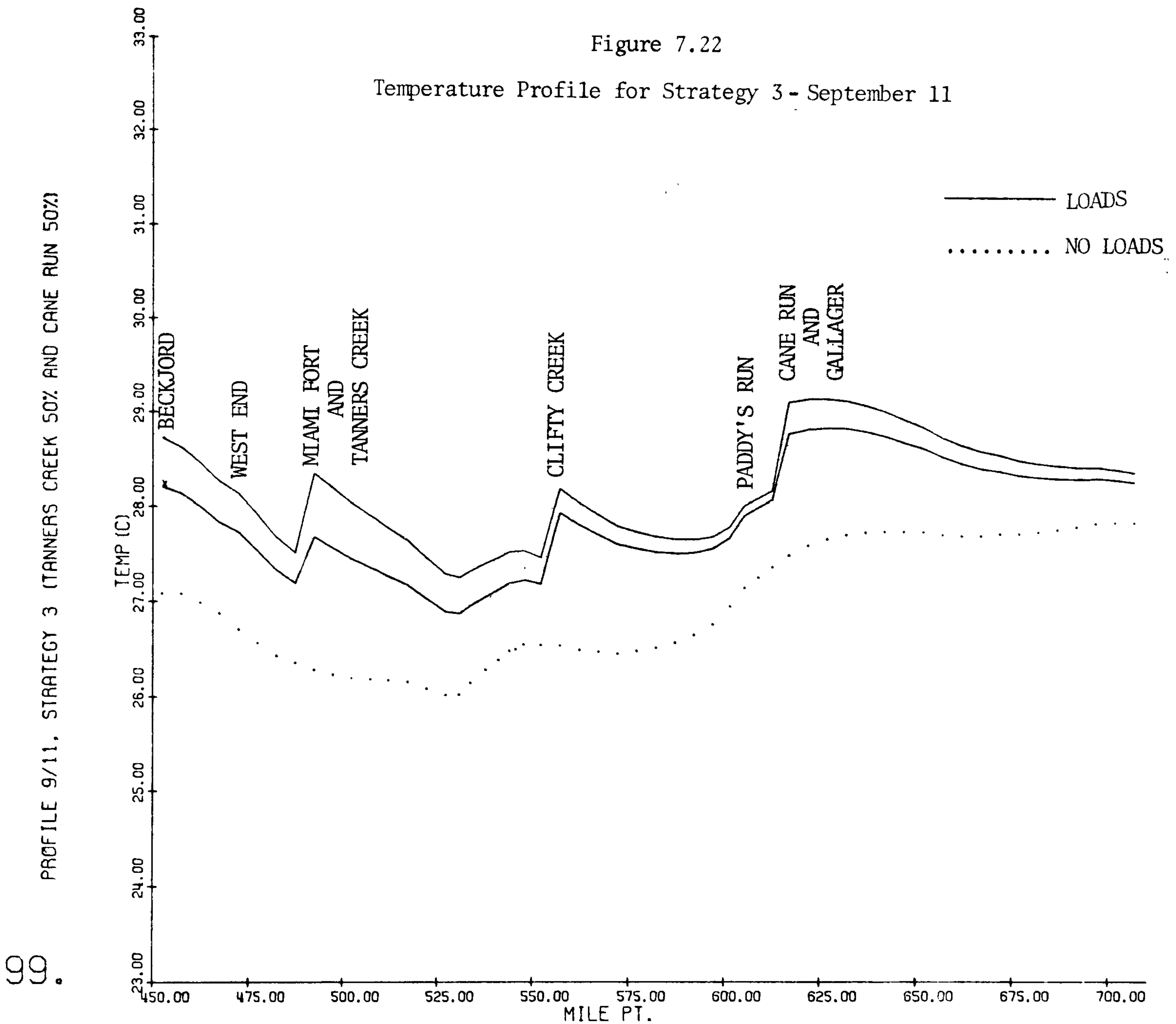
Temperature Profile for Strategy 3 - August 18



98.

Figure 7.22

Temperature Profile for Strategy 3 - September 11



Section 7 References

1. State of Illinois Pollution Control Board, Water Pollution Regulations of Illinois, July 1973.
2. Commonwealth of Pennsylvania Department of Environmental Resources, Water Quality Criteria, July 1973.
3. State of Indiana, Revised and Promulgated Water Quality Standards SPC 1R-3, SPC 7R-2, SPC 10R, July 1973.
4. Ohio River Valley Water Sanitation Commission, Pollution Control Standard No. 2-70.

8. THERMAL PLUMES IN RIVERS WITH EMPHASIS ON THE OHIO RIVER

This section of the report will address the localized thermal plume in rivers like the Ohio River. Unfortunately, the available field data on thermal plumes for the Ohio are extremely sketchy and typically exists either in terms of poor quality aerial infra-red data or sketchy boat temperature measurements. None of the data received from EPA or electric utility sources for this short study were of sufficient quality or quantity to provide any physical insight to individual plume dispersion at any of the investigated locations. This will be discussed in more detail below; therefore some data from other rivers are briefly discussed to provide the insight as to how river plumes behave in low and high river flows.

Section 8.1 discusses the basic physics of river plumes and describes an example of three categories of thermal discharges into rivers: surface discharge into low river flow, surface discharge into high river flow, and a submerged diffuser discharge.

These examples from surface and submerged discharge cases are discussed to indicate the kinds of plume characteristics that can be expected from different kinds of outfall structures. It should be kept in mind that localized river flows and local river topography are important in the design and performance of any discharge. Consequently, the results of the plume studies discussed in Section 8.1 should not be blindly extrapolated to the Ohio River but yet they will provide insight into river plume fundamentals.

Section 8.2 discusses the data available on the Ohio River both by aerial infra-red surveys and boat measurements. The inadequacy and only scoping nature of those surveys are reported.

Section 8.3 describes the controversy over the J. M. Stuart Power Plant involving a three-unit discharge and the compliance with state temperature standards. Mathematical models of plume dispersion utilized by WAPORA and ORSANCO for the J. M. Stuart discharge are critically discussed.

8.1 Thermal Plumes in Rivers

The most common method of disposing of a heated effluent into a river is by means of a channel or canal discharging at the water surface. The vast majority of older plants use this type of outfall structure as part of a once-through cooling system.

There are three important reasons for analyzing the definable thermal plume. The first is the desire to assess and, therefore, avoid possible recirculation of heated water into the intake. The second is the necessity to develop an appropriate design to meet mixing zone limitations or other possible temperature standards imposed by governmental agencies. The third is the desire to help predict biological effects relating to changes in the physical and chemical properties of the water.

A heated effluent discharged into a river by means of a low discharge velocity outfall can result in a stratified plume where little mixing takes place. Such heated layers are usually not acceptable if they extend over a major portion of the river width because most state and federal river standards require a zone of free passage for migrating fish. These heated layers can also extend upstream to the intake location and recirculate under low flow conditions reducing plant efficiency. A high velocity discharge into a river current may, in certain cases, cause too much penetration and blockage of the river. Consequently, many surface discharges into rivers are made at an angle to the river flow (typically 20-60°).

Usually the discharge in a river is located at some distance downstream of the intake to avoid the recirculation possibility noted above. If no significant river current exists during parts of the year, it is wise to locate the discharge at a higher vertical elevation than the intake to avoid or eliminate recirculation. The use of skimmer wall intakes for run-of-the river impoundments is often recommended.

8.1.1 Plume Physics

A heated effluent may pass through several regimes of flow as it is dispersed into the receiving body of water. Motivated by both physical and biological considerations, the discharge plume is divided into two regions, the near and far fields. As the name suggests, the near field is that part of the thermal discharge closest to the actual outfall. The near field normally possesses a significant velocity disparity with the rest of the water body and for that reason is often called the jet regime. Correspondingly, the far field is referred to as the thermal plume or simply as the plume, although the term "plume" is also used to mean any point not at ambient conditions. This rather confusing usage of terms is nevertheless quite common and there is quite often slippage from one usage to the other.

The point of separation between the near and the far fields is quite nebulous. Consequently, the intermediate field, a transition zone possessing properties of both the near and far fields, is commonly discussed. The definitions of near and far fields themselves are somewhat arbitrary, but the generally acknowledged characteristics are:

Near Field

1. Definable thermal plume where temperature and velocity excesses are greater than about 20% of their outfall values.

2. Hydrodynamics of the plume are important. Particulars of the outfall structure must be considered. Characteristic nondimensional groups are the aspect ratio, the initial densimetric Froude number, the ratio of ambient to outfall velocities, the bottom slope, and the ratio of discharge depth to initial water depth.

3. Exposure time for organisms is on the order of an hour.

Far Field

1. Peripheral area of the plume where velocity and temperature excesses are small.

2. Ambient conditions are predominant in determining dilution with virtually no dependence on outfall characteristics. Diffusion by means of ambient turbulence is considered to be the prevailing mechanism.

3. Exposure time for organisms is on the order of several hours to a day.

There are five mechanisms governing dispersion, diffusion, and dissipation of momentum and energy within a thermal plume. They are: jet entrainment, cross flow interaction, ambient-turbulence-induced diffusion, buoyant spreading, and surface heat exchange. These processes are shown schematically in Fig. 8.1. Each mechanism will now be briefly defined and discussed.

1. Jet Entrainment

Entrainment refers to the incorporation of ambient fluid into the momentum dominated jet due to the large shear velocities between the discharged and receiving water. Figure 8.2 illustrates an entraining jet. This gathering of ambient fluid into the jet is assumed to be the principal mechanism for mixing in the near and intermediate fields where jet momentum dominates.

Tank studies by Ellison and Turner[1] indicate that the rate of vertical entrainment decreases as the densimetric Froude Number, IF, increases. For densimetric Froude numbers less than about 1.2, vertical entrainment is negligible.

Because of the above described dependency on local densimetric Froude number, vertical entrainment may be suppressed in certain regions of the plume. The scenario of a typical thermal plume is shown schematically

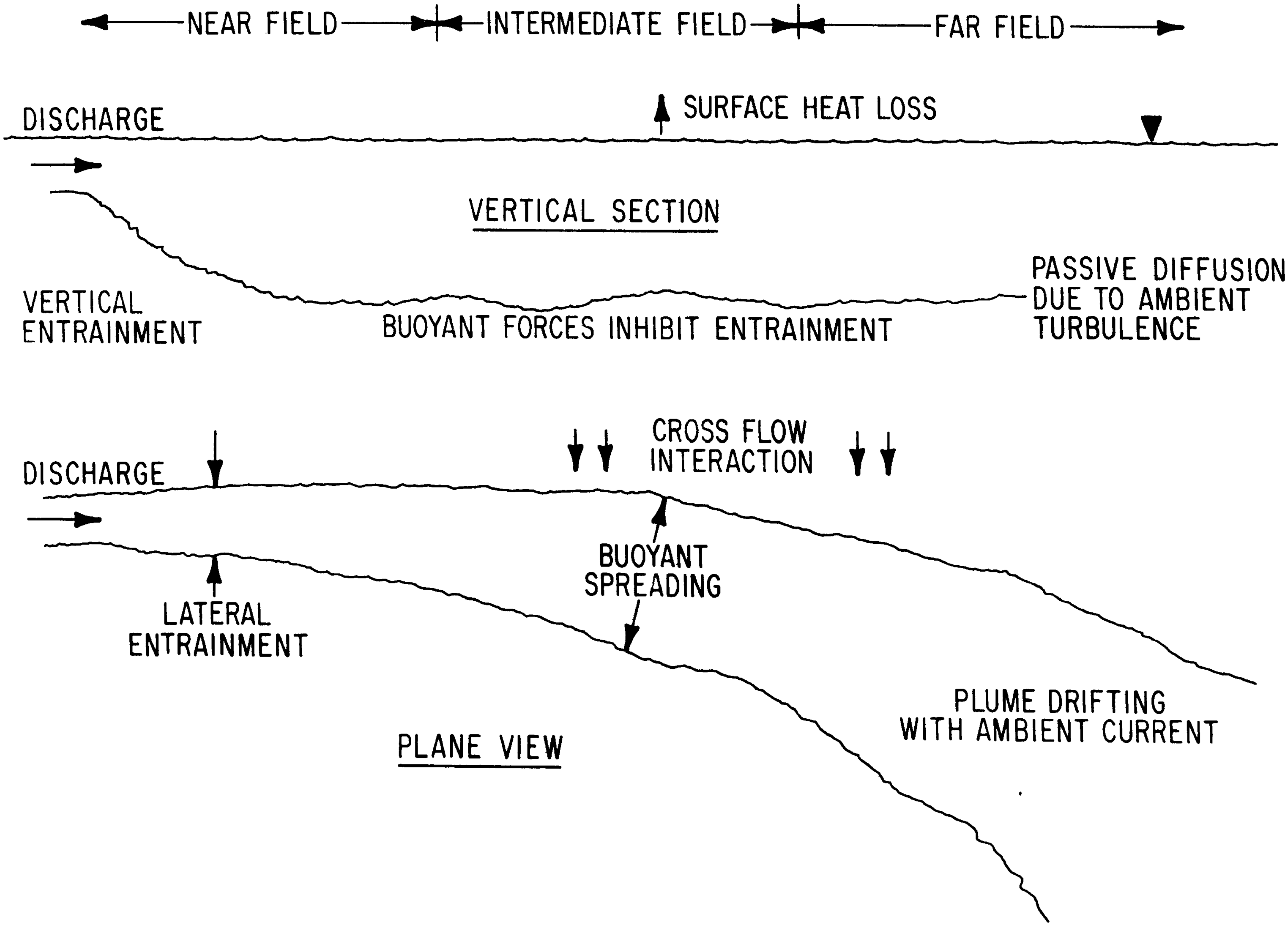
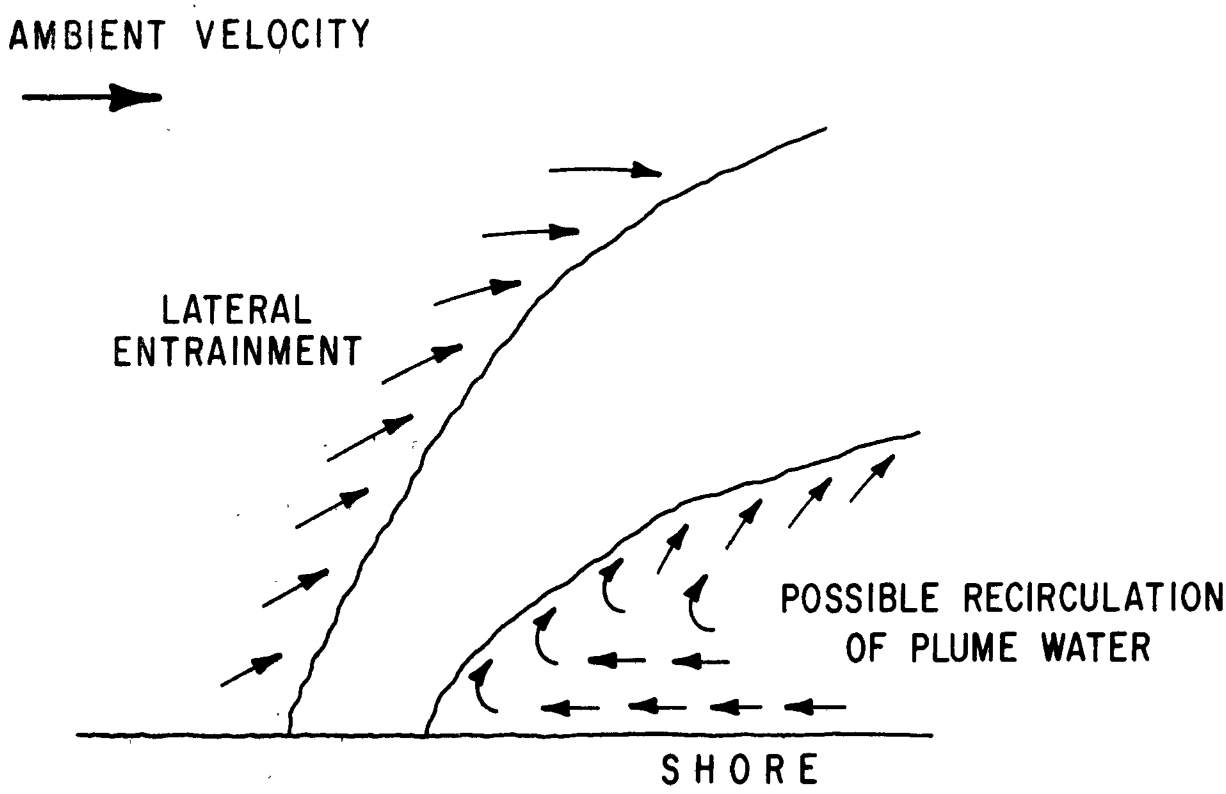


Figure 8.1: Plume Dispersion Process.



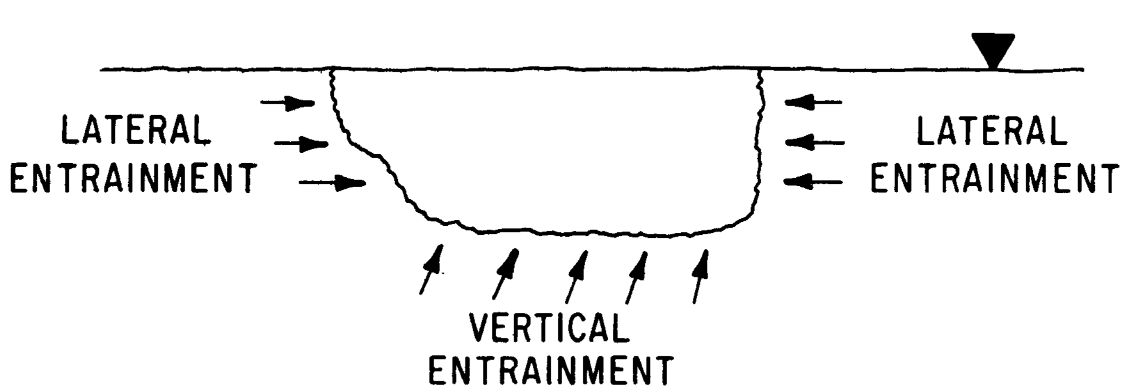


Figure 8.2: Entrainment of a Jet in a River Crossflow.

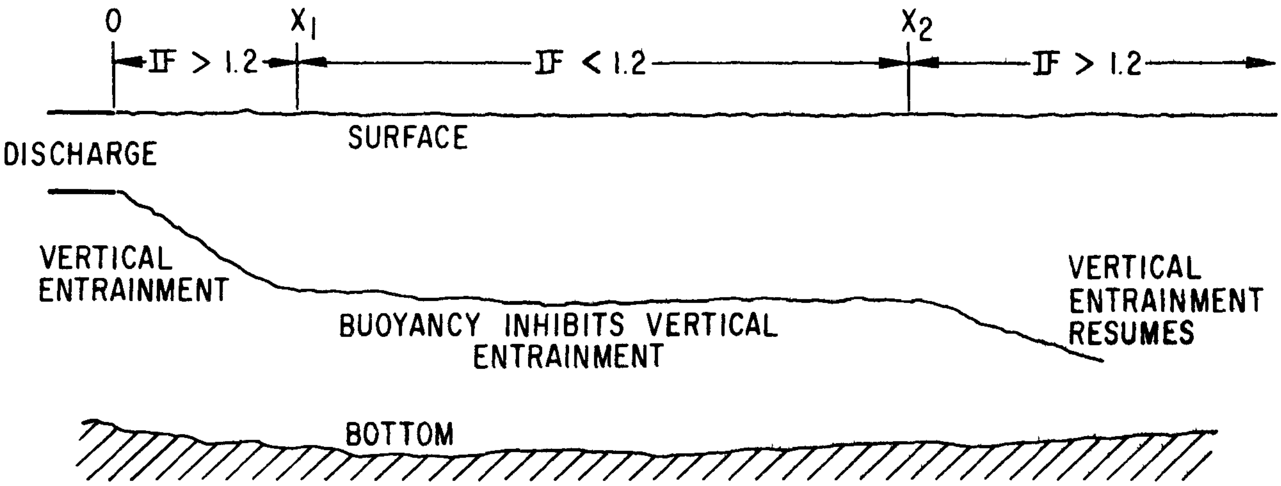
in Fig. 8.3a. At the point of discharge (indicated by "0" in the figure), the densimetric Froude number is larger than 1.2 and the plume will entrain vertically. Rapid mixing causes the densimetric Froude number to decrease until (at position x_1 in the figure) vertical entrainment effectively ceases. The stabilizing effects of buoyancy limit mixing to lateral entrainment alone, hence the densimetric Froude number will level off and may actually begin increasing. If the densimetric Froude number again becomes great enough, vertical entrainment will resume (position x_2 in the figure).

Vertical entrainment may also be limited by interaction with the bottom of the river. This is a common occurrence for discharges into shallow water. Figure 8.3b illustrates such effects indicating that vertical mixing is suppressed in the region where the plume is attached to the bottom.

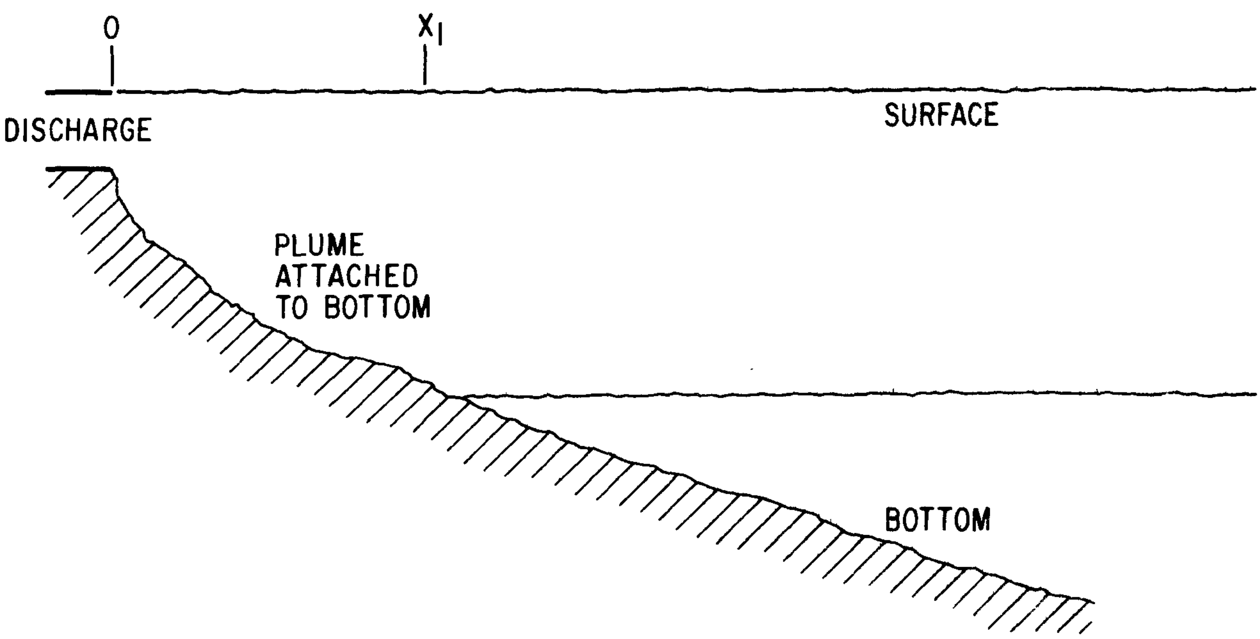
2. Cross Flow Interaction and Advection

In the presence of an ambient cross current, the jet will bend in the downcurrent direction. Such bending is the result of a pressure gradient across the jet produced by the complex interaction of jet and ambient fluid.

There are additional ways that cross flow may affect jet behavior. Jet bending can adversely affect mixing by limiting entrainment on the lee side of the jet by partially isolating it from free ambient water. Cutoff of the lee side from ambient water can lead to the recirculation of partly diluted plume water as illustrated in Fig. 8.2. This is especially the case for river plumes under the influence of large river currents during high flow. Also, jets in the presence of a cross flow will generally exhibit asymmetric velocity and temperature profiles. Cross flow interaction may prevent the jet from becoming fully developed, thereby complicating both the modeling and experimental analysis of jet hydrodynamics.



A. EFFECTS OF BUOYANCY ON VERTICAL ENTRAINMENT



B. EFFECTS OF BOTTOM ON VERTICAL ENTRAINMENT

Figure 8.3: Schematic View of Entrainment Process with the Effects of Buoyancy and Bottom.

3. Ambient-Turbulence-Induced Diffusion

Ambient turbulence refers to the turbulence which exists in all natural bodies of water. The genesis of this turbulence in rivers is normally attributed to bottom friction as the river water flows downcurrent and to wind stress at the water surface. Groins or bends in the river usually generate additional turbulence which aids in plume mixing. For large river flows and ambient currents, this bottom generated turbulence is thought to play a major role in plume dispersion. Ambient turbulence is, in general, more significant in river plume dispersion than in lake plume dispersion. The effects of winds is less in rivers than in lakes due to the much shorter fetch.

4. Buoyant Spreading

Buoyant forces develop due to the density disparity between discharged and receiving water and due to the variable density within the jet. These forces increase horizontal spreading and, as noted earlier, may inhibit vertical entrainment. The importance of buoyancy is measured by the densimetric Froude number discussed earlier. Depending on heat loss and mixing parameters, the discharged fluid may enter a regime of stratified flow where buoyant forces are dominant.

5. Surface Heat Loss

There is a continual heat exchange between water surface and the atmosphere through conduction, radiation, and evaporation as is discussed in Section 5. At a specific water surface temperature, T_e, known as the equilibrium temperature there is no net exchange of heat with the atmosphere. The temperature of a natural body of water continually approaches equilibrium, but seldom reaches it because of the time needed to exchange large amounts of heat with the atmosphere. Consequently, the ambient temperature is lower than equilibrium during spring heating and higher than equilibrium during fall cooling. During winter and summer months the ambient temperature is very close to equilibrium. Normally, however, condenser cooling water will be at a temperature greater than equilibrium and net heat loss from the plume surface will result. Since temperature excesses in the plume are generally small, the rate of surface heat loss is often assumed to be proportional to the difference between the plume temperature and the equilibrium temperature. Most treatments of surface heat exchange use the ambient water surface temperature, T_a, as the equilibrium value even though $T - T_e$ may be quite different from $T - T_a$ at certain times of the year.

For typical values of the surface heat exchange parameter, K, the amount of heat transfer in the measurable plume by this mechanism is small. Unless surface areas are large, surface heat loss has minimal effect on plume temperatures. It is generally thought that only negligible heat is lost to the atmosphere of a thermal plume before it disperses to a fully mixed condition laterally and vertically in the river.

Of the five processes only this one, surface heat exchange, involves actual removal of heat from the ambient surface. The other four are merely ways in which the excess heat is mixed into and moved around the water body. In the regions of greatest interest, the near and intermediate fields, only a few percent of the excess heat is lost to the atmosphere through surface heat exchange. Consequently, the four processes of plume dilution are those of significant importance in modeling these fields.

8.1.2 Some General River Plume Characteristics

There are indeed complex interactions among the various factors that influence the shape of a thermal plume in a river. The primary consideration is whether the thermal plume will tend to be dispersed across the entire width of the river or whether it will hug the shoreline for considerable distances downstream. Each may be considered biologically unsatisfactory for different reasons, the first in terms of possibly interfering with fish migrations and the second in terms of potential damage to aquatic feeding grounds or spawning areas along the generally shallow shoreline affected by the plume.

Edinger, Brady, and Geyer[2] discuss the tendency for the plume to traverse the river to the opposite shore in terms of four major factors:

(a) the lateral component of the discharge momentum,
(b) the buoyancy of the heated discharge,
(c) the lateral diffusion rate of the ambient river water, and
(d) the offshore component of the wind.

The authors note that it is difficult to quantify the relative importance of these factors in relation to the tendency of the ambient river current to sweep the plume directly down the shoreline due to the high variability of meteorological, hydrological, and plant operating conditions.

On the basis of limited analyses of field data of plumes in rivers of low flow, Edinger, et al.,[2] make some generalizations. If the river flow is low and winds are absent, the buoyancy of the heated discharge is usually sufficient to cause the plume to spread to the other side of the river in a relatively thin surface layer within several river widths downstream. Turbulent eddies generated by bottom friction then cause a slow erosion of the plume-ambient interface as the plume moves further downcurrent. This continues until the heated effluent becomes fully-mixed with the river flow. This fully-mixed condition is usually reached before a significant fraction of heat is transferred to the atmosphere by surface heat transfer.[2]

An example of this lateral spreading effect under low flow river conditions is given in Figs. 8.4 and 8.5 which appear in a paper by Stefan and Skoglund.[3] The isotherms plotted are for the Allen S. King Plant on a tributary of the Mississippi River (called Lake St. Croix). Plant and en-

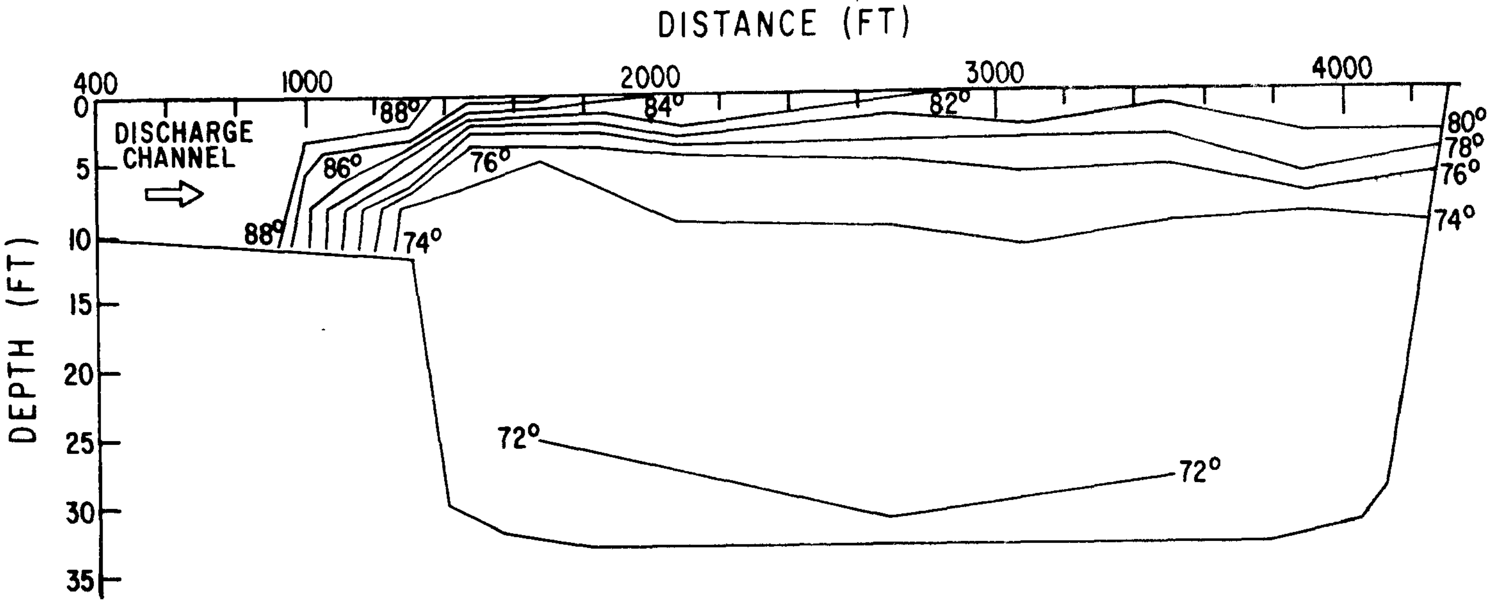


Figure 8.4: Water Temperature Stratification in Lake St. Croix near Cooling Water Outfall of the A. S. King Plant on September 4, 1970. Vertical Section along Axis of Discharge Channel. Temperatures in °F.[3]

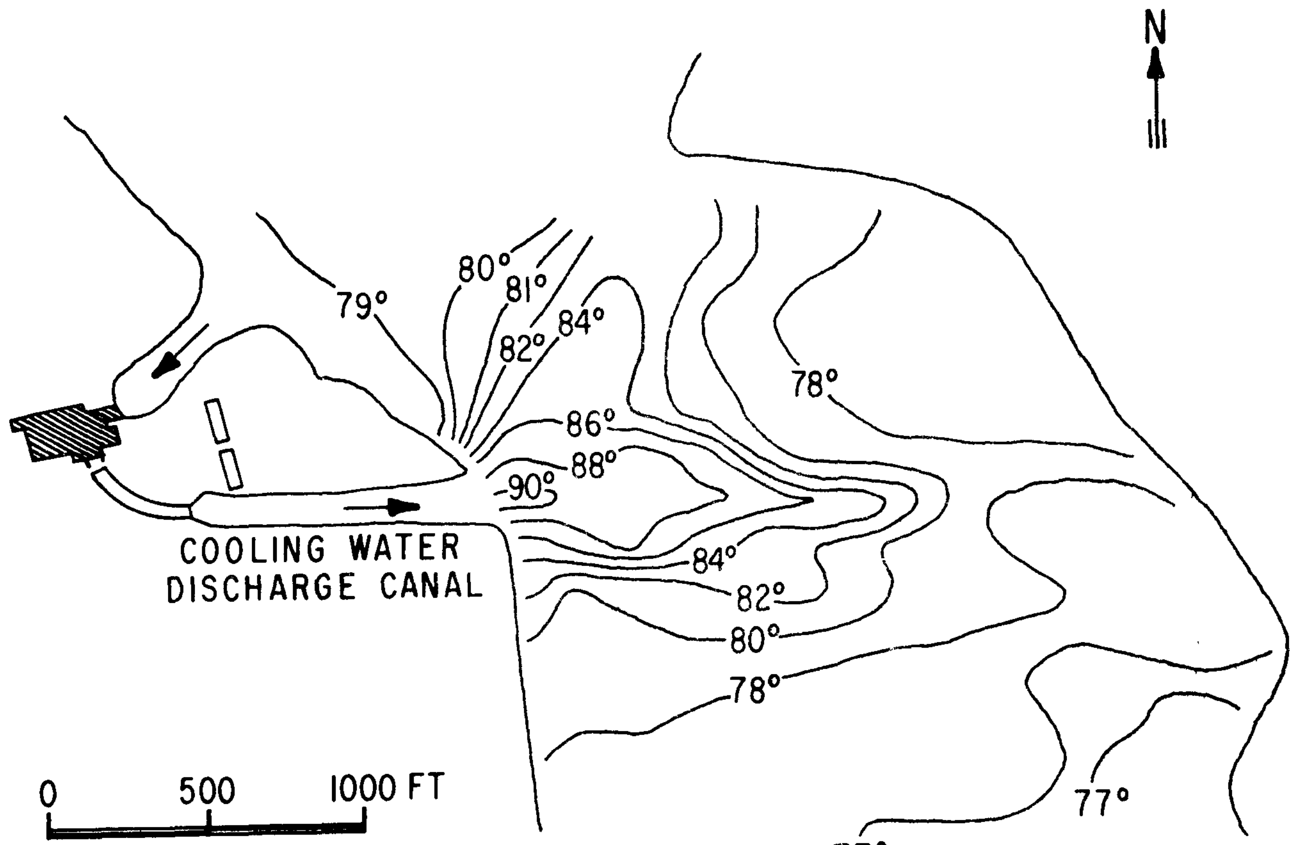


Figure 8.5: Isotherms at 3 inch depth in Lake St. Croix near Cooling Water Outfall of the A. S. King Plant on June 12, 1970. Wind from S.E. 14 mph.[3]

vironmental conditions for these two surveys are given in Table 8.1. The A. S. King discharge is through an open channel normal to the shore. Flow from this outfall is at a low densimetric Froude number which explains the strong temperature stratification from the surface to about a 10 ft depth with its inhibiting effect on turbulent mixing (Fig. 8.4). Figure 8.5 shows for a separate survey that the spread of the plume and wind effects can be significant.

An important physical phenomenon can occur for river discharges of very low initial densimetric Froude number. (Discharges of low initial densimetric Froude number are principly found with older plants. More recent discharge designs are mostly of the high initial densimetric Froude number type.) When the discharge densimetric Froude is very low, a stagnant wedge may be formed. Rather than the plume being swept downstream by the river flow, it may float over the river flow and gradually work its way upstream toward the intake. If the plume reaches the intake, recirculation can be a problem. Obviously, this situation can occur only for rivers with a low flow. The length of the upstream wedge as well as the interfacial profile can be predicted by the stagnant wedge models. Some experimental verification of these models has been done by Polk, et al.,[4] who presented field data from four southeastern plants. Refinements to the models have been proposed to account for downstream advection of heat plus loss due to surface cooling of the warm water wedge.

As the flow rate in a river is increased, the stronger vertical turbulent eddies will eventually impose enough dilution on the early stages of the buoyant plume to inhibit significant lateral progress to the far shore boundary.[2] The process of lateral diffusion is ever present yet is a relatively slow mechanism for lateral spreading. The plume in such larger current cases becomes somewhat more diluted and vertically mixed; it will

Table 8.1: Plant Discharge, River, and Weather Conditions for Allen S. King Power Station[3]

Date of Survey	September 4, 1970	June 12, 1970
Cooling Water Flow Rate, Q_p	614 cfs	639 cfs
River Flow Rate, Q_R	1707 cfs	3784 cfs
Q_p/Q_R	0.36	0.169
Average River Velocity	0.06 fps	0.06 fps
Outfall Temperature	88.4 °F	90.8 °F
Ambient Temperature	74.7 °F	79.3 °F
Wet Bulb Temperature	62.0 °F	66.0 °F
Dry Bulb Temperature	87.2 °F	81.2 °F
Wind Speed	4.2 mph	14 mph
Cloud Cover	10 %	100 %

also tend to follow the shoreline for much greater distances. It is expected that the plume will become dispersed across the full width of the river before much heat has been lost by surface heat transfer.[2]

An example of this case is the Monticello Plant (near Minneapolis-St. Paul) on the Mississippi River seen in Figs. 8.6 and 8.7 (Ref. 3). The outfall here is an open surface channel nearly parallel to the river. Table 8.2 summarizes the basic characteristics of that survey date (July 1, 1971) of Figs. 8.6 and 8.7. In contrast to the A. S. King case, there is a very persistent transverse temperature stratification that develops. Stefan and Skoglund note[3] that a stratification in the horizontal direction does not inhibit turbulent mixing of the plume and ambient water to the same extent that vertical stratification does. Therefore, the surface temperature decay at the low flow A. S. King site is slower than at the high river flow case of Monticello. Figure 8.8 shows how the plume surface areas, A_s, vary as Q_p/Q_R decrease. Note that for each case, the excess temperature should approach Q_p/Q_R for that date. Stefan and Skoglund were able to eliminate Q_p/Q_R as an independent parameter by using the non-dimensionalization that appears in Fig. 8.9. A good data fit (after the data of Fig. 8.9 were replotted) was the function

$$\left(\frac{T_s - T_c}{T_o - T_c} - \frac{Q_p}{Q_R}\right) \Big/ \left(1 - \frac{Q_p}{Q_R}\right) = e^{-0.0035\left(\frac{A_s U}{Q_p}\right)}$$

$$\frac{A_s U}{Q_p} \leq 400$$

$$\left(\frac{T_s - T_c}{T_o - T_c} - \frac{Q_p}{Q_R}\right) \Big/ \left(1 - \frac{Q_p}{Q_R}\right) = \left(\frac{A_s U}{Q_p}\right)^{-0.17}$$

$$\frac{A_s U}{Q_p} > 400$$

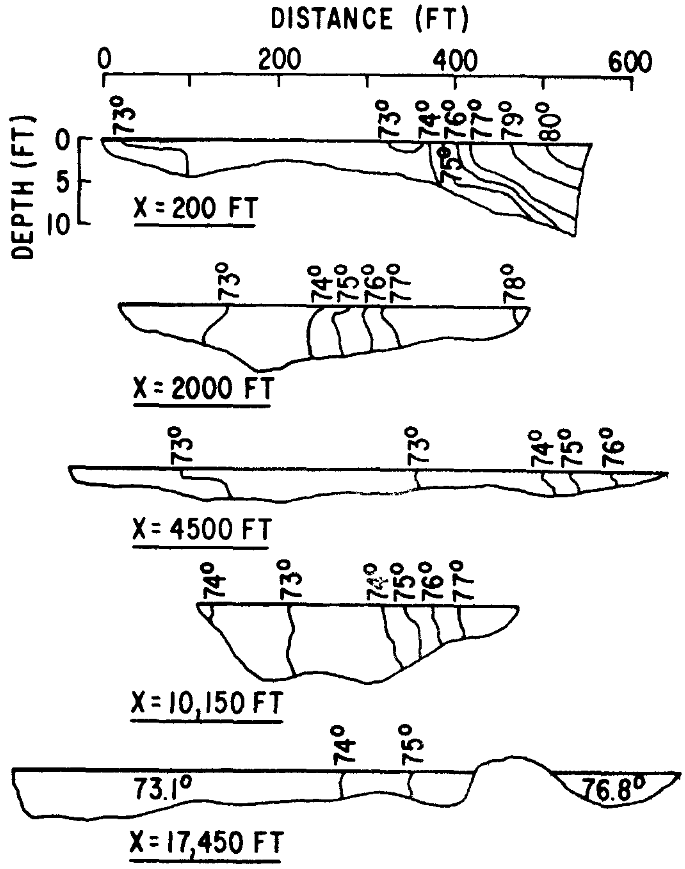


Figure 8.6: Water Temperature Distribution in Mississippi River downstream of Monticello on July 1, 1971. River cross sections at different distances X from the outfall.[3]

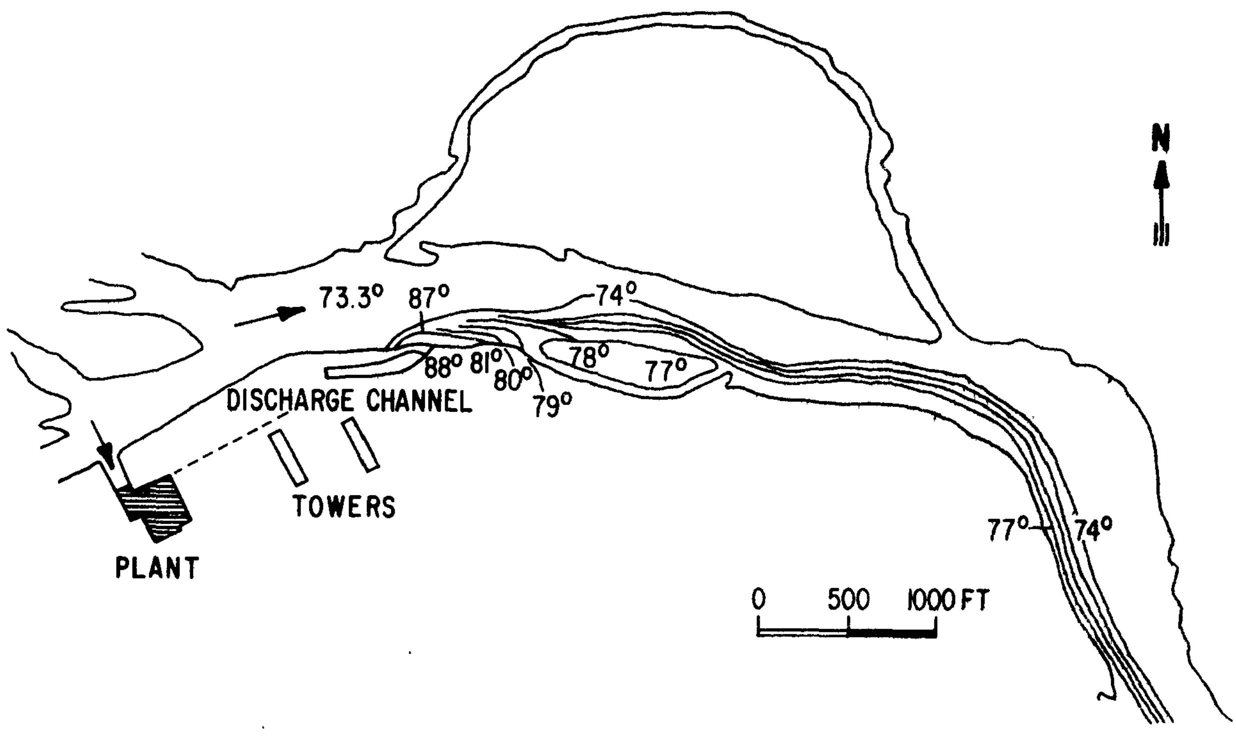


Figure 8.7: Isotherms at Surface of Mississippi River downstream of Monticello on July 1, 1971.[3]

Table 8.2. Plant Discharge, River, and Weather Characteristics for Monticello Site[3]

Date of Survey	Q_p cfs	Q_R cfs	Q_p/Q_R ---	U ft/sec	T_o °F	T_c °F	Wet Bulb Temp. °F	Dry Bulb Temp. °F	Wind mph	Cloud Cover %
6-22-71	555	4224	.131	2.11	90	76	67	80	10.3	13
7-01-71	565	6234	.091	3.25	87	73.3	63.6	73.6	8	50
8-02-71	529	2048	.258	1.74	80.5	66.8	60	66	8	85
9-20-71	633	1215	.521	1.01	74.2	61	59	68	6.5	48
11-09-71	208	18656	.011	6.43	57	33	44	47	7-10	0

Q_p = cooling water flow rate; Q_R = river flow; U = average river velocity; T_o = discharge temperature;

T_c = ambient (cold) temperature.

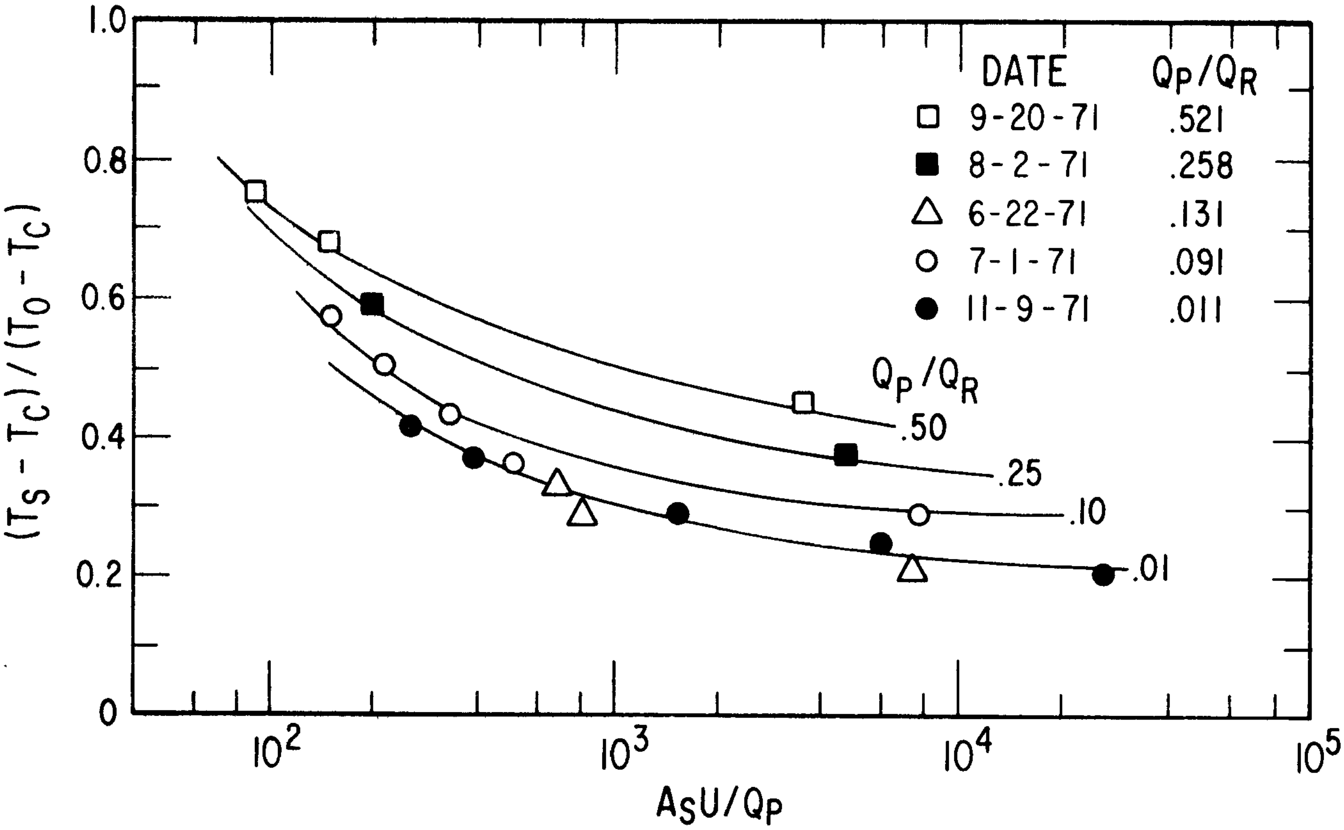


Figure 8.8: Relative Surface Temperature Increment versus Surface Area-Velocity-Discharge Parameter, Downstream of Monticello.[3]

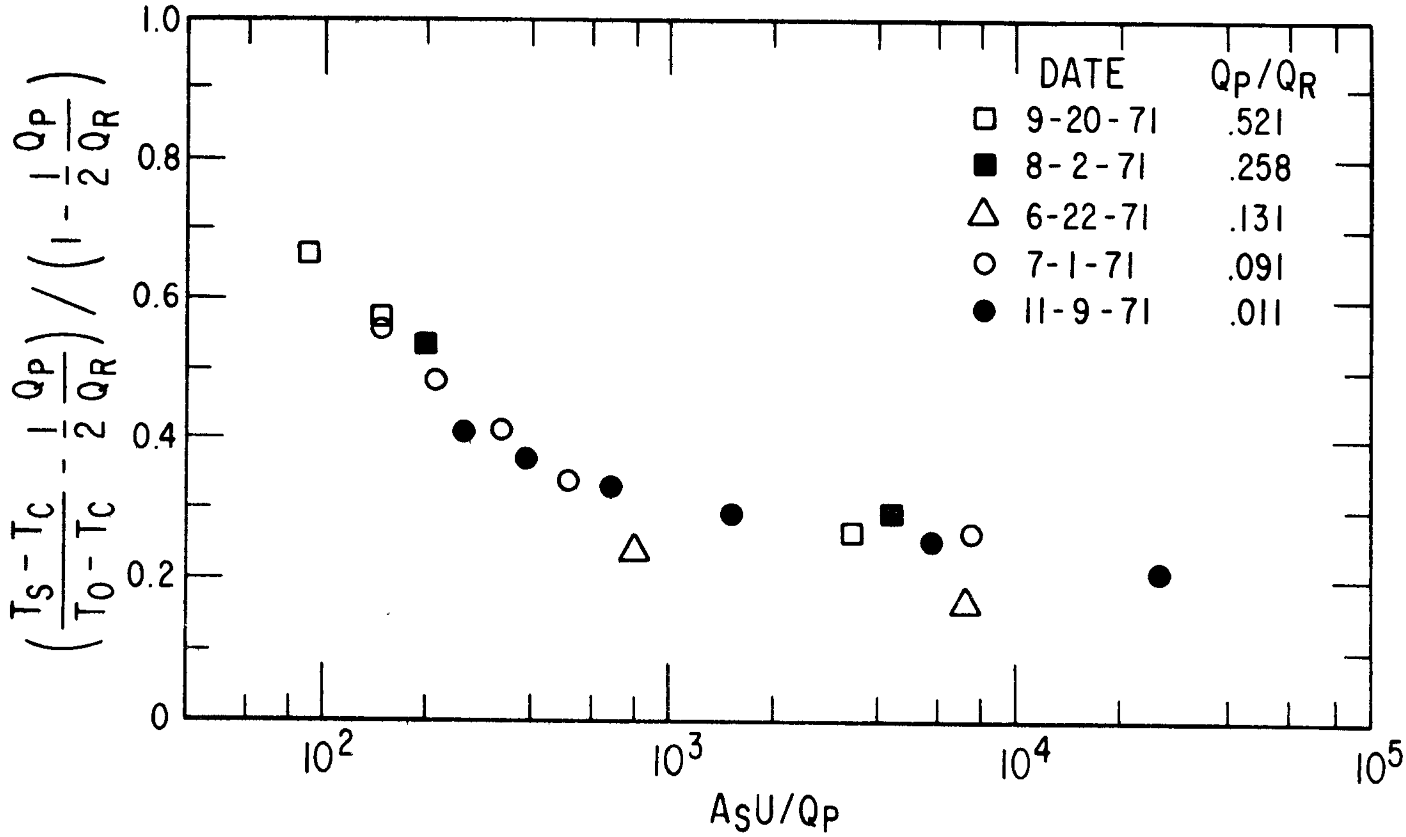


Figure 8.9: Reduced Relative Surface Temperature Increment versus Surface Area-Velocity Discharge Parameter, Downstream of Monticello.[3]

where T_s is the surface temperature.

The data also show consistently larger areas for the A. S. King site than for Monticello. The relative river flows were indeed the major cause yet it must be understood that areas depend on a number of parameters including the cooling water flow rate, average river flow velocity, outfall geometry, densimetric Froude number of the discharge and surface heat loss (only at increasing distances from the outfall).

An increasing number of plants on rivers are using submerged diffusers, single and multi-port. For example, there is the Quad Cities Plant on the Mississippi River using once-through cooling and the Susquehanna Plant using the Susquehanna River for blowdown. Submerging the discharge permits more ambient entrainment water to mix with the effluent than if it were discharged at the surface. Strict state and federal temperature standards imposed in recent years have made submerged discharges much more attactive. Typical of these submerged discharges is the relatively shallow nature of river systems (compared to large lakes and coastal waters), and the low buoyancy of the thermal diffuser discharge as compared to sewage diffusers.

An example of the use of a single port discharge to rapidly dissipate the excess heat from a plant sited on a river is the case of the Baxter Wilson Steam Electric Station located on the Mississippi River near Vicksburg. The Plant is a 500 MWe unit with an average cooling water flow of 412 cfs with an average excess temperature at discharge of 25°F. The condenser cooling water is discharged through an underwater discharge pipe, eight feet in diameter which extends approximately 100 feet from the low water level shoreline. The field data were collected[5] on this discharge for a period of 15 months from June 1969 to August 1970. Of particular interest were plumes taken in August and September since those months were considered critical for the thermal discharge due to the combination of high river temperatures and low river flow. Figure 8.10 sketches the location of boat measuring stations in the river. The stations in the direction of river flow are spaced 20 feet apart. Temperature measurements were taken at each grid point at depths of 1, 5, 10, 15, and 20 feet. Tables 8.3 and 8.4 provide plant and river data for the 17 surveys made and Table 8.5 summarizes the main results in terms of maximum length, L, maximum width, W, and area of the 4 and 5°F surface isotherms. Figures 8.11a and 8.11b plot some horizontal and vertical isotherms for the survey date of August 9, 1970. The measurements tended to show

(a) The heated effluent remained close to the shore and within 300 feet from the shore.

(b) High dilution factors and high ambient river turbulence caused a rapid drop in temperature downstream of the outfall. The excess temperature rise of 2°F was typically at a distance of only 200 feet downcurrent of the outfall.

(c) High temperature rises (greater than 5°F above ambient) were confined to a very small region immediately above the outfall.

(d) Only 6.5% of the river cross section was affected by the plume.

Of special importance was the application of Mississippi stream temperature standards to the plant surveys. The requirements were that the temperature "... shall not be increased more than 10°F above natural temperature nor exceed 93°F after reasonable mixing."* During the 17 surveys the 10°F rise criteria was exceeded only on February 6, 1970 with a 14.5°F temperature rise at a 20 foot depth location immediately above the outfall. The maximum temperature criteria of 93°F was exceeded only on August 9, 1970 when a 95.4°F temperature was observed; the 95°F contour covered an area of 15 feet by 10 feet immediately above the outfall. Rapid temperature decays were observed on those two dates as with the other 15 surveys.

The additional dilution water available to the submerged discharge is the reason for the very high dilutions in this case as compared to typi-

* These standards have since been revised.

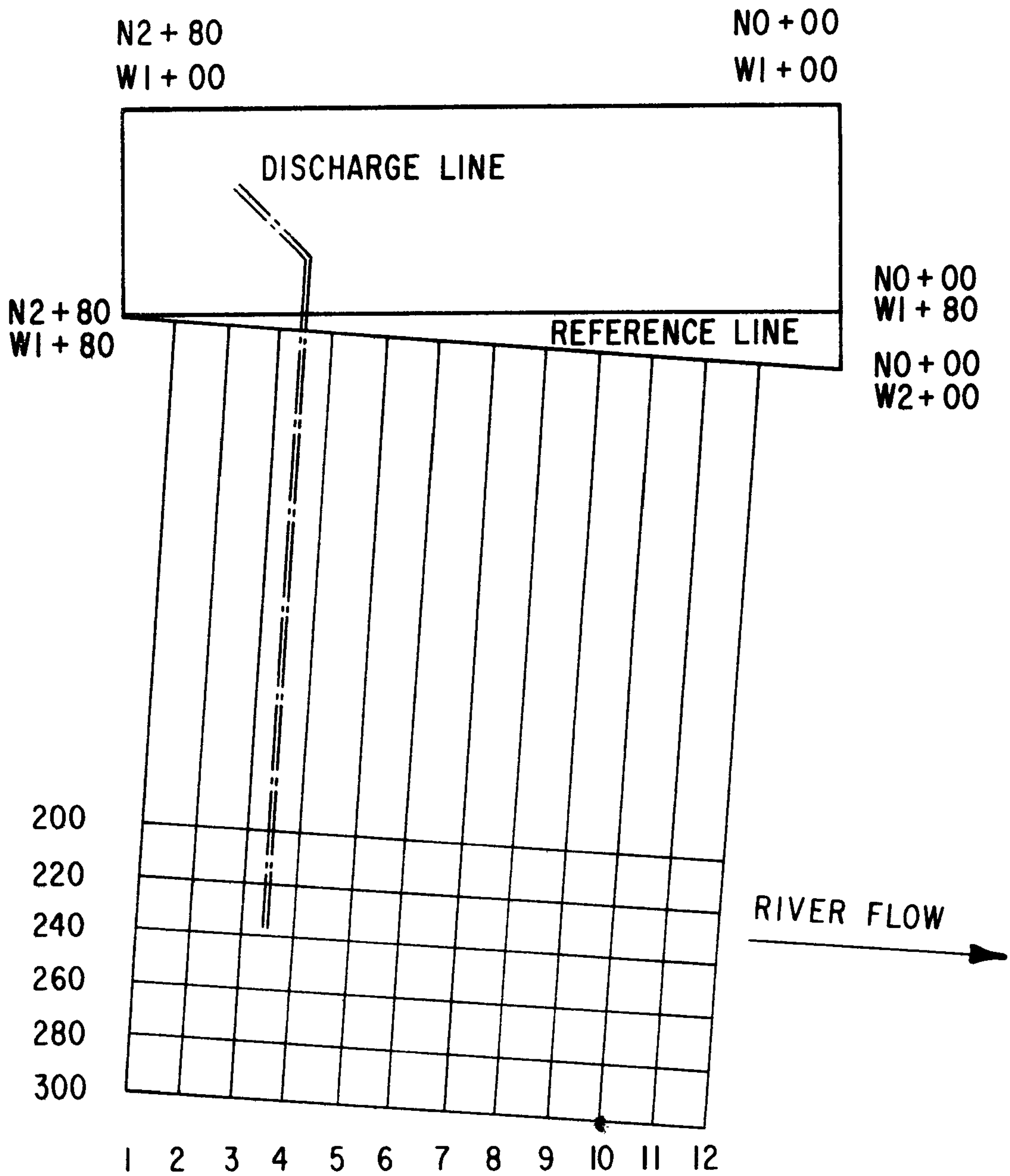


Figure 8.10: Location of Sampling Stations for Temperature Measurements.[5]

Table 8.3

Operational Data for Baxter Wilson Steam Electric Generating Station[5]

NO	SURVEY DATE	PLANT LOAD (MW)	COOLING WATER ($GPM \times 10^{-3}$)	COOLING WATER TEMPERATURE, °F IN	OUT	HEAT ADDED ($BTU/HR \times 10^{-6}$)
1	9/28/69	477	183	76	100	2070
2	10/16/69	500	182	69	93	2160
3	12/11/69	530	175	45	70	2240
4	12/23/69	500	173	44	69	2165
5	2/6/70	552	155	41	69	2150
6	3/6/70	486	191	47	69	2092
7	3/28/70	467	196	50	70	1950
8	6/5/70	540	208	75	98	2348
9	6/12/70	503	194	76	98	2140
10	6/20/70	484	194	79	100	2060
11	7/2/70	503	198	81	103	2140
12	7/18/70	503	184	83	108	2230
13	7/25/70	461	180	81	104	2000
14	8/2/70	526	177	86	113	2320
15	8/9/70	471	181	86	110	2050
16	8/14/70	515	187	83	108	2270
17	8/21/70	486	189	83	107	2110

Table 8.4

Mississippi River Data Near Vicksburg, Mississippi For Survey Dates (Including Air Temperatures)[5]

NO	DATE	STAGE FT.	DISCHARGE $CFS \times 10^{-3}$	AMBIENT TEMP °F	AIR TEMP °F
1	9/28/69	9 8	306	76	71 0
2	10/16/69	6 2	248	69	56.5
3	12/11/69	9.8	328	44	48.3
4	12/23/69	10.9	370	42	49.0
5	2/6/70	12.3	442	39	45.5
6	3/6/70	23 0	647	46	50 5
7	3/28/70	24 5	700	49	59 1
8	6/5/70	26.3	688	74	74.0
9	6/12/70	26.0	705	75	88.5
10	6/20/70	26 0	681	79	85.0
11	7/2/70	23 9	615	81	86 2
12	7/18/70	10.1	320	83	87.5
13	7/25/70	8.4	302	81	82.1
14	8/2/70	6.9	262	85	86.7
15	8/9/70	8.6	312	86	82.7
16	8/14/70	11.7	375	83	92.0
17	8/21/70	13.1	406	83	87.0

Table 8.5

Summary of Observed Temperatures[5]

		Max. Temp.			Max. Down-Str. Temp.		Ambient River Temp.	4°F Rise Isotherm					5°F Rise Isotherm				
								L	W		Center		L	W		Center	
No.	Date	°F	Depth	Rise	°F	Stat.	°F	Ft.	Ft.	A (4° Rise)	Down River	From Shore	Ft.	Ft.	A (5° Rise)	Down River	From Shore
1	9/28/69	82.0	1	6.0	76	10	76	72	48	2301	82	66	44	37	1008	74	68
2	10/16/69	77.75	1	8.75	71	12	69	108	92	8832	96	58	86	86	5411	88	70
3	12/11/69	51.50	1	7.50	47	12	44	182	108	11600	140	63	120	72	6046	115	68
4	12/23/69	51.00	1	9.00	45	12	42	160	86	8800	130	58	133	65	5424	115	63
5	2/06/70	53.50	20	14.50	39	10	39	62	32	1344	80	61	57	29	1095	79	62
6	3/06/70	48.75	25	2.75	46	12	46	15	8	75	164	83	6	4	19	164	83
7	3/28/70	51.25	25	2.25	49	12	49										
8	6/05/70	79.0	25	5.00	74	10	74	26	12	200	68	60					
9	6/12/70	79.50	25	5.50	75	10	75	23	7	124	80	62					
10	6/20/70	82.24	25	3.24	80	12	79										
11	7/02/70	85.50	25	4.50	82	12	81	27	11	211	76	63					
12	7/18/70	91.00	5	8.00	84	12	83	121	93	7100	112	60	78	44	2102	91	68
13	7/25/70	88.00	10	7.00	82	12	81	58	44	1804	86	62	53	35	1244	84	60
14	8/02/70	93.50	1	8.50	87	12	85	122	93	8285	110	78	78	70	4404	94	72
15	8/09/70	95.40	1	9.40	87	12	86	108	108	6083	103	63	70	70	3334	90	58
16	8/14/70	90.00	10	7.00	86	12	83	172	54	4541	138	58	100	24	1518	103	58
17	8/21/70	93.0	5	10.0	85	12	83	104	37	2800	103	57	43	26	709	72	60

L = Maximum Length of Bounding Isotherm

W = Maximum Width of Bounding Isotherm

A = Planimetered Area of Bounding Isotherm

Center Distances Measured Relative to Grid Origin

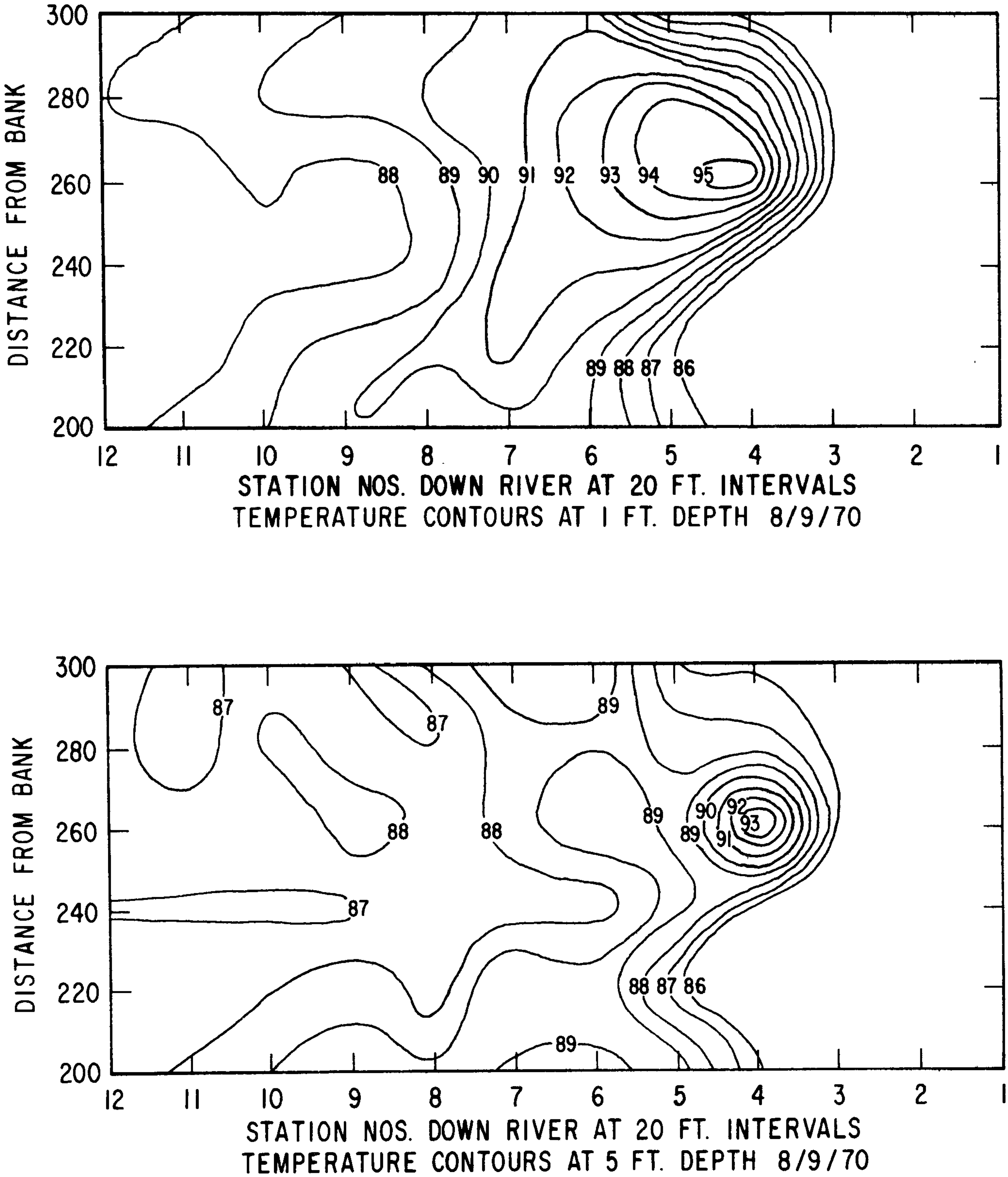
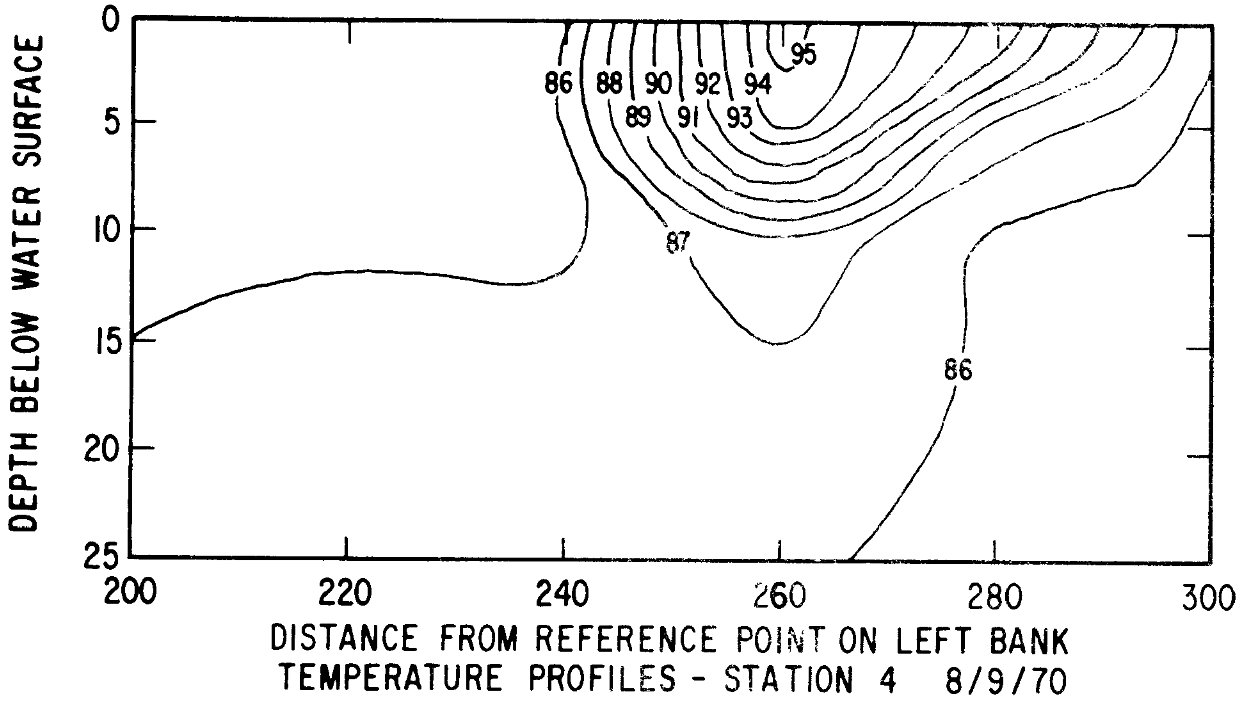


Figure 8.11a: Temperature Contours.[5]



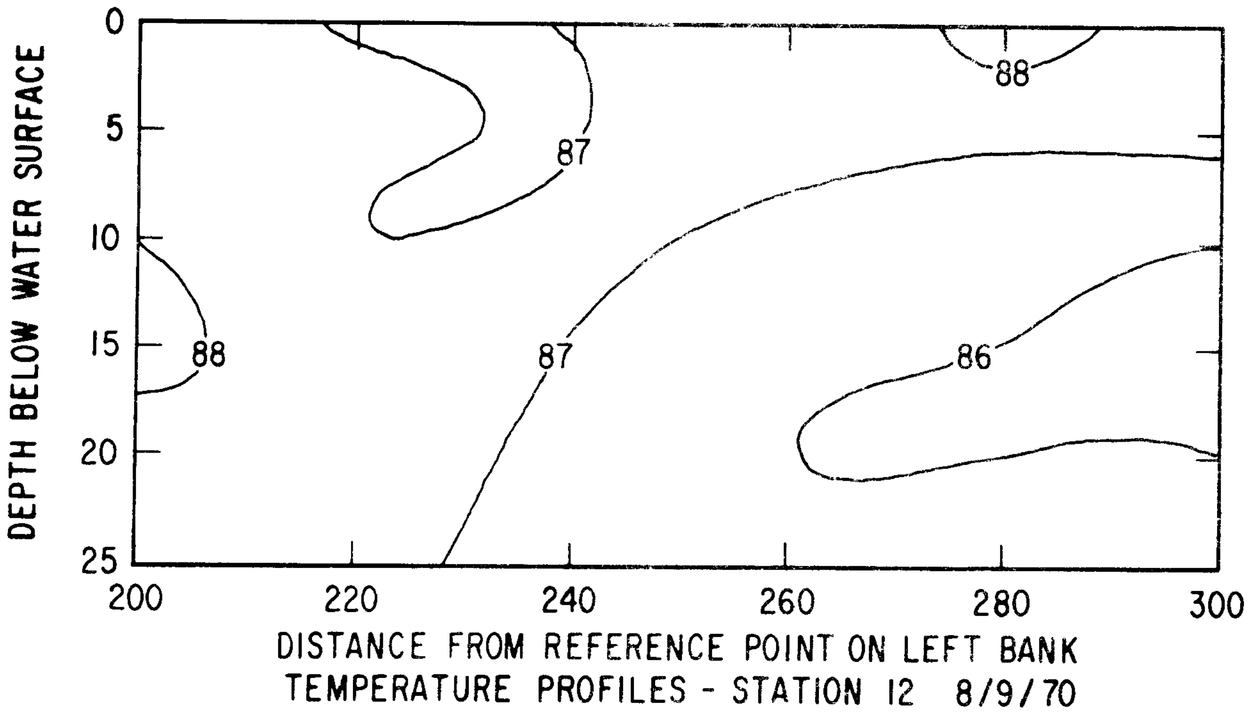


Figure 8.11b: Temperature Profiles[5]

cal onshore surface discharges. Tremendous flow in the Mississippi, even under low flow conditions, caused the very rapid reduction in plume temperature and produced thorough mixing in a small portion of the river. Temperatures decreased rapidly both laterally across the river and in the downstream direction. Unfortunately, not all rivers are as deep or have the large flows that the Mississippi has.

8.1.3 Time-Temperature History in a Thermal Plume

Of particular importance in any analysis of thermal plumes is the length of time organisms spend in the plume. Of interest is the path and temperatures along that path of plankton passing through the intake, then through the discharge, and finably downcurrent in the river. Of importance also is the time-temperature history of phytoplankton or zooplankton entrained into the discharge plume from the ambient river water. Stefan and Skoglund[3] have analyzed their Monticello plant data in terms of such histories. Their approach can be followed with data on other sites and other rivers also. First they calculated the fraction of cross sectional area, for each distance downstream, of excess temperature ration $(T_s - T_c)/(T_o - T_c)$. This is plotted for the high current date of November 9, 1971 and the lower current date of September 20, 1971 in Fig. 8.12. The decreased lateral spreading of the shore-bound plume for the high current date is clearly visible in the top sketch in Fig. 8.12. Temperatures are related to longitudinal distances and lateral cross-sectional areas by assuming (as no plume velocities were measured) that organisms traveling in the plume are moving at the speed of the ambient current. Since the average river velocity for the November 9 and September 20 dates are about 1 ft/sec and 6.4 ft/sec, respectively, the residence times for the same river reach will differ by a factor of about 1 to 6. Consequently, for 17,000 ft say, the residence times are 208 and 40.5

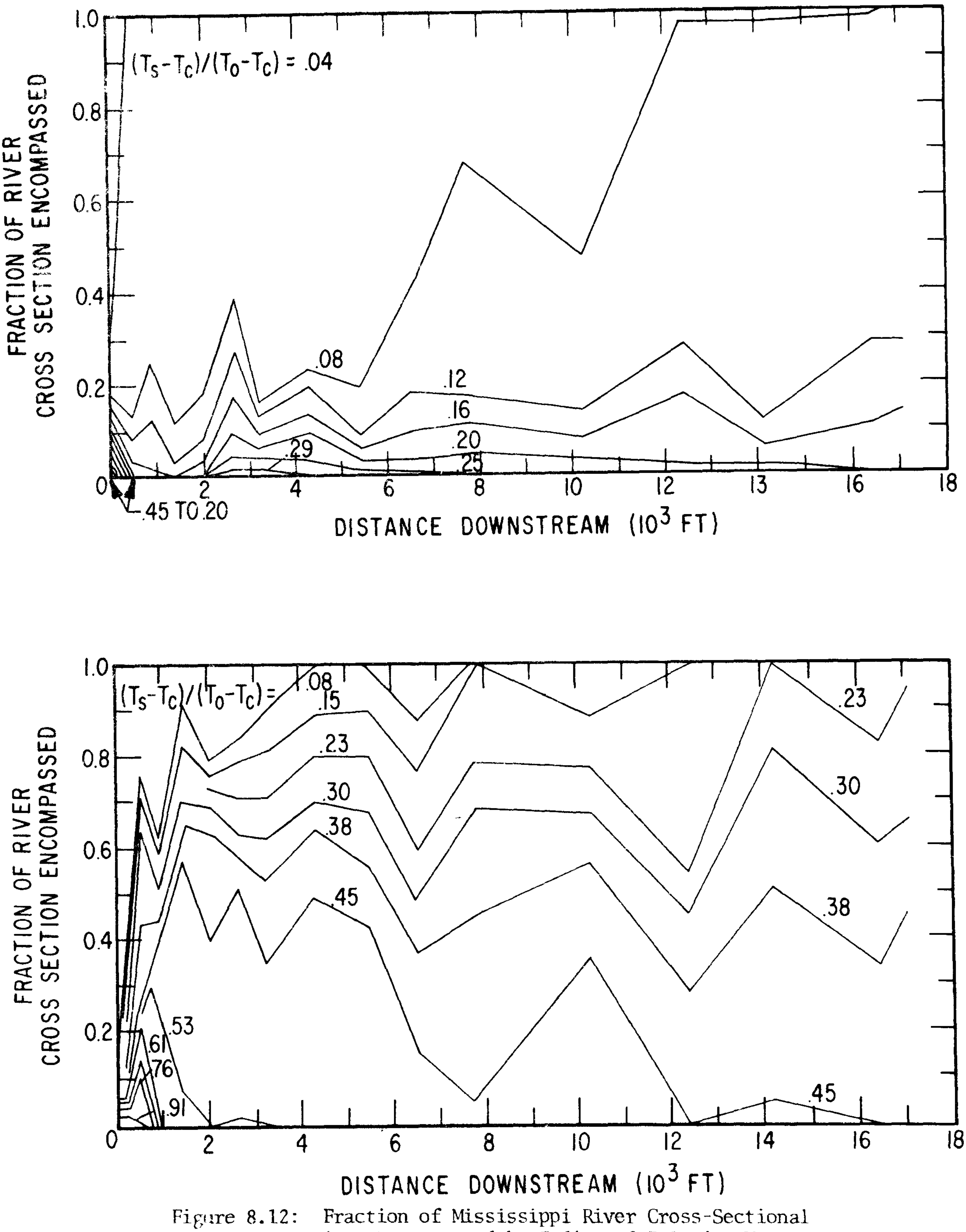


Figure 8.12: Fraction of Mississippi River Cross-Sectional Area Encompassed by Indicated Relative Water Temperature Increments Downstream of Monticello on November 9, 1971, Q_p/Q_R = 0.011 (top) and on September 20, 1971, Q_p/Q_R = 0.521 (bottom).[3]

minutes for those low and high flow situations, respectively. These differences can be observed by comparing graphs like Fig. 8.13 for each date for Monticello. For any given time of travel, the figure reveals the temperatures observed at the cross section the organism is located as well as the area of such isotherms. Figure 8.14 plots the time-temperature history of organisms swept past the plant on three dates at Monticello. Only the warmest possible path is assumed taken by these organisms. Note that the amplitude of the temperature shock is quite small and the exposure time in the plume is also quite short. The higher current appears to reduce the temperature amplitude faster. A larger temperature increase is encountered by organisms entrained into the intake and passed through the condensers. The above curves and discussion were meant only to provide some physical insight into the duration of exposure to temperatures of organisms in the ambient water and to indicate what can be calculated for biological interpretation from good thermal plume measurements. Velocity measurements in the plume would have sharpened the accuracy of the travel times.

8.1.4 Dynamic Nature of Thermal Plumes

It is important to note that thermal plume temperatures from river plants are not constant with time. First, the stream temperatures themselves vary with diurnal and seasonal changes in addition to certain weather-induced random fluctuations. These variations over a time period of a day can typically change on the order of 2-3C°. These variations directly affect the plume temperatures by approximately that amount.

A second type of transient effect exists. This involves the often rapid internal variations within the thermal plume itself which have been noticed even when the initial discharge and receiving body are relatively steady. Data taken[6] at the Piacenza Plant on the Po River in Italy indicate

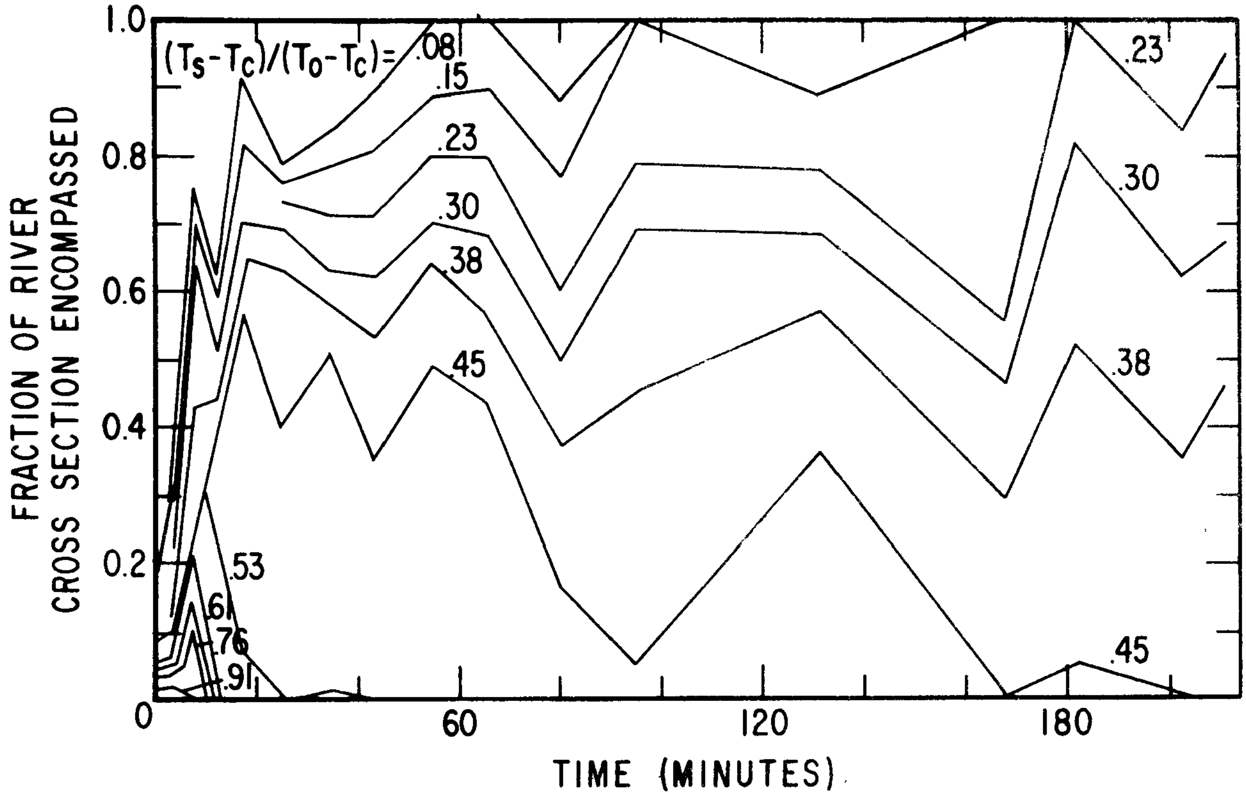


Figure 8.13: Temperature-Area-Time Diagram for Monticello, September 20, 1971.[3]

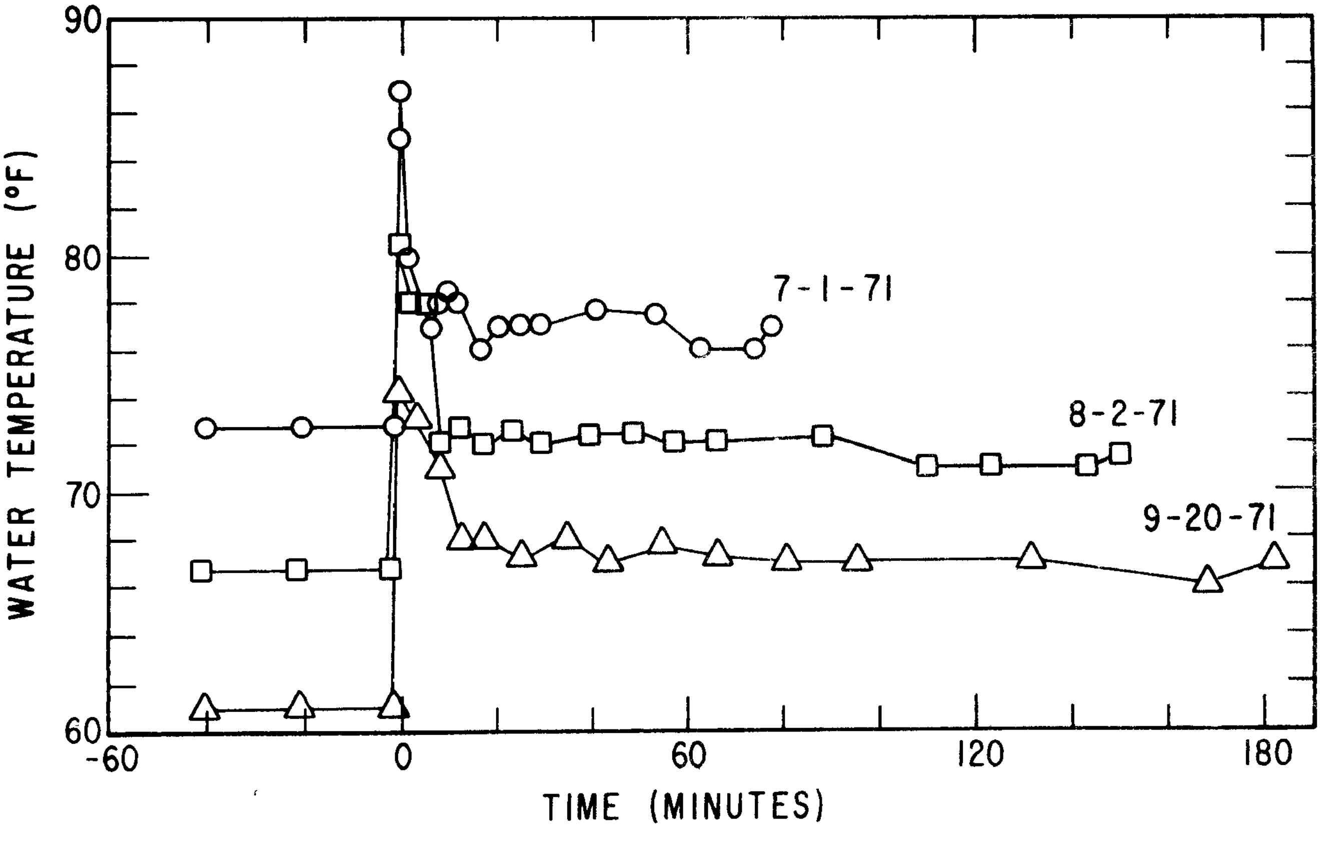


Figure 8.14: Maximum Water Temperatures Encountered by Plankton in Mississippi River Moving past the Cooling Water Outfall of the Monticello Plant on Three Different Dates.[3]

that a 1-3°C variation in temperature over a 60 second period is quite typical in the higher temperature mixing regions of river plumes, at a fixed location. These fluctuations decrease in magnitude as the plume temperatures approach ambient.

Another cause of fluctuating plume temperatures, over a larger time scale, however, is the response of thermal plumes to variations in plant load on an hourly or even shorter time scale as reflected in the differences in cooling water flow rate and effluent temperature.

A fourth cause of plume temperature fluctuations is the effect of the wind which may cause the plume to meander with significant spatial changes in plume location. These flucatuations are probably significant, however, only under the lower river currents and higher winds. Such wind effects are most pronounced with lake plumes or plumes in run-of-river impoundments.

Stefan and Skoglund[3] suggest a fifth cause of temperature fluctuations. When the river temperature reaches 4°C or less, the heated plume will tend to sink as it cools to 4°C, the maximum density of water. This sinking plume phenomenon in winter is sensitive to seasonal and random weather changes at the initial location of sinking as well as the variations (of the order of 4C°) in the temperatures near the river bottom in the vicinity of the outfall. Those temperature variations in the sinking plume itself can occur within very short time periods.

The small scale temperature fluctuations described above all affect the river organisms in terms of metabolic rates, reproduction, death, etc., and consequently should not be ignored in any biological assessment of the impact of a power plant on a river.

8.1.5 Effect of Channel Curvature on Dispersion of Plumes

As a general rule, the winding nature of a river reach will add to the turbulent mixing and act as an aid to plume dispersion. Edinger, Brady, and Geyer[2] describe the complicating effect of upstream channel curvature in relation to the E. D. Edwards Power Station on the Illinois River (see Fig. 8.15). A preliminary analysis of field data from the site indicated greater plume dilution than would be expected had the river been straight with the same hydraulic characteristics. As a result, the test sections for field data acquisition had to be moved closer to the outfall. Also, the plant is small compared to the river size indicating a plume which is not enlarged by re-entrainment effects caused by the far bank. The authors explained the smaller plume as due mainly to the fact that the direction of the turbulent vorticity (rolling eddies) associated with bottom friction in the upstream flow tends to be conserved around the bend in the river channel so that at the discharge cross section, the eddies appear to act strongly in the lateral direction increasing the plume's initial lateral spreading. The direction of these rolling eddies is sketched in Fig. 8.15. It is suspected that this phenomenon lasts only a relatively short distance downstream of the bend until these dominant eddies are transformed into a new flow alignment by the river bottom friction. The authors suggest that this added lateral mixing phenomenon may be used effectively in the siting of discharges on the outside downstream corner of river bends to take advantage of this three-dimensional phenomenon.

An important feature in far-field plume dispersion is the transverse mixing of the plume with ambient river water. A recent report by Holley[7] analyzes mixing in the far field of such a river plume. Transverse diffusion coefficients were determined from dye and temperature tracer studies in the IJssel and Waal Rivers of the Netherlands. Holley found that the nonbuoyant aspect of transverse spreading in a river can result from two different mechanisms, diffusion and advection. The magnitude of the diffusion coefficient can be influenced by at least three different factors: (a) turbulence due to bottom shear, (b) turbulence due to the distrubance caused by structures

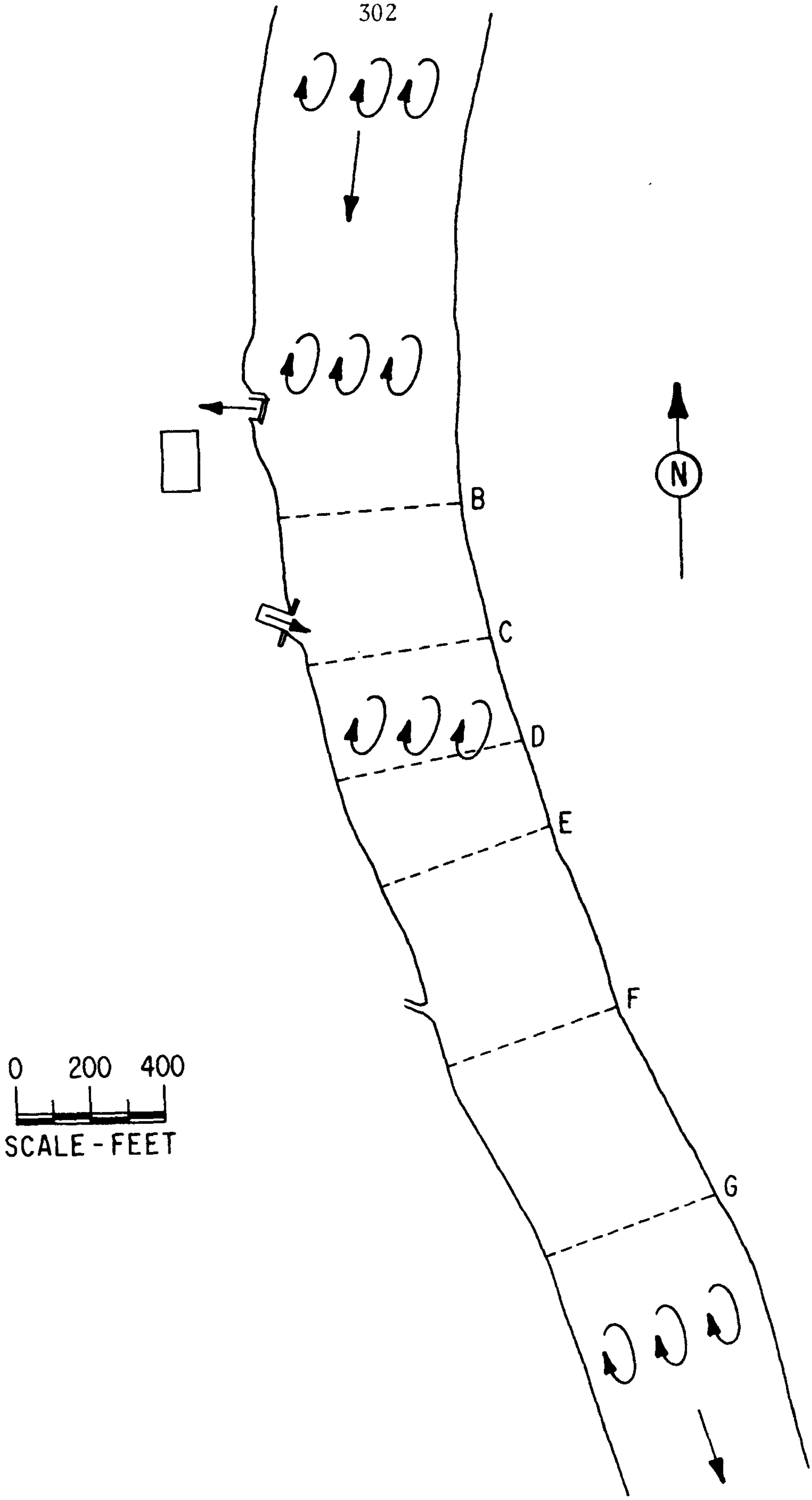


Figure 8.15: Sketch of Edwards Plant Site on Illinois River Showing Effect of Channel Curvature.[2]

such as groins, and (c) secondary motions, particularly those associated with channel bends. The net diffusion coefficient can vary with the local depth and velocity and/or with position in the river cross section. Advection can also cause transverse spreading. Advective motion typically arises from changes in the geometry of the channel with longitudinal distance. These changes in depth and width can produce net transverse velocities which in turn cause plume spreading of the same order of magnitude as that due to diffusion! By the change of moments method, Holley calculates diffusion coefficients accounting for all these factors.

8.1.6 Near and Farshore Boundary Effects and the Fully-Mixed Condition

Some effects of the near and far shore boundaries on plume dispersion in a river have been discussed by Edinger.[8] Edinger first notes that an effect of the near and far shore boundaries of a river is to contain the released heat as it reaches the fully-mixed condition. It is generally thought that the fully-mixed state is reached before surface heqt dissipation becomes effective. Compared to the unbounded situation of a thermal discharge into a large lake or coastal region, the centerline temperature decreases more slowly with distance in a river due to the greater lateral mixing that takes place for the unbounded case. Also, centerline temperatures for the unbounded case approach a zero temperature rise while for a river, these temperatures approach the fully-mixed temperature excess. As alluded to above, temperature rises should decrease laterally less rapidly for a river than for the unbounded case. Consequently, the lake or coastal plume should be relatively shorter but wider; the effects of the river boundaries is to confine the plume laterally but stretch it out longitudinally.

A more subtle aspect of the thermal plume from a river plant is that it can cause a discrepancy between the theoretical and observed fully-mixed temperature of that discharge on the stream.

The concept of fully-mixed excess temperature, θ_m, is generally used in one-dimensional analyses of heat dissipation from multiple sources on a river. Each thermal discharge in these analyses is assumed to be fully-mixed with the available river water passing the station. The thermal plume itself is ignored as well as the distance to which the plume becomes fully-mized with the ambient river water. In short, these stream analyses and mathematical models of water quality assume each heated discharge mixes freely with the river at the point of discharge. That fully-mixed temperature is defined:

$$\theta_m = \frac{H_p}{\rho\ C_p\ Q_r} \tag{8.1}$$

Here H_p is the heat rejection rate of the plant and Q_r is the river flow rate. This can be written:

$$\theta_m = \frac{r}{\rho\ C_p} \left(\frac{MWe}{Q_r}\right) \tag{8.2}$$

where r is the heat rejection rate per unit megawatt plant electrical production. The computation of further downstream heat decay depends on the accuracy of the above formulas in describing θ_m.

Edinger, Brady, and Geyer[2] attempted to evaluate that assumption by collecting data at a number of sites. The data are presented for three plants in Fig. 8.16. Equation (8.2) gives a linear relationship between θ_m and $\frac{MWe}{Q_r}$ is seen in the figure. It is seen, however, that the data for θ_m only approaches the theoretical θ_m as an upper limit. The authors ascribe the lower fully mixed temperatures determined in the field to many factors including:

(1) The heat storage and heat loss to the atmosphere within the thermal plume itself before complete mixing is attained,

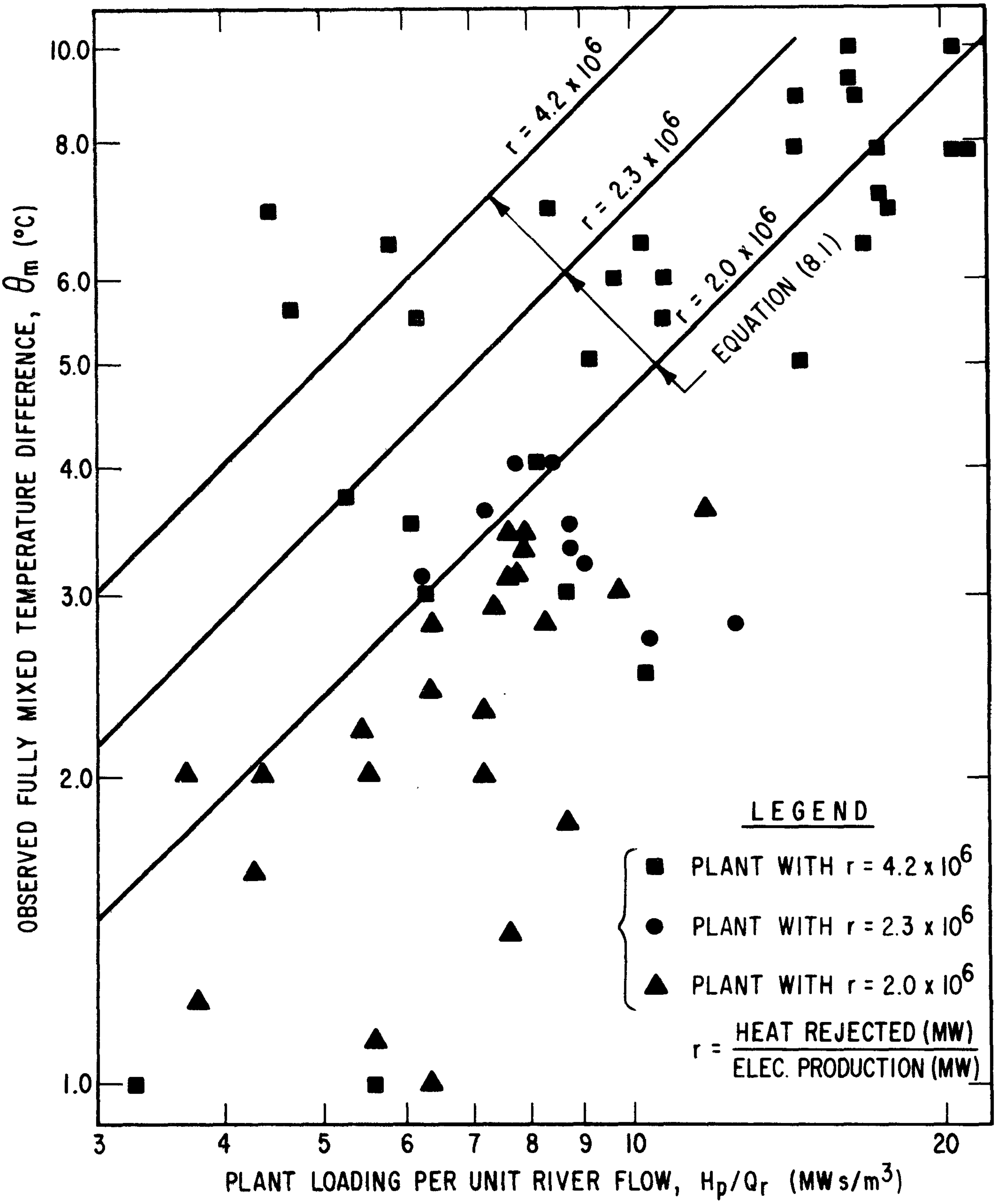


Figure 8.16: Comparison of Fully Mixed Excess Temperatures and Computed Plant Loading per unit River Flow for Three Plants.[2]

(2) The short term variations in river flow and plant loading that are not accounted for,

(3) The difficulty in measuring in the field small temperature increases at low plant loadings or high river flows,

(4) Dilution water that is unaccounted for which may enter from the ground or surface sources downstream of the point of discharge.

Due to all these probable reasons, the fully-mixed excess temperature as computed from plant and river conditions is a fiction which is seldom attained in the field yet may be approached usually as an upper limit. Using the theoretical fully-mixed temperature for those one-dimensional heat dissipation models will underestimate the temperatures of the thermal plumes and will overestimate, to a varying degree, the temperatures in the down current fully-mixed portion of the heated discharge.

8.2 Thermal Plumes on the Ohio River

As stated in the introduction to Chapter 8, the plume temperature data available for the Ohio River is either of a general scoping nature (two poor quality infra-red surveys) or of a sketchy nature (sparsely spaced boat measurements) intended to provide information on thermal plume mixing zones and possible temperature standards violations. Particularly lacking for the boat measurements were plant operating conditions and ambient river currents; although superfluous for ascertaining standards violations, that additional data is most necessary for a physical and analytical interpretation of the plumes. Consequently, neither set of data noted above and available in the literature can give any real insight into plume behavior on the Ohio River.

There is, however, reasonably good data, though proprietary, on the Philip Sporn Plant encompassing fourteen detailed temperature surveys. Two of these surveys have been published and one of them will be discussed in Section 8.2.2.

8.2.1 Boat Measurements Taken for Temperature Standards Compliance

Among the boat surveys done on the Ohio River are the series entitled, "Point Source and Stream Survey Report," done[9-13] by Reising, King, and Kramer of the EPA Indiana Office. Those surveys were done in four days in August 1973. The purpose of the studies was to monitor the Culley, ALCOA, Ohio River, Gallagher, Tanner's Creek, and Clifty Creek Power Plants on the Ohio River for possible state and federal temperature standards violations. All these plants are on the Indiana side of the Ohio River facing Kentucky on the opposite shore.

The Indiana-Kentucky Water Quality Standards fail to adequately define the boundaries of a 5°F mixing zone. The Indiana water quality standards suggest that an unspecified mixing zone "should be limited to no more than 1/4 of the cross-sectional area and/or volume of flow of the stream, leaving at least 3/4 free as a zone of passage for aquatic biota nor should it extend over 1/2 of the width of the stream." The Kentucky standards also provide for zone of passage for fish and drift organisms yet do not specify its dimensions. Indiana requires that the maximum temperature limit for the main stem of the Ohio River determined on a monthly basis not be exceeded. The monthly maximum for August is 89°F.

In these surveys, temperature measurements were made at four cross sections of the river, one upstream of the discharge for ambient conditions and three downstream to check for violations. Water temperatures were measured by a YSI Model 54 Oxygen Meter equipped with a 50-foot probe. Ryan Model F thermographs were used to continuously monitor temperature fluctuations. Intake velocities and chlorine residual at the discharge were also measured in these studies.

The data and a brief discussion appears in Tables 8.6-8.10 and Figs. 8.17-8.21. The data are not in sufficient detail to be able to as-

Table 8.6a. Survey of Culley Generating Station, Southern Indiana Gas and Electric Company[9a]

Location: near Newburgh, Indiana, Mile Point 773.4

Generating Capacity: 385 MWe

Date of Survey: August 9, 1973

Plant Discharge Rate: 120.16 MGD

River Flow Data: The 7 day, 10 year low flow is 14,300 cfs and the flow at the time of the survey was 30,500 cfs. The study was conducted under normal summer flow conditions.

Ambient Temperature: 82.4°F

Outfall Temperature: 94.1°F

River Cross Sections Monitored:

(A) 900 feet upstream (L, 1/5, 3/5, R)* from surface to 5 m depth at 1 m intervals,

(B) point of discharge (L, 1/5, 3/5, R) from surface to 5 m depth at 1 m intervals,

(C) 0.4 mile downstream (L, 1/5, 2/5, 3/5, R) from surface to 4 m depth at 1 m intervals. The ALCOA cooling water intake is located here,

(A^1) point of discharge for ALCOA Plant, (L, 1/4, 1/2, 3/4, R) from surface to 5 m depth at 1 m intervals,

(B^1) 4,500 feet downstream of ALOCA discharge (L, 1/5, 1/4, 2/5 (island)) from surface to 6 m depth at 1 m intervals,

(C^1) 2.9 miles downstream of ALCOA discharge (L, 1/3, 2/3, R) from surface to 6 m depth at 1 m intervals.

Results:

(1) The heated plume from the Culley Station spread across about 1/4 of the river width at 0.4 mile downstream where it intersected the cooling water intake of the ALCOA Power Plant. The maximum temperature at ALCOA's cooling water intake was 87.8°F with a ΔT of 5.4 °F.

(2) The heated discharge from the Culley Station does not reach ambient temperature before it is recirculated through the ALCOA Power Plant.

(3) Maximum temperature rises of 5.4°F were measured at Sections C and C' downstream of both the Culley and ALCOA Power Plants.

(4) Both plants discharge their heated effluents into the Ohio River within 3,500 feet of each other. The discharges are then influences by an island which restricts the mixing of the heated water with the cooler river water and in effect channels the heated water along the near shore bank of the Ohio River for over 3 miles downstream.

(5) Temperature fluctuations were measured by two Ryan thermographs installed in the Ohio River over an eight day period. The first thermograph, A', was located at the right side of the river directly across from the Culley water intake to measure ambient temperature. The second thermograph, B', was located at approximately 3,500 feet downstream of the ALCOA water discharge. The upstream thermograph was attached to a navigation buoy at a 1.5 m depth. The buoy was located on the right side of the river directly across from the Culley Station water intake but in an area unaffected by the cooling water discharge. The downstream thermograph was placed on the bottom near the left edge of the river in 1.5 meters of water at approximately 3,500 feet downstream of the ALCOA cooling water discharge. A maximum increase of 4.5°F between the two thermographs A and B was observed over that eight-day period.

*L and R refer to left and right sides of river facing upstream.

Table 8.6b: Aluminum Company of America (ALCOA) Station[9b]

Location: Newburgh, Indiana, Mile Point 773.7 (0.3 mile downstream of Culley Station)

Generating Capacity: 750 MWe

Date of Survey: August 9, 1973

Plant Discharge Rate: 400.52 MGD

River Flow Rate: (see Table 8.6a)

Ambient Temperature: 84.2°F (the ALCOA intake was, at the time of the survey drawing water from the river surface to a depth of 12 feet. The intake water temperature varied with depth due to the heated plume from the Culley Plant located 0.3 mile upstream. The average temperature of the ALCOA intake water was 84.2°F).

Outfall Temperature: 104°F

River Cross Sections Monitored: (see Table 8.6a)

<u>Results</u>:

(1) At a point 4,500 feet downstream of this discharge, the maximum river temperature was 89.6°F with an excess above ambient (measured as the ALCOA intake temperature) of 5.4°F and at 2.9 miles downstream the river temperature ranged from 82.4 to 84.2°F.

(2) The heated water discharge from both the Culley and ALCOA Power Plants was restricted to the north one-third of the river due to a series of islands which acted as a barrier and prohibited mixing with the entire river.

(3) Complete mixing was achieved at 2.9 miles downstream from the ALCOA discharge and was assisted by the new Newburgh lock and dam located 2.4 miles downstream.

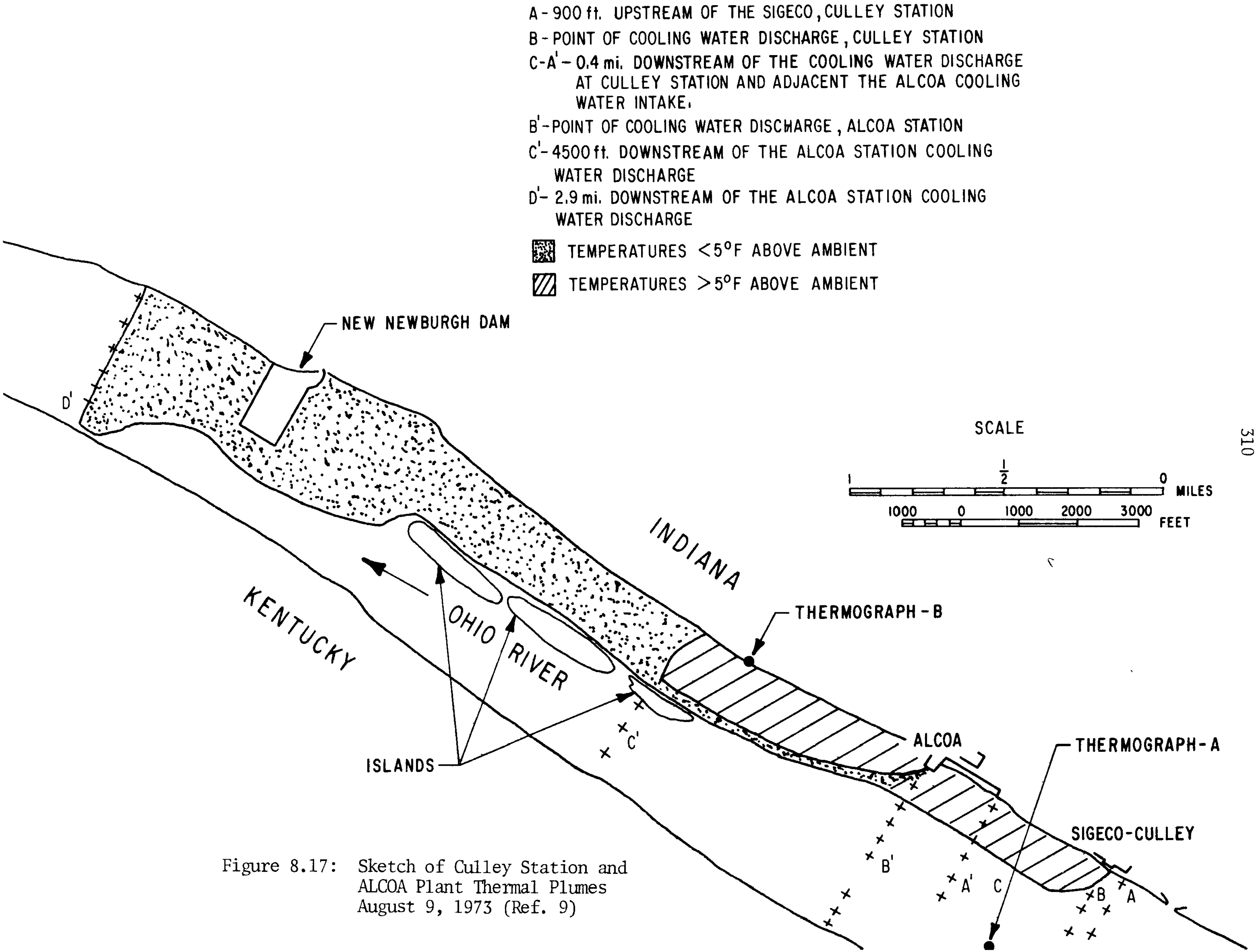


Figure 8.17: Sketch of Culley Station and ALCOA Plant Thermal Plumes August 9, 1973 (Ref. 9)

Table 8.7: Survey of Ohio River Station, Southern Indiana Gas and Electric Company[10]

Location: Evansville, Indiana, Mile Point 793.7

Generating Capacity: 112 MWe

Date of Survey: August 10, 1973

Plant Discharge Rate: 150 MGD

River Flow Rate: The 7 day, once in 10 year low flow is 14,300 cfs, and the flow at the time of the survey was 34,400 cfs. The study was conducted under normal summer flow conditions.

Ambient Temperature: 82.4°F

Outfall Temperature: 89.6°F

River Cross Sections Monitored:

(A) 500 feet upstream (L, 1/3, 2/3, R) from surface to 7 m depth at 1 m intervals,

(B) point of discharge (L, 1/3, 2/3, R) from surface to 9 m depth at 1 m intervals,

(C) 1,000 feet downstream (L, 1/4, 3/4, R) from surface to 10 m depth at 1 m intervals.

Results:

(1) The river returned to ambient temperature in less than 1,000 feet downstream.

(2) Lower ambient water temperatures were observed along the right bank of the river. The cooler water from the Green River which enters the Ohio River 9 miles upstream from this discharge is causing the lower temperature along the right bank of the river.

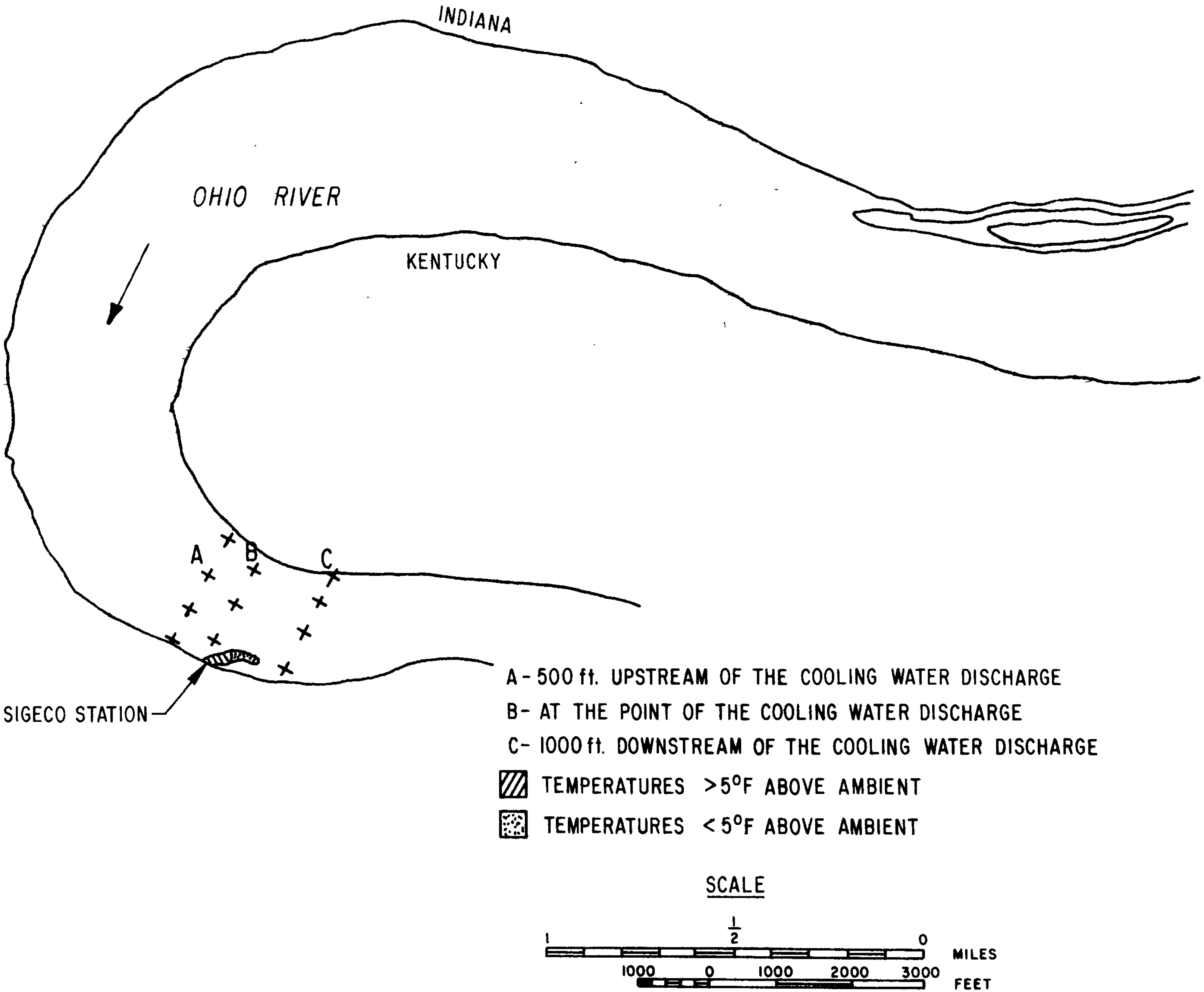


Figure 8.18: Sketch of the Ohio River Station Thermal Plume, August 10, 1973 (Ref. 10).

Table 8.8: Survey of Gallagher Station, Public Service Company of Indiana[11]

Location: New Albany, Indiana, Mile Point 610

Generating Capacity: 600 MWe

Date of Survey: August 20, 1973

Plant Discharge Rate: 462.7 MGD

River Flow Rate: The 7 day, once in 10 year low flow is 14,300 cfs and the flow at the time of the survey was 50,000 cfs. The study was conducted under higher than usual summer flow. The discharge is located in the Cannelton pool and the pool elevation was 4.4 feet above normal during this study.

Ambient Temperature: 84.2°F

Outfall Temperature: 96.8°F

River Cross Sections Monitored:

(A) 500 feet upstream (L, 1/4, 3/4, R) from surface to 6 m depth at 1 m intervals.

(B) Point of discharge (L, 1/4, 3/4, R) from surface to 8 m depth at 1 m intervals.

(C) 1,000 feet downstream (L, 1/4, 3/4, R) from surface to 7 m depth at 1 m intervals.

(D) 3,500 feet downstream (L, 1/4, 3/4, R) from surface to 7 m depth at 1 m intervals.

Results:

(1) An excess temperature of 2.6°F above ambient was measured 1,000 feet downstream of the discharge. The river returned to ambient temperature at a distance of 3,500 feet downstream.

(2) The ambient temperature on the Indiana side of the river was slightly higher (1-2°F) than the remainder of the river.

(3) The plume extended beyond 1/4 of the distance across the river from the Indiana bank.

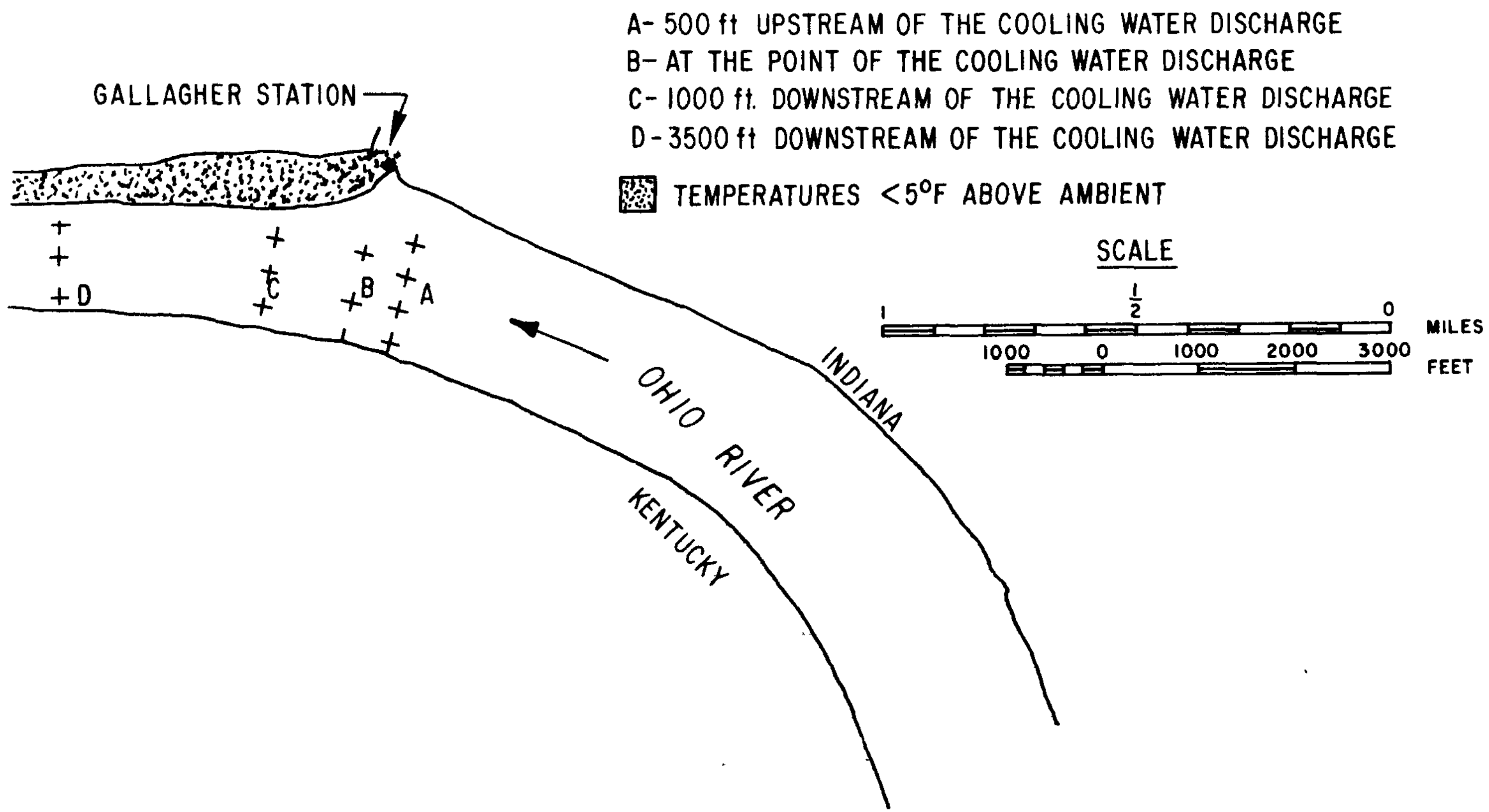


Figure 8.19: Sketch of the Gallagher Station Thermal Plume, August 20, 1973 (Ref. 11).

Table 8.9: Survey of Tanner's Creek Power Station, Indiana-Michigan Electric Company[12]

Location: Near Lawrenceburg, Indiana, Mile Point 494

Generating Capacity: 1098 MWe

Date of Survey: August 21, 1973

Plant Discharge Rate: 996.4 MGD (combined cooling water from both outfalls)

River Flow Rate: The 7 day, once in 10 year low flow is 12,100 cfs and the flow at the time of the survey was 39,000 cfs. The study was conducted under normal summer flow conditions.

Ambient Temperature: 81.5°F

Outfall Temperature: 90.5°F

River Cross Sections Monitored:

(A) 0.2 mile upstream (L, 1/4, 3/4, R) from surface to 10 m depth at 1 m intervals,

(B) point of discharge (L, 1/4, 3/4, R) from surface to 13 m depth at 1 m intervals,

(C) 2,200 feet downstream (L, 1/4, 3/4, R) from surface to 12 m depth at 1 m intervals,

(D) 0.8 miles downstream (L, 1/4, 3/4, R) from surface to 19 m depth at 1 m intervals.

Results:

(1) The heated plume spread laterally across the river toward the opposite shore from the plant (towards Kentucky bank) and covered more than 75% of the river at 2,200 feet downstream of the discharge.

(2) The maximum temperature excess was 1.8°F at 0.8 miles downstream with the top two meters of the river being between 0.9°F and 1.8°F above ambient temperature.

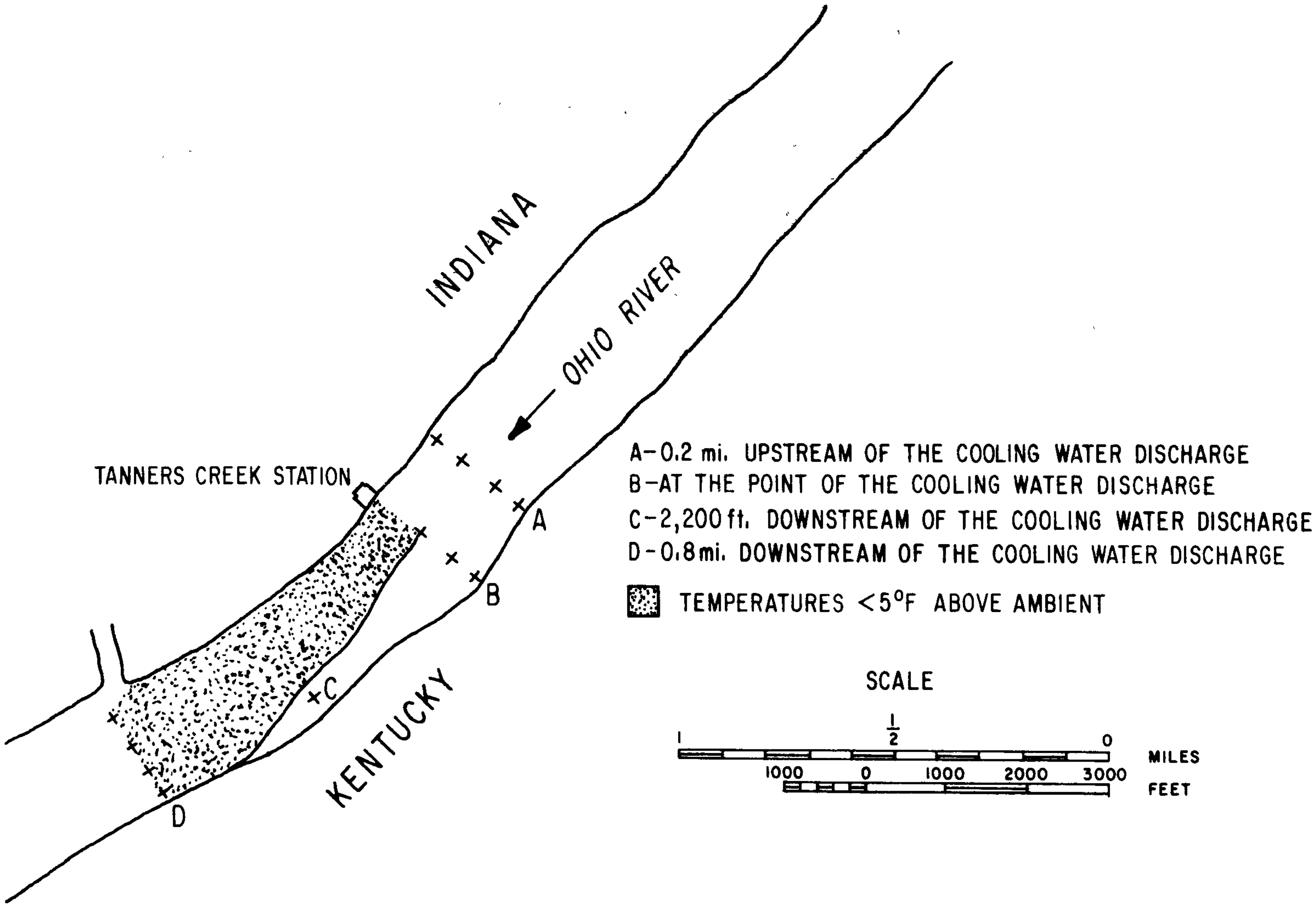


Figure 8.20: Sketch of the Tanner's Creek Station Thermal Plume, August 21, 1973 (Ref. 12).

Table 8.10: Survey of Clifty Creek Power Station, Indiana-Kentucky Electric Corporation[13]

Location: Near Madison, Indiana, Mile Point 560

Generating Capacity: 1304 MWe

Date of Survey: August 21, 1973

Plant Discharge Rate: 1382.4 MGD

River Flow Rate: The 7 day, once in 10 year low flow is 12,100 cfs and the flow at the time of the survey was 45,000 cfs. The study was conducted under normal summer flow conditions.

Ambient Temperature: 80.6°F

Outfall Temperature: 91.4°F

River Cross Sections Monitored:

(A) 0.2 mile upstream (L, 1/3, 2/3, R) from surface to 9 m depth at 1 m intervals,

(B) point of discharge (L, 1/3, 2/3, R) from surface to 10 m depth at 1 m intervals,

(C) 1,000 feet downstream (L, 2/5, 2/3, R) from surface to 10 m depth at 1 m intervals,

(D) 0.8 mile downstream (L, 1/4, 3/4, R) from surface to 10 m depth at 1 m intervals.

Results:

(1) The heated plume extended across the river beyond two-thirds the distance to the opposite (Kentucky) shore and extended beyond 1,000 feet downstream of the discharge at which point the maximum temperature measured was 5.4°F above ambient.

(2) At 0.9 mile downstream of the discharge, the plume extended beyond 3/4 of the distance across the river with a maximum 1.8°F excess temperature attained at the surface.

Notes:

The centerline of the plume appears to be from 2/5-3/4 the river width from the plant side of the river, determined from the measurements at the 1,000 feet and 0.9 mile cross sections. The bifurcated-shaped plume as illustrated in Figure 8.21 is an EPA representation of the measurements which did not accompany the original EPA report.[13] The representation in the figure illustrates an appearance of bifurcation after Section C. This is only an appearance since ambient temperature was measured at the 1/3 width measuring station at Section D. Transect D location in the river was determined by the point where the river returned to ambient temperature (within 1°C). This occurred at a distance of 0.9 mile downstream of the cooling water discharge. The plume interpretation given in Figure 8.21 is thus really an unqualified interpretation of the plume shape because temperatures were not collected between 1000 feet and 0.9 mile. In short, there is no data to substantiate the bifurcated-shape of the plume.

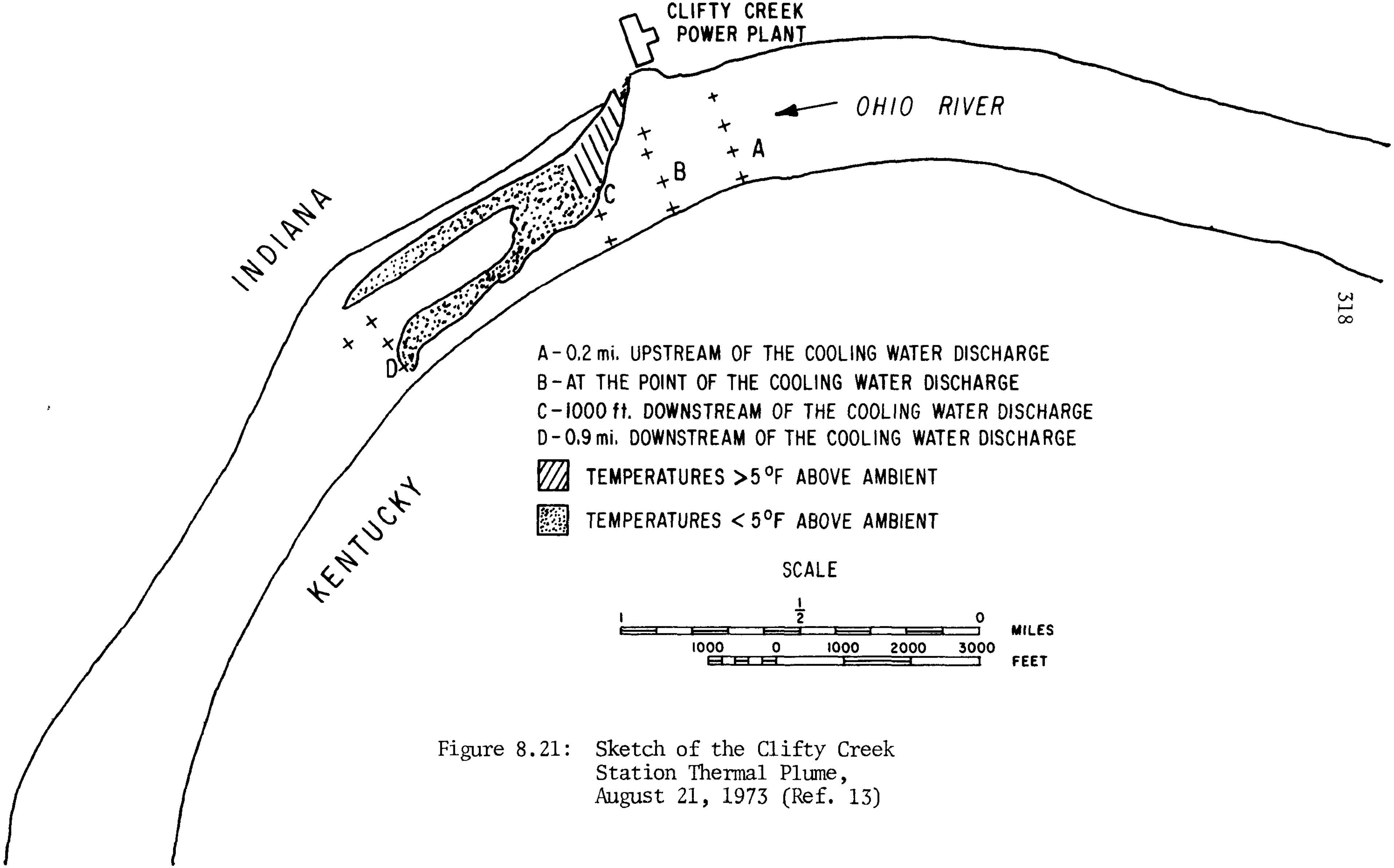


Figure 8.21: Sketch of the Clifty Creek Station Thermal Plume, August 21, 1973 (Ref. 13)

certain specific plume characteristics from these surveys other than some general notes on some individual temperatures and plume spreading. Plant conditions are given in terms of capacity. The actual load conditions were not determined; also no ambient river velocities were measured. Only an approximate river velocity can be determined by dividing an approximate river discharge rate by an estimated river cross sectional area. Thus the surveys can be used only as surveys and only a scoping interest can be satisfied.

Other scoping surveys have been done[14] yet without data reduction plotting, and discussion. These surveys are listed in Table 8.11. Typically, temperatures with depth were measured and recorded in tabular form at about 15 locations in the river (in total, above and below the discharge). Plant power level and discharge flow are given only in terms of rated values. Again, those studies may be sufficient for the monitoring of plants as to state and federal temperature violations, but not for model development and verification or as an aid to understanding plume dispersion.

8.2.2 Comprehensive Surveys by Boat at the Philip Sporn Plant

We are aware of only one plant on the Ohio River where systematic measurements have been obtained of the plume temperature field. Fourteen weekly synopic surveys were made by Geyer et al.[15] from July 12, 1967 to October 25, 1967. Only two surveys (July 19, 1967 and August 23, 1967) appear in the literature.[15,16]

This site (see Fig. 8.22) represents the classical oblique river discharge case since the geometrical river boundaries are quite regular with fairly regular (non-fluctuating) flow conditions. The Ohio River at the Sporn site (near New Haven, West Virginia) is wide and relatively shallow. The river width is approximately 1000 feet; the mean annual flow is about

Table 8.11: Additional Plume Surveys for Temperature Standards Verification[14]

Plant	River	Power Company	Date	No. of Cross Sections Temp. was Measured	No. of Depths Measured	No. of Points Per Cross Section
Kanawha River Plant	Kanawha River	Appalachian Power Company	10/10/68	3	2-7	5
Mitchell Power Plant	Monongahela River	West Penn Power Company	7/15/68	3	2-5	5
Mitchell Power Plant	Monongahela River	West Penn Power Company	10/11/68	3	2-5	5
Elrama Power Plant	Monongahela River	Duquesne Light Company	7/16/68	3	2-6	5
Elrama Power Plant	Monongahela River	Duquesne Light Company	9/11/68	3	2-5	5
Conesville Station	Muskingum River	Columbus & Southern Electric	9/25/69	6	2-3	3-5
Philo Station	Muskingum River	Ohio Power Company	9/23/69	6	2-3	3-5
Beverly Power Plant	Muskingum River	Ohio Power Company	9/23/69	6	2-7	3-5
Reed Power Plant	Ohio River	Duquesne Light Company	7/17/68	3	2-5	2-5
Phillips Power Plant	Ohio River	Duquesne Light Company	7/18/68	4	2-6	5
Phillips Power Plant	Ohio River	Duquesne Light Company	7/18/69	4	7-6	4
Sammis Power Plant	Ohio River	Ohio Edison Company	9/13/68	3	1-8	5
Sammis Power Plant	Ohio River	Ohio Edison Company	12/20/68	3	2-9	1-5
Sammis Power Plant	Ohio River	Ohio Edison Company	7/2/69	3	3-8	5
Cardinal & Tidd Power Plant	Ohio River	Ohio Edison Company	10/3/68	4	4-10	5
Cardinal & Tidd Power Plant	Ohio River	Ohio Edison Company	9/30/69	6	2-9	3-5
Burger Power Plant	Ohio River	Ohio Edison Company	10/4/69	4	2-7	4-5
Burger Power Plant	Ohio River	Ohio Edison Company	10/1/70	6	2-7	3-5
Kammer Power Plant	Ohio River	Ohio Power Company	10/11/68	4	2-7	5
Willow Island Power Plant	Ohio River	Monongahela Power Company	10/4/68	4	2-5	5
Philip Sporn	Ohio River	Appalachian Power Company	10/10/68	4	2-7	5
Philip Sporn	Ohio River	Appalachian Power Company	6/26/69	4	3-7	5
Philip Sporn	Ohio River	Appalachian Power Company	8/8/70	4	2-7	5
Kyger Creek	Ohio River	Ohio Valley Electric Company	10/9/68	4	3-9	5
Beckjord Power Plant	Ohio River	Cincinnati Power & Light Company	10/3/72	4	---	1-7
J. M. Stuart	Little Three Mile Creek - Ohio River	Dayton Power and Light Company	10/3/72	4	---	1-8
Miami Fort Station	Ohio River	Cincinnati Gas and Electric Company	10/3/72	3	---	1-8
Tanners Creek Station	Ohio River	Indiana and Michigan Power Company	10/3/72	3	---	1-5

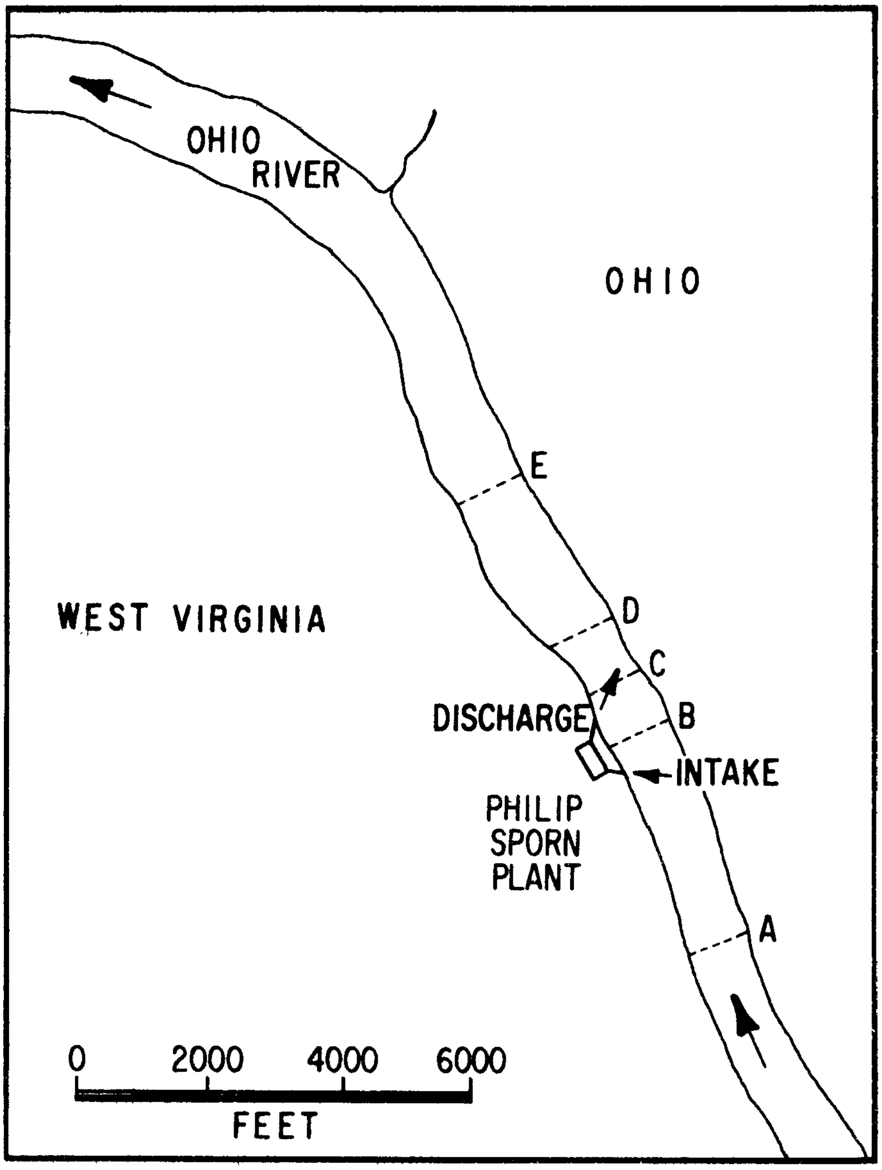


Figure 8.22: Philip Sport Power Plant on Ohio River with Field Data Locations.[17]

50,000 cfs with a maximum depth of flow of 27 feet. The plant's electrical capacity is 1050 MW with a nominal discharge flow of 1,350 cfs. The discharge enters the river on the downstream side of a 250 ft long sheet piling wall which is at 45° to the downstream river direction. One complicating feature is the location of various concrete walls and coal barge docking facilities downstream of the sheet piling wall. With barges present, the discharge can be effectively directed 90° to the shore! The outfall width is approximately 80 feet with a depth of 20 feet. The presence of moored barges may reduce the effective discharge width.

The Sporn site, especially the August 23, 1967 data, is a favorite for analytical model comparisons[16,17] since that data and the site in general often represents periods of quasi-steady conditions. That data of August 23 represents the least change in upstream conditions during all fourteen survey periods (see Table 8.12).

The survey data collected at the site were lateral and vertical temperatures traverses at each of six river sections located in Fig. 8.22. Most surveys were conducted over a period of five hours. Data were taken and recorded on sheets illustrated by Table 8.13, one set for each survey date. Table 8.13 lists the temperature data collected from the August 23, 1967 survey. Isotherms for the data at Sections C (1000 feet downstream of plant), D (3000 feet downstream of plant) and E (4400 feet downstream of plant) are given in Fig. 8.23. Since the ambient velocity is greater than the initial jet velocity on that date, it is expected that the plume hugs the nearshore for a considerable distance downstream. Lateral spreading is slow and results from turbulent mixing with the ambient river water as well as some lateral buoyant spreading. Edinger et al.[2] attempt to explain sets

Table 8.12: Atmospheric and River Conditions for August 23, 1967, and Maximum Discharge Situation for Philip Sporn Plant[16,17]

Meteorological Conditions During Period Selected for Study	
Air temperature	64°F
Relative humidity	91%
Dewpoint temperature	62°F
Solar radiation	0.23 Cal cm^{-2} min^{-1}
	1200 Btu ft^{-2} day^{-1}
Wind speed	5 mi hr^{-1}
Wind direction	100°A

Hydrological Conditions During Period Selected for Study	
River stage	539 ft
River flow	19,000 ft^3 sec^{-1}
Intake temperature	77.5°F
Discharge flow	120 x 10^6 ft^3 day^{-1}
	1400 ft^3 sec^{-1}
River velocity	1.13 ft/sec

Heated Effluent Under Maximum Discharge	
Temperature	89.6°F
Flow rate	1,400 cfs
Velocity	0.87 ft/sec
Mixed temperature rise	0.9°F

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Table 8.13: Philip Sporn Data for August 23, 1967[16]

AMERICAN ELECTRIC POWER
PHILIP SPORN PLANT
RACINE, WEST VIRGINIA

DAY OF SURVEY: WEDNESDAY

DATE OF SURVEY: 8/23/67

SHEET 2 OF 2

MONITORED DATA		TIME, HOUR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	METEOROLOG. STATION	AIR TEMPERATURE, F		66	65	64	63	62	60	62	64	68	71	73	75	78	78	79	79	79	78	76	74	72	70	68	67
		RELATIVE HUMIDITY, %		100	100	100	100	100	100	100	91	85	76	74	68	62	60	60	62	66	70	76	81	84	87	94	95
		SOLAR RADIATION, cal cm^{-2} min^{-1}		0	0	0	0	0	0	.05	.20	.43	.73	.90	.72	.80	.85	.75	.55	.50	.25	.11	0	0	0	0	0
		WIND SPEED, MPH		4.2	4.2	4.6	5.4	5.1	3.6	4.6	4.8	5.7	5.4	5.4	5.4	8.5	8.5	8.5	7.7	4.5	4.9	3.4	4.0	4.9	4.5	3.1	2.9
		WIND DIRECTION, °AZIMUTH		100	150	135	135	60	60	90	90	120	150	120	120	130	100	120	150	150	160	160	170	120	160	[illegible]	150
		RIVER STAGE, FT.		538.3	538.3	538.3	538.3	538.3	538.9	538.9	538.9	538.9	538.9	538.8	538.7	538.6	538.3	538.0	538.0	538.0	538.0	538.0	538.0	538.0	538.0	538.0	538.0
		RIVER FLOW-AVG. DAILY VALUE cfs		8/22/67 – 18,700							8/23/67 – 19,100					8/24/67 – 17,000											
	PLANT INFORMATION	PLANT LOADING, MW		612	610	613	609	620	645	765	887	876	899	909	894	878	901	903	906	900	890	877	886	877	870	867	814
		HEAT REJECTED, 10^9 BTU HR^{-1}		2.76	2.75	2.77	2.74	2.79	2.88	3.34	3.84	3.80	3.90	3.94	3.86	3.81	3.91	3.91	3.93	3.91	3.87	3.80	3.85	3.90	3.77	3.52	3.54
		COND. FLOW, 10^6 FT^3 DAY^{-1}		117.7	117.6	118.5	115.9	119.1	104.4	105.4	122.2	124.7	126.7	125.4	125.7	110.6	110.1	113.2	112.7	113.7	117.3	116.1	112.9	114.6	118.0	109.1	111.4
		COND. INT. TEMP., F		78.0	77.9	77.8	77.7	77.6	77.5	77.4	77.5	77.9	78.0	77.8	77.8	77.5	77.6	77.6	77.6	77.7	77.8	77.8	78.0	77.9	77.9	77.1	77.1
		COND. DISCG. TEMP., F		87.0	86.9	86.8	86.8	86.6	87.9	89.6	89.6	89.6	89.9	89.9	89.7	90.5	91.0	90.9	91.0	91.0	90.5	90.4	91.1	91.0	90.1	90.0	89.3
		PLANT WIND SPEED, MPH		RECORDER NOT INSTALLED																							
		PLANT WIND DIRECTION, °AZ																									

REMARKS: UNIT 1 OUT OF SERVICE ALL DAY

Table 8.13 (contd.)[16]

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RESEARCH PROJECT RP49

AMERICAN ELECTRIC POWER
PHILIP SPORN PLANT
RACINE, WEST VIRGINIA

DAY OF SURVEY. WEDNESDAY — DATE OF SURVEY: 8/23/67 — SHEET 1 OF 2

1	RIVER SEC. A	START 0711 FINISH 0720 DRYBULB 66.0 °F WETBULB 61.9 °F															
2	DIST. FROM LEFT BANK	1/4	1/2	3/4													
3	SURFACE TEMP.	78.0	77.8	78.0													
4	1' LEVEL	78.2	78.2	78.2													
5	3' LEVEL	78.0	77.8	78.0													
6	5' LEVEL	78.2	78.0	78.0													
7	10' LEVEL	78.4	78.4	78.2													
8	15' LEVEL	78.4	78.2	78.0													
9	20' LEVEL	78.0	78.0	78.0													
10	25' LEVEL	78.2	78.2	78.0													
11	30' LEVEL																
12	35' LEVEL																
13	RIVER SEC. B	START 0726 FINISH 0752 DRYBULB 66.4 °F WETBULB 61.6 °F															
14	DIST. FROM LEFT BANK	0	80	160	240	320	400	480	[illegible]	640	720	800	880	960	1000		
15	SURFACE TEMP	78.0	78.0	77.8	77.6	78.0	78.2	78.2	78.2	78.2	78.0	77.8	78.0	78.0	77.8		
16	1' LEVEL	78.2	78.2	78.0	78.0	78.2	78.2	78.2	78.2	78.2	78.0	78.0	78.0	78.0	78.0		
17	3' LEVEL	77.8	77.8	77.4	77.8	77.6	78.2	78.2	78.2	78.0	78.0	78.2	78.2	78.0	78.0		
18	5' LEVEL	78.2	78.0	78.0	78.0	78.2	78.2	78.2	78.2	78.2	78.2	78.0	78.2	78.0	78.0		
19	10' LEVEL	78.2	78.2	78.2	78.4	78.4	78.4	78.4	78.4	78.4	78.4	78.2	78.2	78.0			
20	15' LEVEL	78.0	78.0	78.0	78.2	78.4	78.4	78.4	78.2	78.4	78.2	78.2	78.2	78.0			
21	20' LEVEL	78.0	78.2	78.2	78.2	78.4	78.2	78.2	78.0	78.2	78.0	78.0	78.0				
22	25' LEVEL				78.2	78.2	78.2	78.2	78.4	78.2	78.0	78.0					
23	30' LEVEL																
24	35' LEVEL																
25	RIVER SEC. C	START 0805 FINISH 0825 DRYBULB 67.0 °F WETBULB 62.8 °F															
26	DIST. FROM LEFT BANK	0	40	80	120	160	200	240	280	320	360	400	440	660	800	960	
27	SURFACE TEMP.	83.9	84.1	81.8	83.2	86.2	86.1	86.8	85.0	84.3	82.1	79.2	78.1	78.1	78.0	78.0	
28	1' LEVEL	83.8	84.0	81.9	84.2	86.8	86.0	86.8	84.9	84.9	84.0	78.8	78.4	78.3	78.2	78.1	
29	3' LEVEL	83.1	83.8	81.4	81.8	85.8	84.2	82.3	82.9	83.9	82.2	78.3	78.4	78.3	78.1	77.9	
30	5' LEVEL	81.5	82.3	81.4	79.0	[illegible]	80.8	80.2	81.8	82.3	81.8	78.5	78.5	78.4	78.2	83.1	
31	10' LEVEL	80.0	79.8	78.2	80.1	79.0	80.3	80.0	79.8	79.9	78.8	78.8	78.6	78.8	78.5		
32	15' LEVEL	79.8		79.8	78.2	78.4	78.8	78.9	79.0	78.9	78.7	78.8	78.5	78.6	78.2		
33	20' LEVEL				78.2	78.7	78.8	78.3	78.3	78.5	78.5	78.8	79.5	78.3	78.3		
34	25' LEVEL							78.6	78.7	78.8	78.8	78.5	78.5	78.5			
35	30' LEVEL																
[illegible]	[illegible] LEVEL																

Table 8.13 (contd.)[16]

THE JOHNS HOPKINS UNIVERSITY DEPT OF ENVIRONMENTAL ENG. SCIENCES EEI COOLING WATER DISCHARGE RESEARCH PROJECT RP49	AMERICAN ELECTRIC POWER PHILIP SPORN PLANT RACINE, WEST VIRGINIA

DAY OF SURVEY: WEDNESDAY — DATE OF SURVEY: 8/23/67 — SHEET 1 OF 2

1	RIVER SEC. D	START 0850 FINISH 0925 DRYBULB 70.2 °F WETBULB 64.5 °F															
2	DIST. FROM LEFT BANK	0	40	80	120	160	200	240	280	320	360	400	440	480	520	560	600
3	SURFACE TEMP.	79.2	80.0	80.9	81.0	80.2	80.2	80.1	80.1	82.2	82.3	81.9	81.0	80.2	81.0	81.0	80.3
4	1' LEVEL	79.8	79.9	81.0	81.0	80.5	80.1	80.0	80.0	82.2	82.5	81.9	80.4	80.2	81.0	81.0	80.2
5	3' LEVEL	79.0	79.0	80.0	79.0	79.9	80.0	79.2	79.0	79.0	79.8	79.6	79.8	79.9	79.5	79.8	79.4
6	5' LEVEL	79.5	78.8	79.1	79.0	79.2	79.8	79.2	79.0	79.0	79.0	79.0	79.0	79.2	79.0	79.2	79.1
7	10' LEVEL		78.9	79.0	78.8	78.9	79.1	79.1	79.0	79.0	78.9	78.9	79.0	79.1	79.0	79.0	79.1
8	15' LEVEL				78.9	78.9	79.0	79.0	79.0	78.8	78.7	78.8	78.8	78.9	78.8	78.8	78.9
9	20' LEVEL							79.1	78.8	79.0	78.8	78.8	78.8	78.9	78.8	79.0	78.8
10	25' LEVEL																
11	30' LEVEL																
12	35' LEVEL																
13	RIVER SEC. D (CONT'D.)	START FINISH DRYBULB °F WETBULB °F															
14	DIST. FROM LEFT BANK	640	680	720	760	800	840	880	920	960	1000	1040					
15	SURFACE TEMP	80.1	79.2	79.0	79.0	79.0	79.0	79.0	79.0	78.7	78.9	78.3					
16	1' LEVEL	80.0	79.5	79.1	79.1	79.1	79.0	79.0	79.0	78.9	79.5	79.0					
17	3' LEVEL	79.2	79.0	79.0	79.0	79.0	78.9	79.0	78.9	78.8	79.2	79.0					
18	5' LEVEL	79.1	79.1	79.0	79.0	79.0	79.0	79.0	79.0	78.9	79.1	79.0					
19	10' LEVEL	79.1	79.1	79.1	79.1	79.1	79.1	79.1	79.0	79.0	79.1	79.0					
20	15' LEVEL	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	78.9	79.0	78.8					
21	20' LEVEL	79.0	79.0	79.0	79.0	79.1	79.0	79.0	79.0	78.9	78.9	79.0					
22	25' LEVEL																
23	30' LEVEL																
24	35' LEVEL																
25	RIVER SEC. E	START 930 FINISH 1010 DRYBULB 71.0 °F WETBULB 65.0 °F															
26	DIST. FROM LEFT BANK	0	40	80	120	160	200	240	280	320	360	400	440	480	520	560	600
27	SURFACE TEMP.	80.0	80.0	80.0	79.9	80.0	80.0	80.5	80.5	81.0	80.5	81.9	79.1	78.9	78.5	79.0	79.0
28	1' LEVEL	80.1	80.1	80.1	80.1	80.1	80.1	80.4	81.0	81.0	80.5	82.1	79.1	78.9	78.9	79.1	78.9
29	3' LEVEL	79.5	79.4	79.7	79.7	79.9	79.9	79.9	80.0	79.9	80.0	80.0	78.8	78.9	76.9	78.8	78.9
30	5' LEVEL	79.7	79.4	79.5	79.5	79.8	79.4	79.9	79.7	79.5	80.1	79.1	78.8	78.7	78.9	78.8	78.9
31	10' LEVEL		78.3	78.9	78.7	79.0	79.3	79.2	79.5	79.1	79.4	79.6	78.9	78.9	79.0	78.9	79.0
32	15' LEVEL			78.9	78.7	78.7	78.8	78.8	78.8	78.5	78.8	78.9	78.8	78.8	78.7	78.9	78.9
33	20' LEVEL					78.7	78.8	78.8	78.8	78.8	78.8	78.5	78.5	78.5	78.7	78.8	78.8
34	25' LEVEL									78.8		78.7	78.7	78.8	78.8	78.9	78.9
35	30' LEVEL																
36	35' LEVEL																

Table 8.13 (contd.)[16]

THE JOHNS HOPKINS UNIVERSITY
DEPT. OF ENVIRONMENTAL ENG. SCIENCES
EEI COOLING WATER DISCHARGE
RESEARCH PROJECT RP49

AMERICAN ELECTRIC POWER
PHILIP SPORN PLANT
RACINE, WEST VIRGINIA

DAY OF SURVEY: WEDNESDAY   DATE OF SURVEY: 8/23/67   SHEET 1 OF 2

1	RIVER SEC. E CONT'D.	START FINISH DRYBULB °F WETBULB °F															
2	DIST. FROM LEFT BANK	640	680	720	760	800	840	880	920	960	1000	1040	1080	1120			
3	SURFACE TEMP.	81.0	79.9	79.7	79.5	79.8	80.0	80.3	80.5	80.4	80.0	79.4	79.2	79.1			
4	1' LEVEL	80.8	79.9	79.7	79.5	79.9	80.0	80.1	80.0	80.2	79.9	79.5	79.3	79.2			
5	3' LEVEL	80.0	79.5	79.1	79.0	79.5	79.8	79.8	79.4	79.8	79.4	79.4	78.9	79.0			
6	5' LEVEL	78.8	79.4	79.2	79.0	79.4	79.3	78.4	79.2	79.4	79.2	78.8	78.8	78.9			
7	10' LEVEL	79.2	79.8	79.1	79.1	79.2	79.5	79.4	79.2	79.2	79.1	78.8	78.9				
8	15' LEVEL	78.9	79.2	79.4	78.8	79.0	79.0	79.0	78.9	78.8	78.8	78.8					
9	20' LEVEL	78.8	79.2	79.2	78.5	78.8	78.7	78.8	78.5	78.6	78.8						
10	25' LEVEL	78.8	79.8	78.8	78.7	78.8	78.8	78.8	78.8	78.7							
11	30' LEVEL																
12	35' LEVEL																
13	RIVER SEC. F	START 1024 FINISH 1040 DRYBULB 74.5 °F WETBULB 66.5 °F															
14	DIST. FROM LEFT BANK	0	80	160	240	320	400	480	560	640	720	800	880	960	1040		
15	SURFACE TEMP	78.0	78.0	78.9	79.2	78.9	79.0	78.8	79.1	79.0	79.0	79.0	79.0	78.9	78.9		
16	1' LEVEL	78.8	78.9	79.0	79.1	79.0	79.1	79.1	79.1	79.1	79.1	79.1	79.1	79.0	79.1		
17	3' LEVEL	78.5	78.9	78.9	79.0	78.9	79.0	79.1	78.9	79.0	79.1	79.0	79.2	79.1	79.2		
18	5' LEVEL	78.8	78.9	78.9	78.9	79.0	79.0	79.1	79.1	79.1	79.2	79.1	79.1	79.1	79.3		
19	10' LEVEL		78.6	78.9	79.0	79.0	79.0	79.1	79.0	79.3	79.6	79.8	79.2	79.2			
20	15' LEVEL		78.6	78.9	78.9	79.0	79.0	79.1	79.0	79.2	79.3	79.5	79.1	79.1			
21	20' LEVEL		78.4	78.9	79.0	79.0	79.0	79.1	79.0	79.1	79.3	79.2	79.1	79.1			
22	25' LEVEL									79.2	79.3	79.2					
23	30' LEVEL																
24	35' LEVEL																
25	RIVER SEC. A-2ND	START 12:12 FINISH 12:20 DRYBULB 77.8 °F WETBULB 68.3 °F															
26	DIST. FROM LEFT BANK	1/4	1/2	3/4													
27	SURFACE TEMP.	78.5	78.6	78.9													
28	1' LEVEL	78.5	78.7	78.7													
29	3' LEVEL	78.5	78.7	78.7													
30	5' LEVEL	78.4	78.4	78.5													
31	10' LEVEL	78.3	78.3	78.5													
32	15' LEVEL	78.3	78.3	78.3													
33	20' LEVEL	78.3	78.3	78.3													
34	25' LEVEL	78.4	78.3	78.4													
35	30' LEVEL																
36	35' LEVEL																

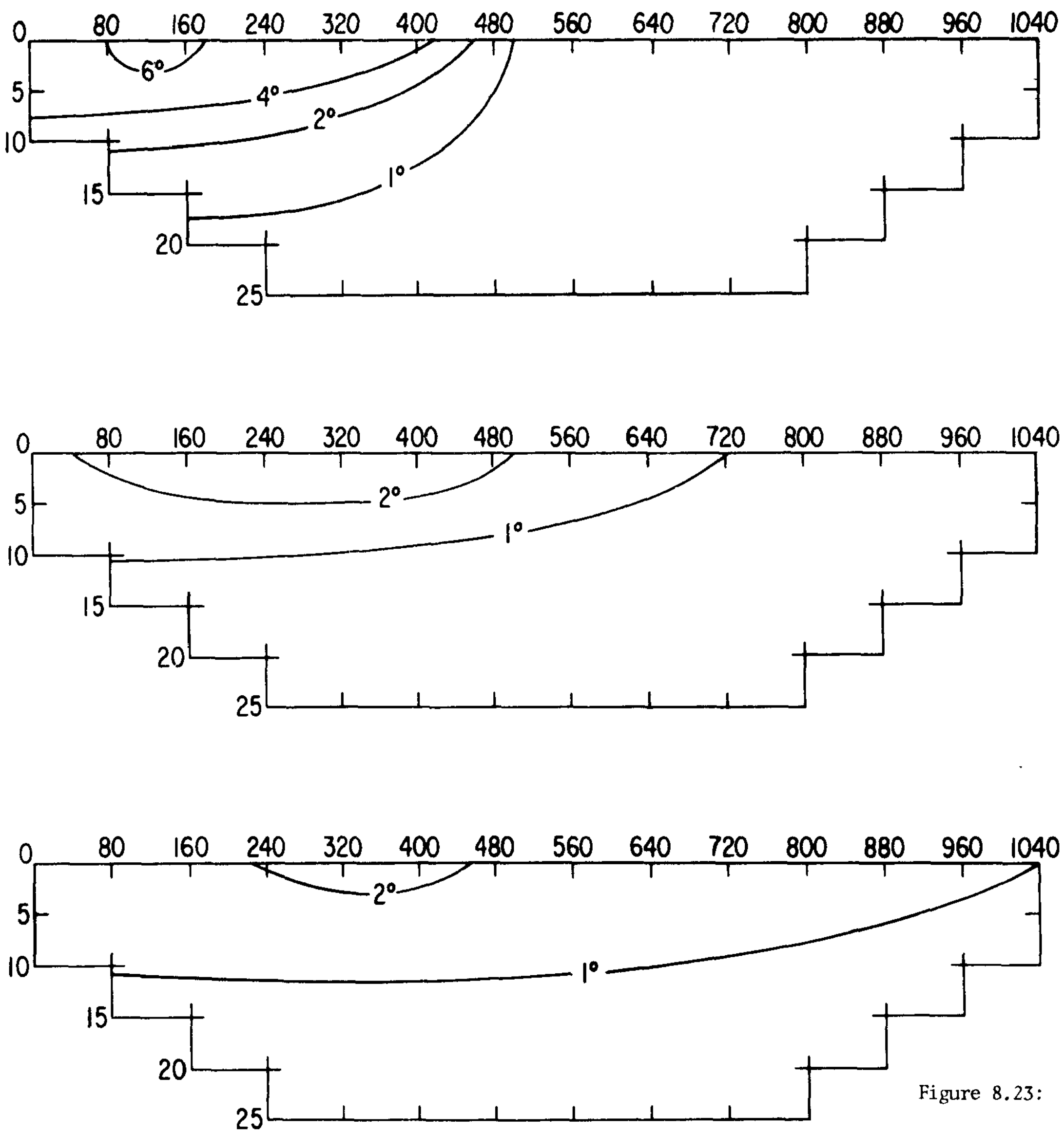

Figure 8.23: Isotherms from Field Data at the Philip Sporn Plant for August 23, 1967 at positions C, D, and E at 1000, 3000, and 4400 ft, respectively, from the discharge.[17]

of Philip Sporn data by averaging similar sets of data (for similar plant and environmental conditions) and plotting the results using a computerized contouring program. They attempt to show the general trend of the plume shape after most of the eddy noise has been smoothed out. The authors are presently modifying the discussion in their draft report and their results will be presented in the final published version of Reference 2.

The Philip Sporn data is interesting in that it represents many different conditions. Plumes are seen on days of low flow to spread to the opposite shore while on days of high flow the plume hugs the nearshore for considerable distances downstream. Moreover, the presence of barges effectively directs the plume at a 90° angle to the shore with altered outfall conditions. An interesting study could be made by analyzing that data when it becomes non-proprietary.

8.2.3 Scoping Studies by Aerial Infra-red Mappings

On August 25, 1972, aerial infra-red photographs were taken by EPA[18] over portions of the Monongahela, Ohio, and Allegheny Rivers in the Pittsburgh, Pennsylvania area between the hours 1158 and 1358 EDT. Thermal infra-red (8-14 micron wavelength) imagery was obtained using an HRB-Singer AN/AAS-14A optical/mechanical scanner. The aircraft altitude varied between 4000 and 8700 feet above terrain. Ground coverage obtained of interpretative value is a swath along the flight path approximately 80° wide, which from the altitude flown, results in a path 6700-14,600 feet wide. It was expected that temperatures to within 0.5°C could be quantitatively observed and discussed; however, the poor resolution of the optical equipment has made any quantitative measurements impossible at this time.

A schematic of the area covered during the flight is shown in Fig. 8.24 along with the observable plumes numbered for reference. These plumes

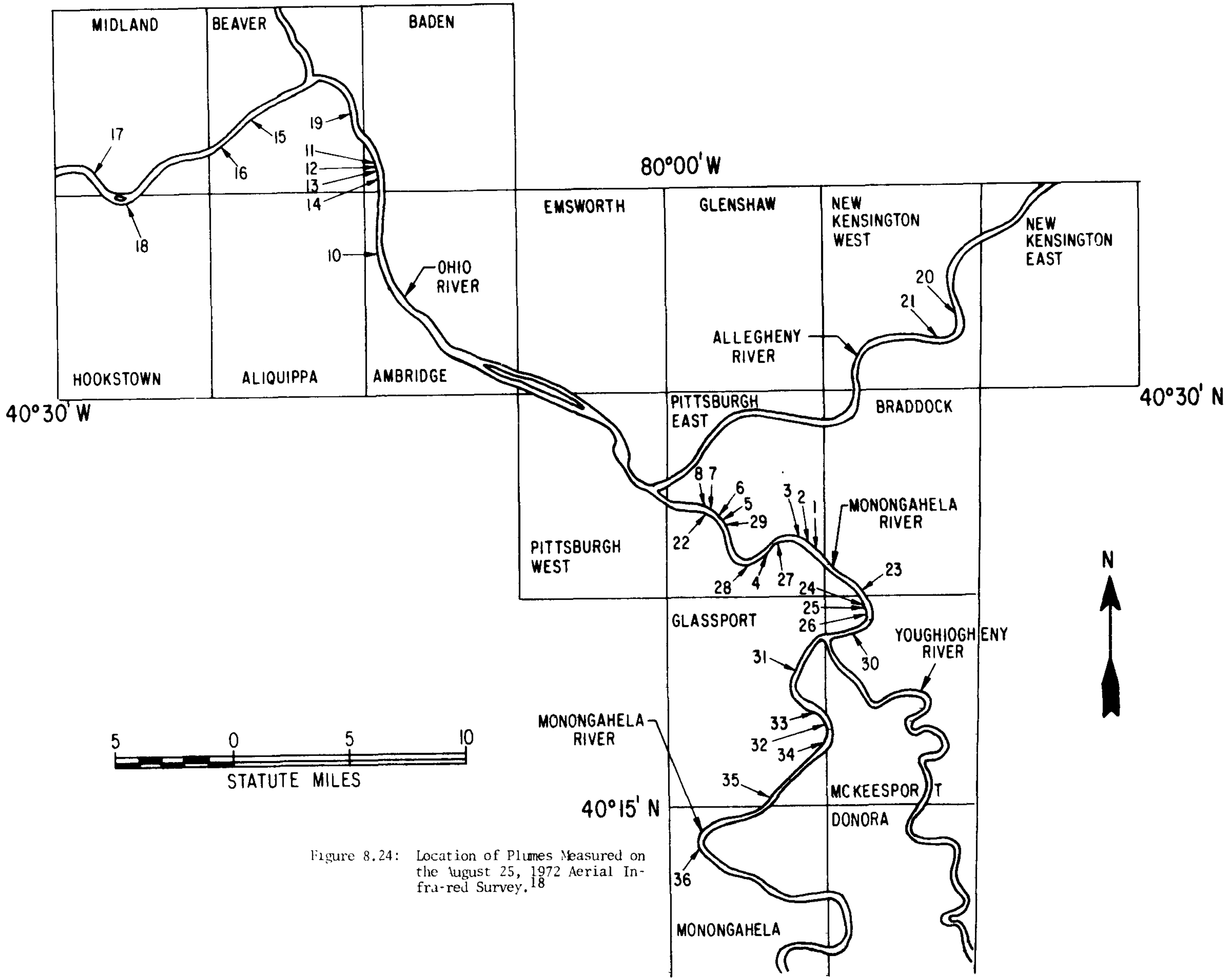

Figure 8.24: Location of Plumes Measured on the August 25, 1972 Aerial Infra-red Survey.[18]

are identified wherever possible from Table 8.14. Only latitude-longitude locations of the individual plumes were readily available; mile point locations were not known for unidentified plants. Only names and mile points of plants on the Ohio River could be determined in the time available for this study. Also included in the Table is the areal extent and length of each plume determined approximately from the imagery. These numbers are rough approximations because it is difficult on an infra-red photograph to distinguish the precise plume boundaries. Figures 8.25-8.38 are graphical interpretations of the plumes photographed. Plumes from the Allegheny and Monongahela Rivers are included in this discussion for completeness and as a contrast to the Ohio River plumes. No attempt could be made to distinguish the actual temperature level of the plume, but instead, the qualitative evidence of contrast between the river ambient and the heated discharge was taken to determine the extent of the plume.

In general, thermal discharges along the Ohio River on this August 25 date are convected downstream with an apparently large current. Even the larger plumes along the Ohio do not show evidence of reaching the opposite shore, while the reverse is in evidence along the Monongahela and Allegheny Rivers. The two plumes associated with the Allegheny appear to be quite narrow, their length to width ratio are much less than is usual for a plume in the absence of a longshore current. The plumes along the northern Monongahela show signs of convection toward the Pittsburgh area due to apparently large currents, while plumes on the sourthern portions of the Monongahela bend less downstream due to apparent small currents in that section of the river. This might be explained in that the Monongahela is increased in flow from the sourthern portion to the northern by the addition of a large tributary slightly downstream of plume 31.

Table 8.14: Index[4] of Thermal Plumes Measured by the Aerial Infra-red Survey of August 25, 1972 (Ref. 18)

Discharge #	River	Quadrangle Map	Location N-Lat	Location W-Long	Area of Thermal Influence (ft^2) (approx)	Furthest Extent of Influence (ft) (approx)	Time (EDT)	Remarks
1	Monongahela	Pittsburgh E., Pa.	40°24'38"	79°53'20"	300,000	600	1146	
2	Monongahela	Pittsburgh E., Pa.	40°24'41"	79°53'24"	360,000	600	1146	Two thermal levels (5)
3	Monongahela	Pittsburgh E., Pa.	40°24'45"	70°53'32"	240,000	600	1149	
4	Monongahela	Pittsburgh E., Pa.	40°24'41"	79°54'54"	400,000	800	1153	
5	Monongahela	Pittsburgh E., Pa.	40°24'45"	79°57'6"	160,000	800	1158	
6	Monongahela	Pittsburgh E., Pa.	40°25'3"	79°57'6"	100,000	700	1158	
7	Monongahela	Pittsburgh E., Pa.	40°25'36"	79°57'26"	320,000	900	1158	
8	Monongahela	Pittsburgh E., Pa.	40°25'39"	79°57'30"	NA	NA	1158	Included in #7
9	Ohio	Ambridge, Pa.	40°31'54"	80°10'08"	120,000	800	1201	No discharge exists here
10	Ohio	Ambridge, Pa.	40°34'15"	80°14'00"	720,000	1800	1205	Two thermal levels (5)
11	Ohio	Baden, Pa.	40°37'45"	80°14'08"	360,000	1200	1206	Location question (2)
12	Ohio	Baden, Pa.	40°37'48"	80°14'08"	80,000	400	1206	Location question (2)
13	Ohio	Baden, Pa.	40°37'56"	80°14'08"	1,360,000	3400	1207	Two thermal levels (5)
14	Ohio	Baden, Pa.	40°38'02"	80°14'12"	180,000	900	1207	Two thermal levels (5)
15	Ohio	Beaver, Pa.	40°40'22"	80°20'20"	720,000	1800	1213	
16	Ohio	Beaver, Pa.	40°39'30"	80°21'26"	400,000	2000	1215	
17	Ohio	Midland, Pa.	40°38'19"	80°28'05"	1,200,000	2000	1216	Two thermal levels (5)
18	Ohio	Hookstown, Pa.	40°37'13"	80°26'20"	480,000	1200	1216	(1); Two thermal levels (5)
19	Ohio	Beaver, Pa.	40°41'10"	80°15'45"	720,000	1200	1210	(1)
20	Allegheny	New Kensington W., Pa.	40°32'42"	79°46'02"		1600	1306	(2)
21	Allegheny	New Kensington W., Pa.	40°32'13"	79°47'36"		1700	1306	(2); "spans" river (3)
22	Monongahela	Pittsburgh E., Pa.	40°25'9"	80°57'21"	960,000	1600	1320	(2); "spans" river (3)
23	Monongahela	Braddock, Pa.	40°22'43"	79°50'37"	600,000	800	1311	
24	Monongahela	Braddock, Pa.	40°22'29"	79°50'24"	600,000	1200	1311	Two thermal levels (5)
25	Monongahela	McKeesport, Pa.	40°22'15"	79°50'24"	720,000	1200	1310	(2)
26	Monongahela	McKeesport, Pa.	40°22'10"	79°50'23"	640,000	800	1309	
27	Monongahela	Pittsburgh E., Pa.	40°24'51"	79°54'29"	40,000	400	1321	
28	Monongahela	Pittsburgh E., Pa.	40°23'54"	79°55'42"	140,000	1400	1321	(1)
29	Monongahela	Pittsburgh E., Pa.	40°24'30"	79°57'05"	1,400,000	1800	1325	Two thermal levels (5)
30	Monongahela	McKeesport, Pa.	40°21'18"	79°51'13"	160,000	400	1332	
31	Monongahela	Glassport, Pa.	40°20'15"	79°53'42"	120,000	600	1337	
32	Monongahela	McKeesport, Pa.	40°17'42"	79°52'06"	40,000	400	1338	
33	Monongahela	Glassport, Pa.	40°18'34"	79°52'54"	240,000	600	1337	
34	Monongahela	McKeesport, Pa.	40°17'18"	79°52'25"	400,000	800	1341	Two thermal levels (5)
35	Monongahela	Glassport, Pa.	40°15'10"	79°55'00"	480,000	1200	1343	
36	Monongahela	Monongahela, Pa.	40°13'21"	79°58'16"	720,000	1600	1352	

(1) Questionable if discharge is actually present.

(2) Thermal area evident; exact discharge location in question.

(3) Warmer effluent extends from one river bank to other.

(4) The key to plant names for the Allegheny and Monongahela plumes is presently unavailable.

(5) Relative scale which indicates clear evidence of discharge being present.

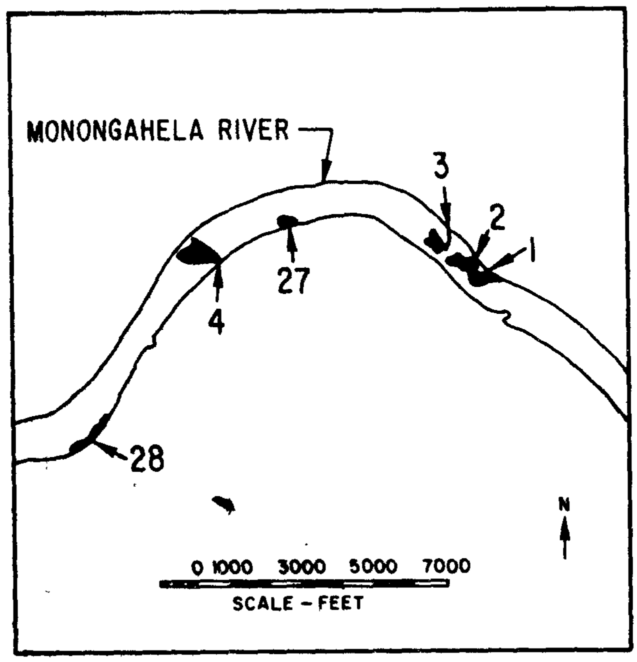

Figure 8.25: Sketches of Thermal Plumes 1-4, 27, 28 on the Monongahela River drawn from Infra-red Photographs of August 25, 1972. (Ref. 18).

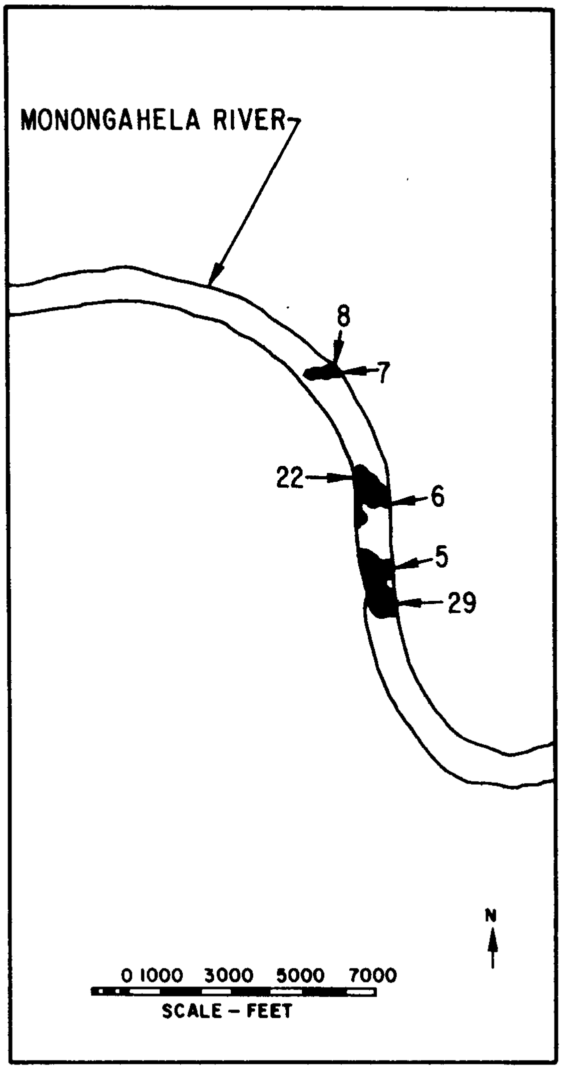

Figure 8.26: Sketches of Thermal Plumes 5-8, 22, 29 on the Monongahela River drawn from Infra-red Photographs of August 25, 1972. (Ref. 18).

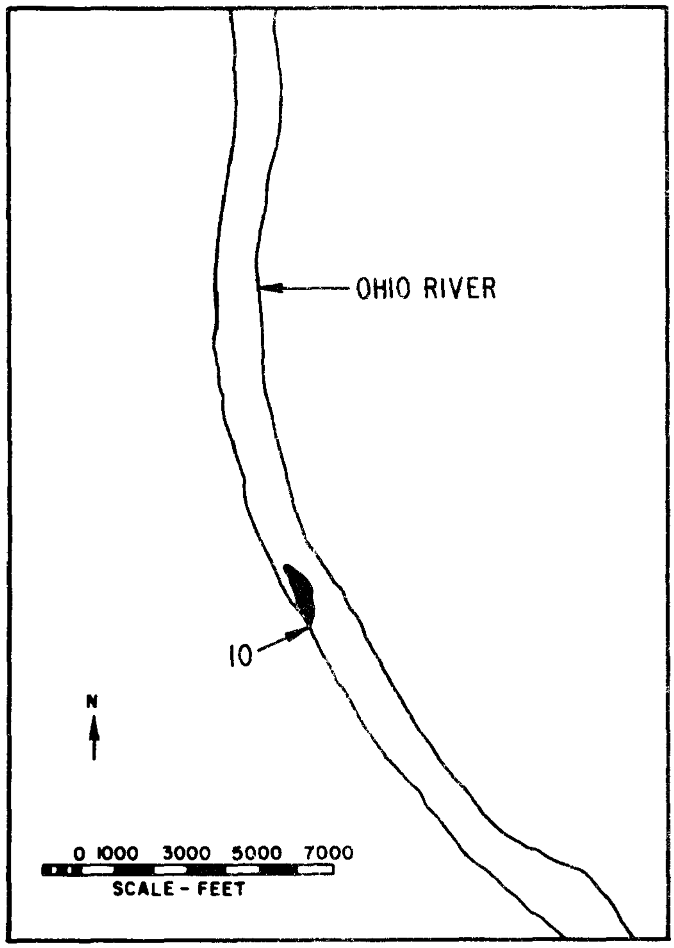

Figure 8.27: Sketch of Thermal Plume 10 on the Ohio River drawn from Infra-red Photographs of August 25, 1972[18] (Plume 10: F. Phillips Plant, Duquesne Power and Light).

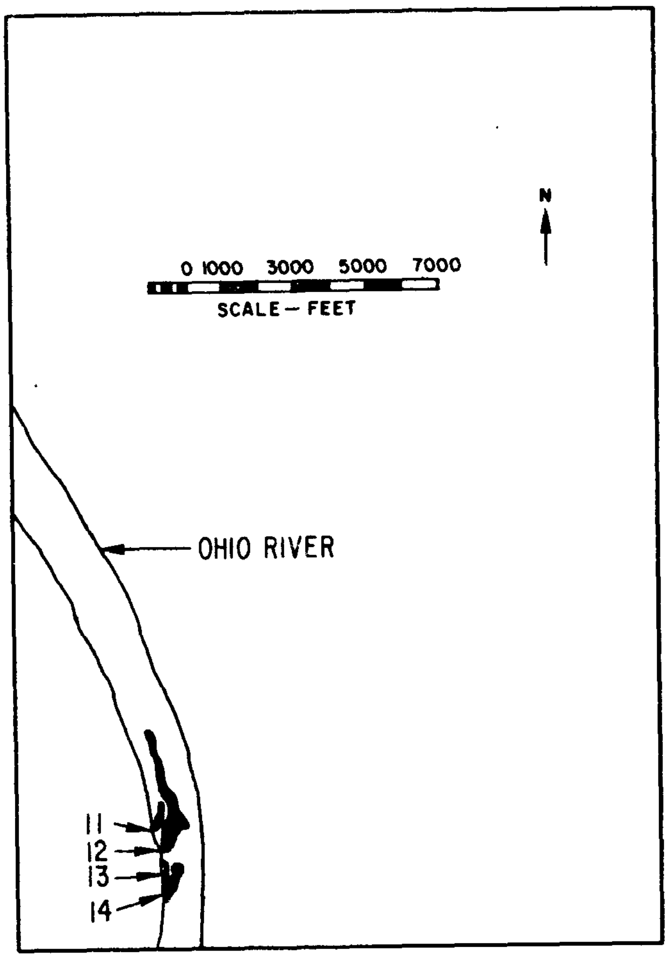

Figure 8.28: Sketch of Thermal Plumes 11-14 on the Ohio River drawn from Infra-red Photographs of August 25, 1972[18] (Plumes 11-14: Jones and Laughlin Steel Co.).

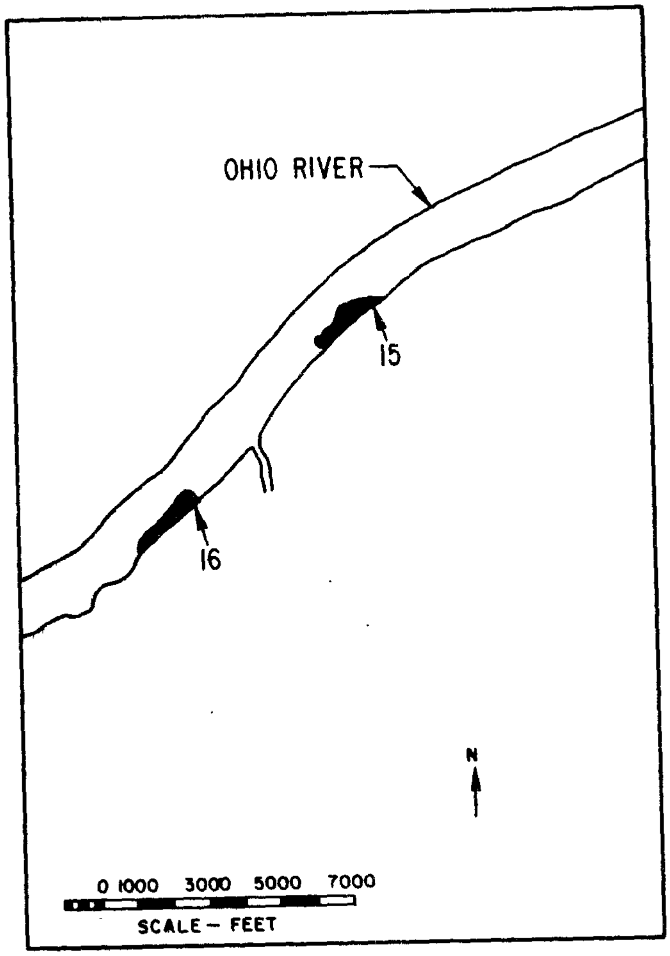

Figure 8.29: Sketch of Thermal Plumes 15, 16 on the Ohio River drawn from Infra-red Photographs of August 25, 1972[18] (Plume 15: St. Joseph Lead Company, Plume 16: Koppers Corporation).

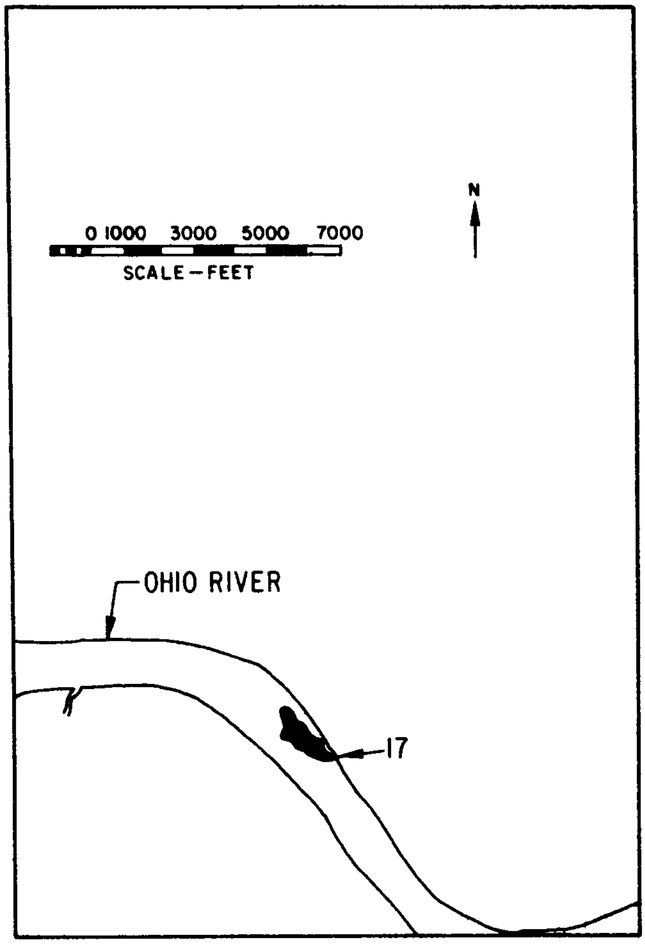

Figure 8.30: Sketch of Thermal Plume 17 on the Ohio River drawn from Infra-red Photographs of August 25, 1972[18] (Plume 17: Crucible Steel Company).

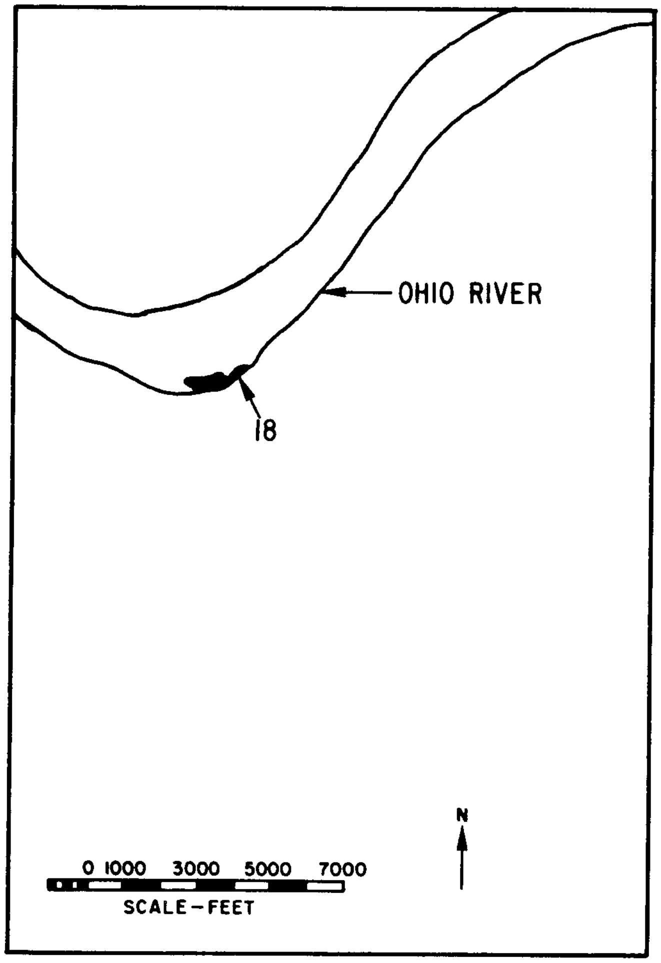

Figure 8.31: Sketch of Thermal Plume 18 on the Ohio River drawn from Infra-red Photographs of August 25, 1972[18] (Plume 18: Shippingport Power Plant, Duquesne Power and Light)

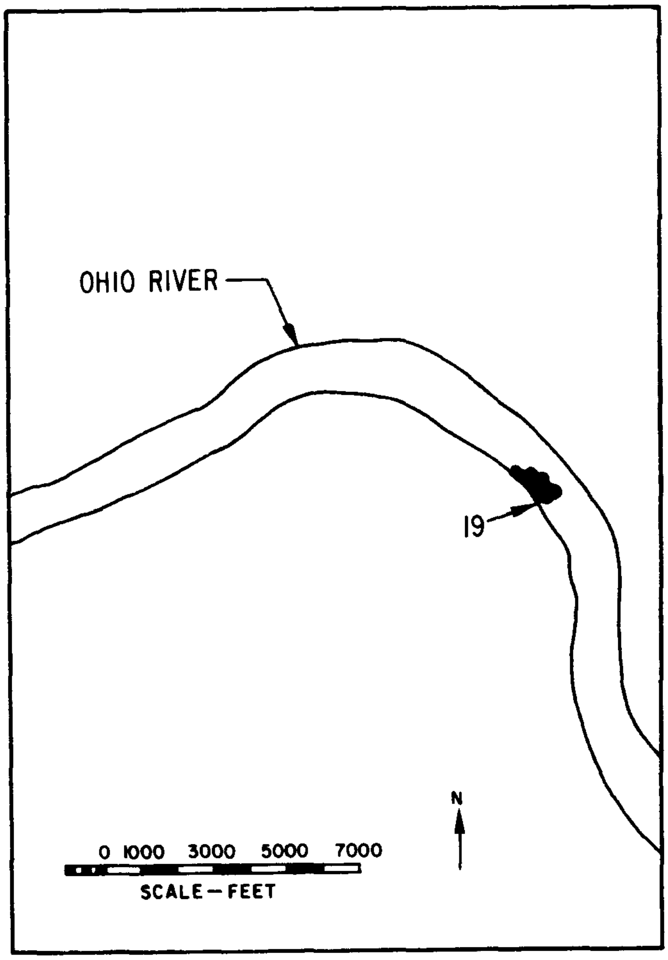

Figure 8.32: Sketch of Thermal Plume 19 on the Ohio River drawn from Infra-red Photographs of August 25, 1972[18] (Plume 19: Colonial Steel Corporation).

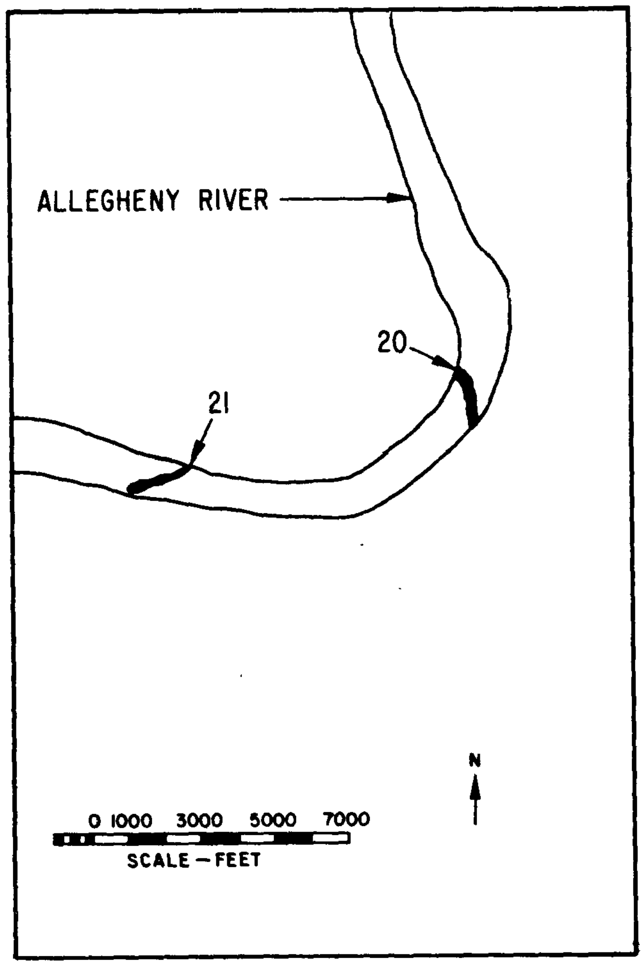

Figure 8.33: Sketch of Thermal Plumes 20, 21 on the Allegheny River drawn from Infra-red Photographs of August 25, 1972 (Ref. 18).

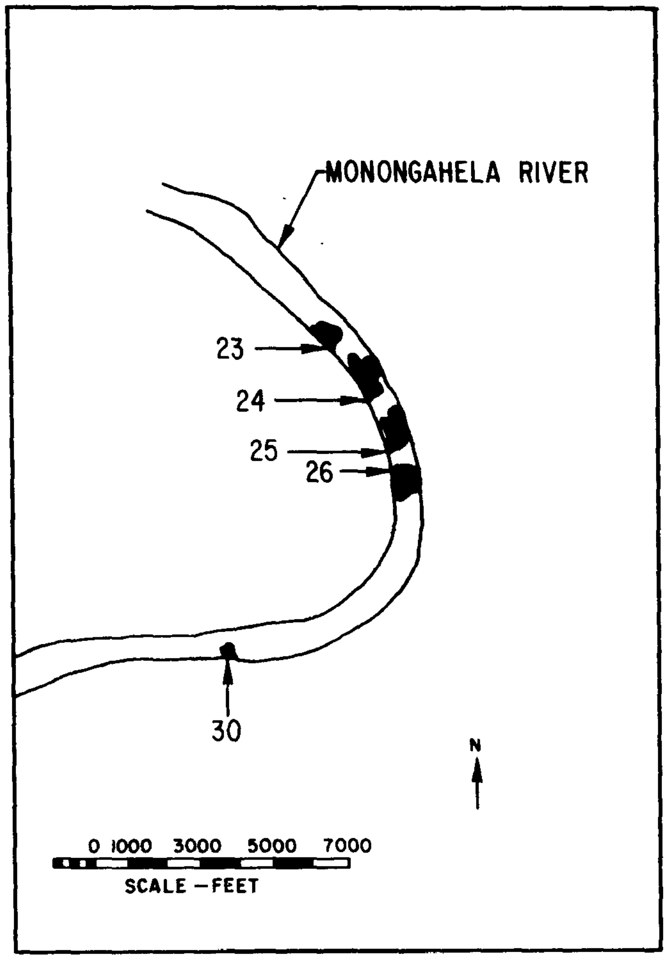

Figure 8.34: Sketch of Thermal Plumes 23-26, 30 on the Monongahela River drawn from Infra-red Photographs of August 25, 1972 (Ref. 18).

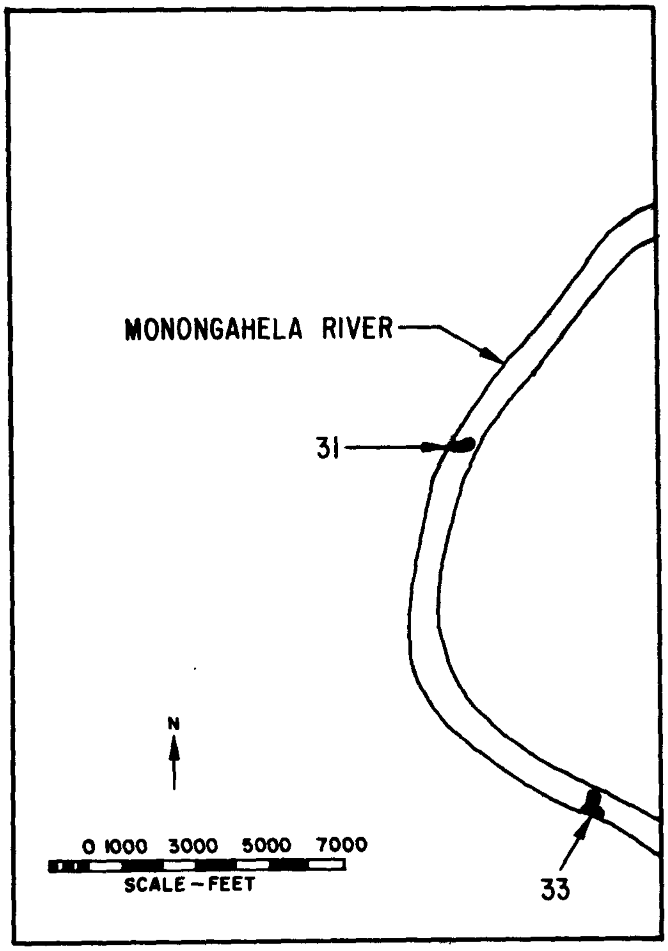

Figure 8.35: Sketch of Thermal Plumes 31, 33 on the Monongahela River drawn from Infra-red Photographs of August 25, 1972 (Ref. 18).

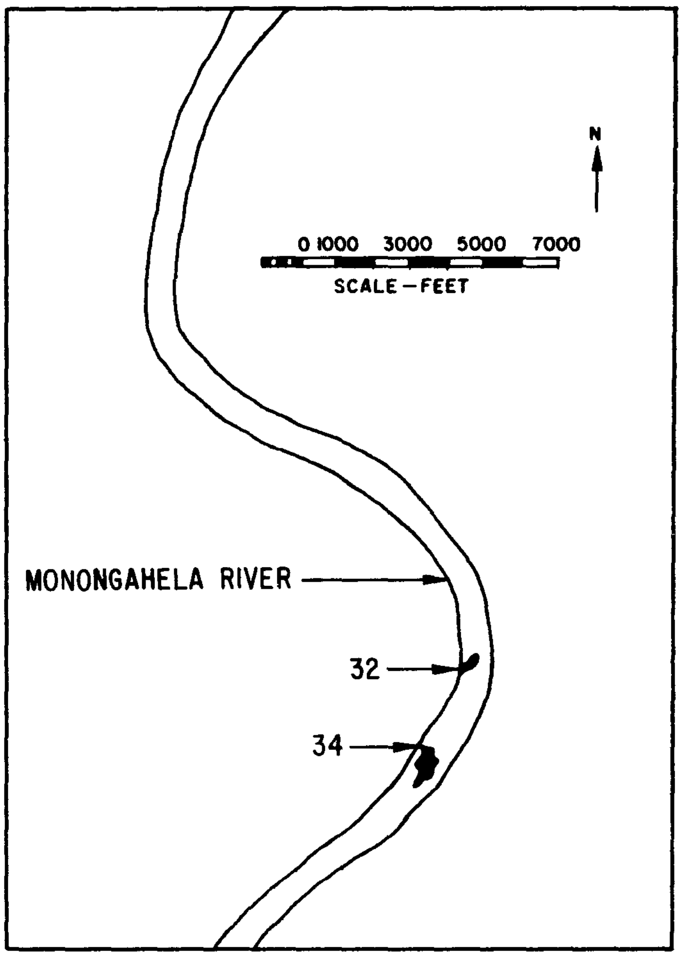

Figure 8.36: Sketch of Thermal Plumes 32, 34 on the Monongahela River drawn from Infra-red Photographs of August 25, 1972 (Ref. 18).

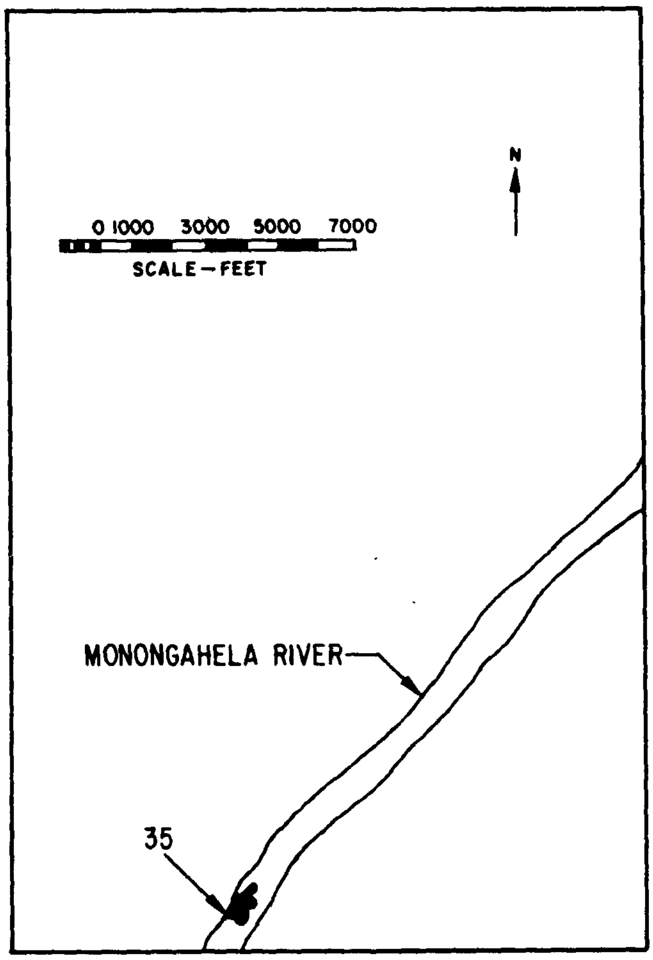

Figure 8.37: Sketch of Thermal Plume 35 on the Monongahela River drawn from Infra-red Photographs of August 25, 1972 (Ref. 18).

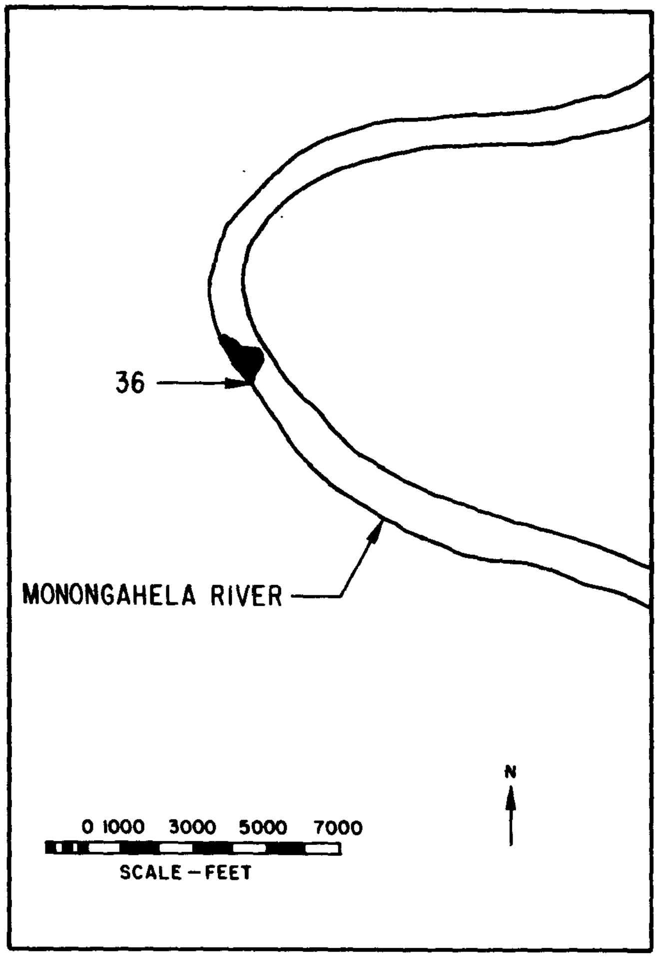

Figure 8.38: Sketch of Thermal Plume 36 on the Monongahela River drawn from Infra-red Photographs of August 25, 1972 (Ref. 18).

On October 3, 1972 a second EPA aerial survey was performed;[19] this time about 500 miles of the Ohio River were photographed. The equipment was essentially the same as that used in the previous survey; again, the results of this survey were not of quantitative value. A list of the plumes seen and their respective time of overflight and location is given in Table 8.15. Observed lengths and widths were calculated from the scale determined from the camera height and the local length of the camera. During most of the flight, the altitude was kept at 5200 feet; however, to observe the plumes more closely, the altitude was lowered to 2500 feet above the river. Sketches of the plumes are shown in Figs. 8.39-8.44. A brief description of each plume is given below:

(1) Sammis Power Plant:

There are three submerged outfalls from the Sammis Power Plant which discharge the heated effluent upstream of the New Cumberland Locks and Dam. The dam serves as an excellent mixer for the heated discharge since all the water that flows over or under the gates of the dam becomes essentially vertically mixed. As can be seen from Fig. 8.39, below the dam there is no measurable temperature gradient. The discharge spreads out both laterally and longitudinally; however, the plume does not reach the far shore.

(2) Cardinal/Tidd Power Plants:

The heated discharge associated with the Cardinal Power Plant has a secondary source, that being the Tidd Power Plant located 1/2 mile upstream from the Cardinal Plant. Both discharges are of surface type; the heated water is inertially driven so that the plume does reach the opposite shore, but the reasonably strong current does convect the plume along shore at distances far from the plant. These plants appear to alter the ambient substantially since there is a distinct temperature contrast between the upstream river water and that located 5 miles below the plant. A third traverse of the plant was made at an altitude of 1000 feet, and at this altitude, clearly discernible wave-like disturbances can be seen. The waves appear to be propagating away from the discharge outlet, but no distinct wavelength is observable.

(3) J. M. Stuart Power Plant:

The Stuart Power Plant has a surface discharge located 4 miles upstream of Maysville, Kentucky. The effluent is first discharged into Little Three Mile Creek which then flows into the river. At

Table 8.15: Index of Thermal Plumes Measured by the Aerial Infra-red Survey of August 25, 1972 (Ref. 18)

Plant	Ohio River Mile Point	Generating Capacity (MWe)	Plume Length (ft)	Plume Width (ft)
W. H. Sammis	55.0	2303.5	2,700	800
Cardinal/Tidd	75.0/74.5	1230.5/226.3	5,100	1,100
J. M. Stuart	405.7	1220.4	10,000	800
W. C. Beckjord	453.3	1220.3	9,000	500
Miami Fort	490.3	393.2	N/A	N/A
Tanners Creek	494.5	1100.3	N/A	N/A

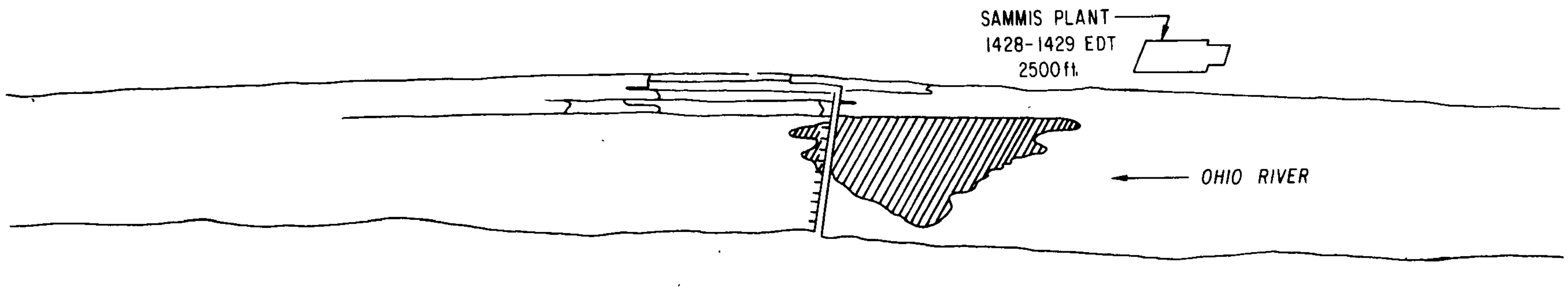

Figure 8.39: Sketch of Thermal Plume from Sammis Power Plant from Infrared Photographs of October 3, 1972 (Ref. 19). Scale: 1 inch = 1000 ft.

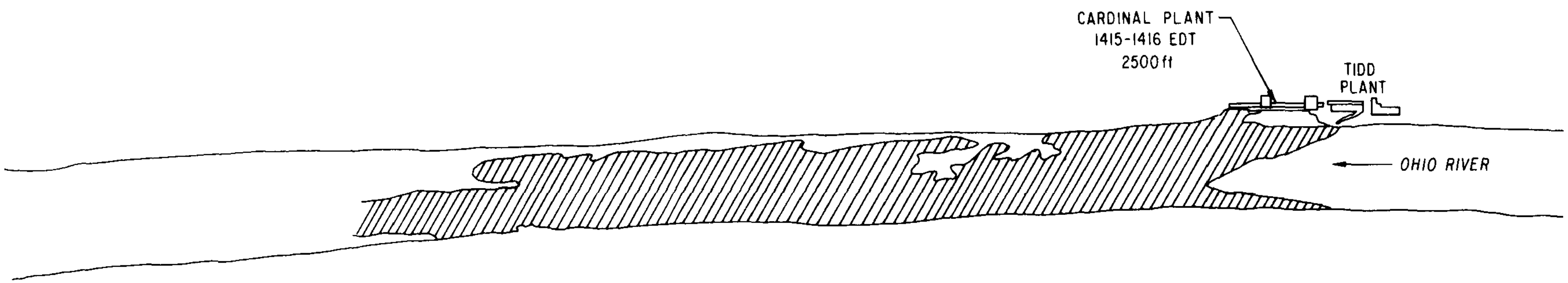

Figure 8.40 Sketch of Thermal Plume from Cardinal-Tidd Power Plants from Infra-red Photographs of October 3, 1972 (Ref. 19). Scale 1 inch = 1000 ft.

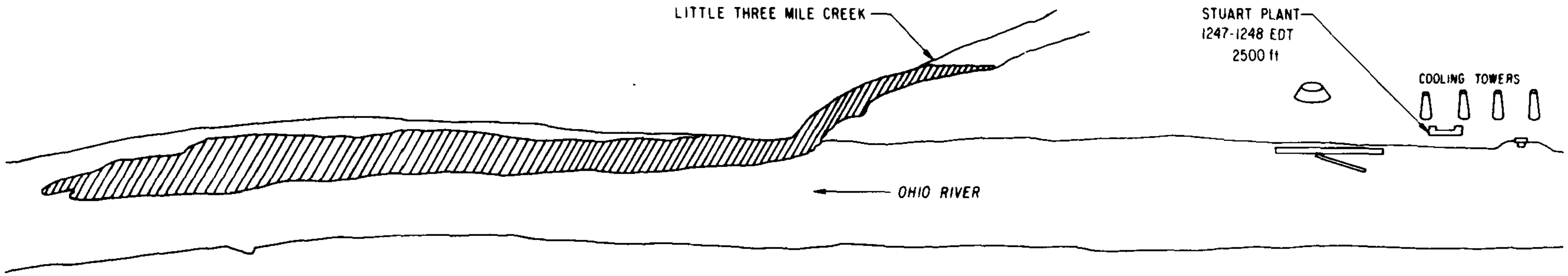

Figure 8.41 Sketch of Thermal Plume from J. M. Stuart Power Plant from Infra-red Photographs of October 3, 1972 (Ref. 19) Scale 1 inch = 1000 ft.

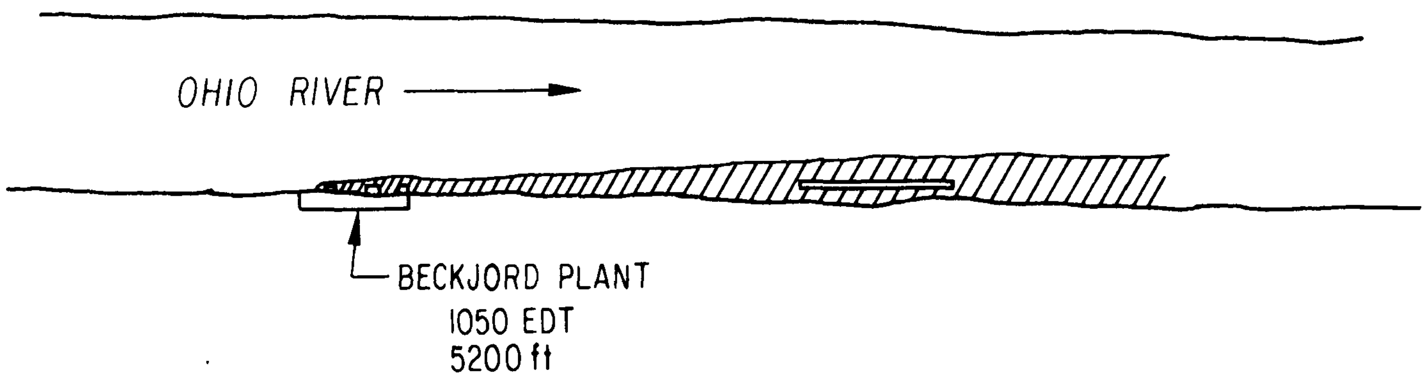

Figure 8.42: Sketch of Thermal Plume from the Beckjord Power Plant from Infrared Photographs of October 3, 1972 (Ref. 19). Scale: 1 inch = 2080 ft.

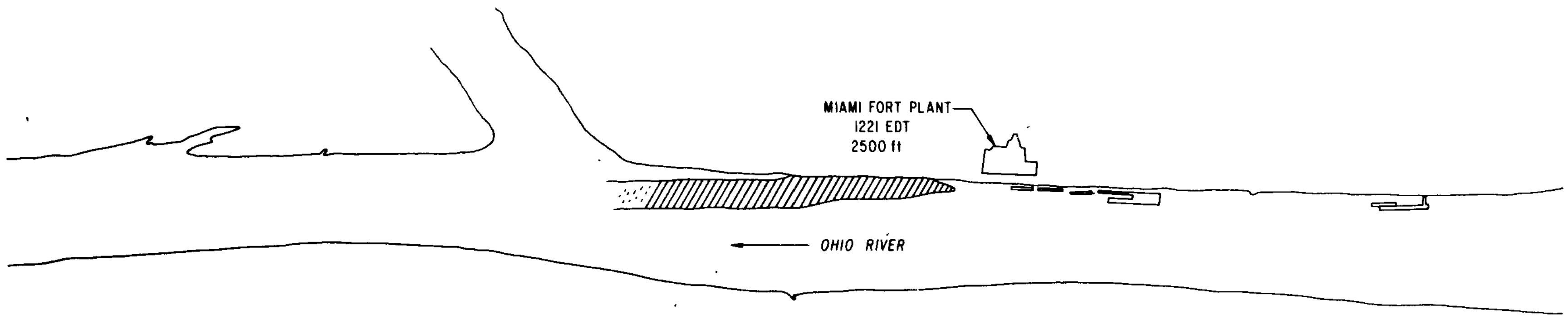

Figure 8.43 Sketch of Thermal Plume from the Miami Fort Power Plant from Infra-red Photographs of October 3, 1972 (Ref. 19) Scale 1 inch = 1000 ft

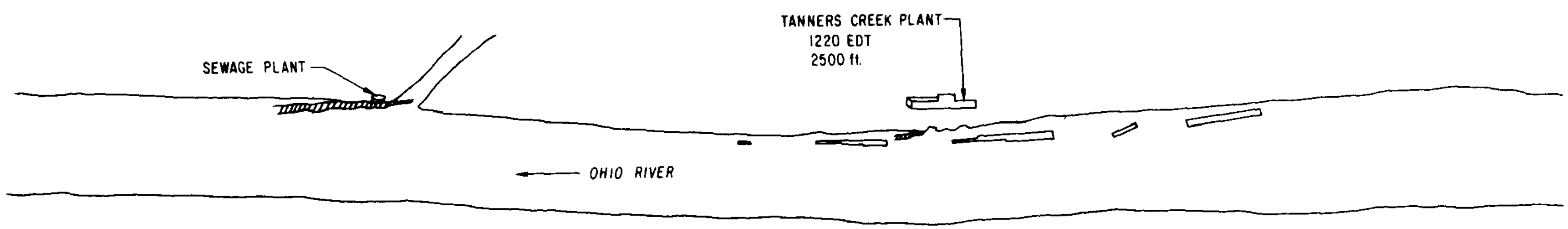

Figure 8.44 Sketch of Thermal Plume from the Tanners Creek Power Plant from Infra-red Photographs of October 3, 1972 (Ref. 19) Scale 1 inch = 1000 ft.

this location, the river flow is rapid enough that the plume does not cross half the width of the river. The river ambient is much lighter at this location, and therefore the full extent of the plume is more difficult to evaluate; however, a clearly defined plume does extend more than 2 miles below the plant.

(4) Beckjord Power Plant:

The Beckjord Power Plant discharges the heated effluent through a pipe on the bottom aligned in the downstream direction. The plant is located 3 miles downstream of New Richmond, Ohio, on the north side of the river. The plume was quite visible and extended downstream for nearly 2 miles, but stayed very close to the shore. In the far field, the plume was difficult to recognize due to contrast with the ambient; if more resolution were available, it is probable that the location of heated waters further downstream would have been more distinguishable.

(5) Miami Fort Power Plant:

The Miami Fort Power Plant consists of a submerged discharge about 500 feet downstream of the power plant. The plume was extremely difficult to discern since the ambient river temperature was quite warm and, therefore, the river color quite light. The Great Miami River discharges cold water into the Ohio River 2 miles downstream of the power plant. That discharge was clearly visible with respect to the warmer Ohio River.

(6) Tanners Creek Power Plant:

The Tanners Creek Power Plant is located 4 miles downstream of the Miami Fort Plant. Similar to Miami Fort, the discharge from Tanners Creek is submerged, and is released very close to the bottom of the river. On this survey, only a small plume was observed whose origin could be traced to the Tanners Creek area. A plume was located emanating from Tanners Creek, but that location corresponds to the Lawrenceburg Sewage Treatment Plant outfall.

As was mentioned earlier, usual thermal scanning techniques are capable of measuring temperatures to within 0.5°C, yet no quantitative results were evidenced from these surveys. A brief description of the difficulties encountered are given below:

(1) This scanner does not take reference temperatures on each transect of the plume, rather, it takes a reference at the beginning of the flight.

(2) Because these photographs were reproduced electrically from a pre-amplified signal, they are subject to inherent electrical noise during amplification. Recent techniques save the pre-amplified signal for later processing.

(3) Errors associated with sinuous flight paths and changes in altitude cause distortions, evidenced by the lack of clarity away from the center of the photograph.

(4) In addition, poor weather conditions, flight procedures and operation of the scanner all cause additional inaccuracies in the measurements.

It is believed that the EPA-NERC procedures can be modified[18,19] to perfect the technique to give quantitative results, hopefully, near the theoretical limit of .5°C; as to this report, qualitative differences are all that have any significance.

8.3 The J. M. Stuart Power Station Controversy[20-23]

The Dayton Power and Light Company of Dayton, Ohio presently has three fossil-fueled plants in operation discharging into Little Three Mile Creek just before that Creek enters the Ohio River. The Federal EPA feels that biological damage has already occurred in Little Three Mile Creek even before the third unit went into operation, and that a company proposal to transfer the three unit discharge to the Ohio River will not satisfy Ohio temperature standards.[21] At the time EPA recommended that the following criteria be met:[21]

(1) a 600 foot mixing zone beyond which temperatures must not exceed a 5°F temperature excess,

(2) a set of monthly maximum temperatures that cannot be exceeded beyond the mixing zone,

(3) a passageway for fish which should contain preferably 75% of the cross-sectional area and/or volume of flow of the stream, and

(4) a minimal temperature rise at the Beckjord Plant 47.3 miles downstream.*

*It should be noted that Ohio water quality standards have been substantially changed since this controversy.

The Power Company with their consultants WAPORA, Inc. argues that the removal of the three-unit heated discharge from Little Three Mile Creek to the Ohio River by means of a submerged discharge will satisfy Ohio temperature standards. A sketchy EPA field survey[14] taken October 3, 1972 showed that about 2500 ft downstream of the Little Three Mile Creek - Ohio River confluence, the temperature excess was 4.5°F. Clearly, existing temperature standards were being violated by discharging the three unit effluent into Three Mile Creek.

Argonne National Laboratory was requested to review the controversy and evaluate the WAPORA and ORSANCO modeling efforts in this regard.

Conditions at the Stuart site used in the mathematical modeling are given in Table 8.16. Information on maximum permissible temperatures for the river with and without the heated discharge is given in Table 8.17 along with observed maximum daily temperatures and minimum daily flows near the Stuart site. Column 4 of Table 8.17 evaluates the increased river temperature if the discharged heat from the Stuart Plant is fully mixed with the river flow. Column 5 compares those maximum temperatures to the permissible monthly maximum temperatures required by ORSANCO and the EPA.

After evaluating several alternative designs, WAPORA suggests an 800 foot line diffuser with 11 circular ports of 4 foot diamter with a port spacing of 80 feet. Each port will be discharging in the direction of the river flow. This choice was made to prevent interference between jets which would cause re-entrainment and inefficient dilution. WAPORA used the Hirst model[24] to justify their conclusion that the above diffuser will satisfy the temperature standards. The results of the Hirst model application is given in Table 8.18 and Figs. 8.45-8.52. Plotted is the centerline trajectory, time of travel, and isotherms in the vertical section through the orifice centerline. Table 8.19 summarizes the percent of river cross section area

Table 8.16: River and Plant Data Required for Modeling the Stuart Discharge[20a]

River Flow:

Critical:	9,700 cfs	(ORSANCO data)
Average:	91,000 cfs	(USGS data)

Plant Flow:

Units 1 and 2:	1004 cfs
Units 1, 2, 3:	1506 cfs

Temperature Rise Across Condensers:

23.2°F

Ambient Surface Water Temperature:

Non Stratified:	69.3°F (ORSANCO data)
Stratified:	84.4°F

Ambient Bottom Water Temperature for Stratified Case:

78°F

Linear Temperature Stratification (for sample stratified case only):

$$\frac{1}{\rho_a}\frac{d\rho_a}{dz} = 5 \times 10^{-5}\ ft^{-1}$$

Average Width of River: 1600 ft

Average Depth of River: 33 ft

Depth of River at Point Of Discharge: 41 ft

Average River Cross Section: 53,000 ft^2

Table 8.17: Analyses of Maximum Mixed Temperature Rise[20c]

	Maximum Daily Temperature at Cincinnati, °F	Minimum Daily Flow (cfs) Maysville, Kentucky	Mixed Temperature Rise,* °F	Maximum Temperature,** °F	Permissible Temperature,*** °F
January	46.9	25,000	1.4	48.3	50
February	46.9	20,000	1.8	48.7	50
March	53.3	27,000	1.3	54.6	60
April	64.0	50,000	0.7	64.7	70
May	75.6	25,000	1.4	77.0	80
June	81.9	17,000	2.1	84.0	87
July	85.0	15,800	2.2	87.2	89
August	84.3	9,500	3.7	88.0	89
September	82.8	9,000	3.9	86.7	87
October	75	6,300	5.6	80.6	78
November	69	7,400	4.7	73.7	70
December	56.6	13,000	2.7	59.3	57

*Using minimum flow

**Using minimum flow and maximum water temperatures

***ORSANCO Pollution Control Standard No. 2-70

Table 8.18: Solution of Hirst Model[20a]

Case No.	Jet Axis Distance from Discharge, ft	x, Horizontal Distance, ft	z, Vertical Distance ft	Dilution	Temperature Rise**	Jet Half-Width, ft	Analysis Condition*
9	56.1	34.2	38.8	.114	2.5	10.1	N-C -U3-D4
10	38.7	29.4	21.8		.3	5.9	S-C -U3-D4
11	70.6	58.4	37.3	.025	.6	24.5	N-N1-U3-D4
12	41.9	35.8	19.8		.0	7.8	S-N1-U3-D4
13	53.9	28.5	40.8	.078	1.7	12.2	N-C -U2-D4
14	32.0	22.9	19.6		-1.5	5.8	S-C -U2-D4
15	83.4	72.1	40.4	.017	.4	25.4	N-N1-U2-D4
16	34.6	29.8	16.4		-1.2	7.4	S-N1-U2-D4

* N - Non-stratified intake temperature = 69.3°F

S - Stratified, intake temperature = 78°F, Surface temperature = 84.4; $\frac{1}{\rho_a}\frac{d\rho_a}{dz} = 5 \times 10^{-5}\ ft^{-1}$

C - Critical river flow = 9300 cfs

N1 - Normal river flow = 91000 cfs

U3 - No. of units = 3

U2 - No. of units = 2

D14 - Diameter of discharge = 14'

D4 - Diameter of discharge = 4'

**ΔT above intake temperature, °F at surface or equilibrium location

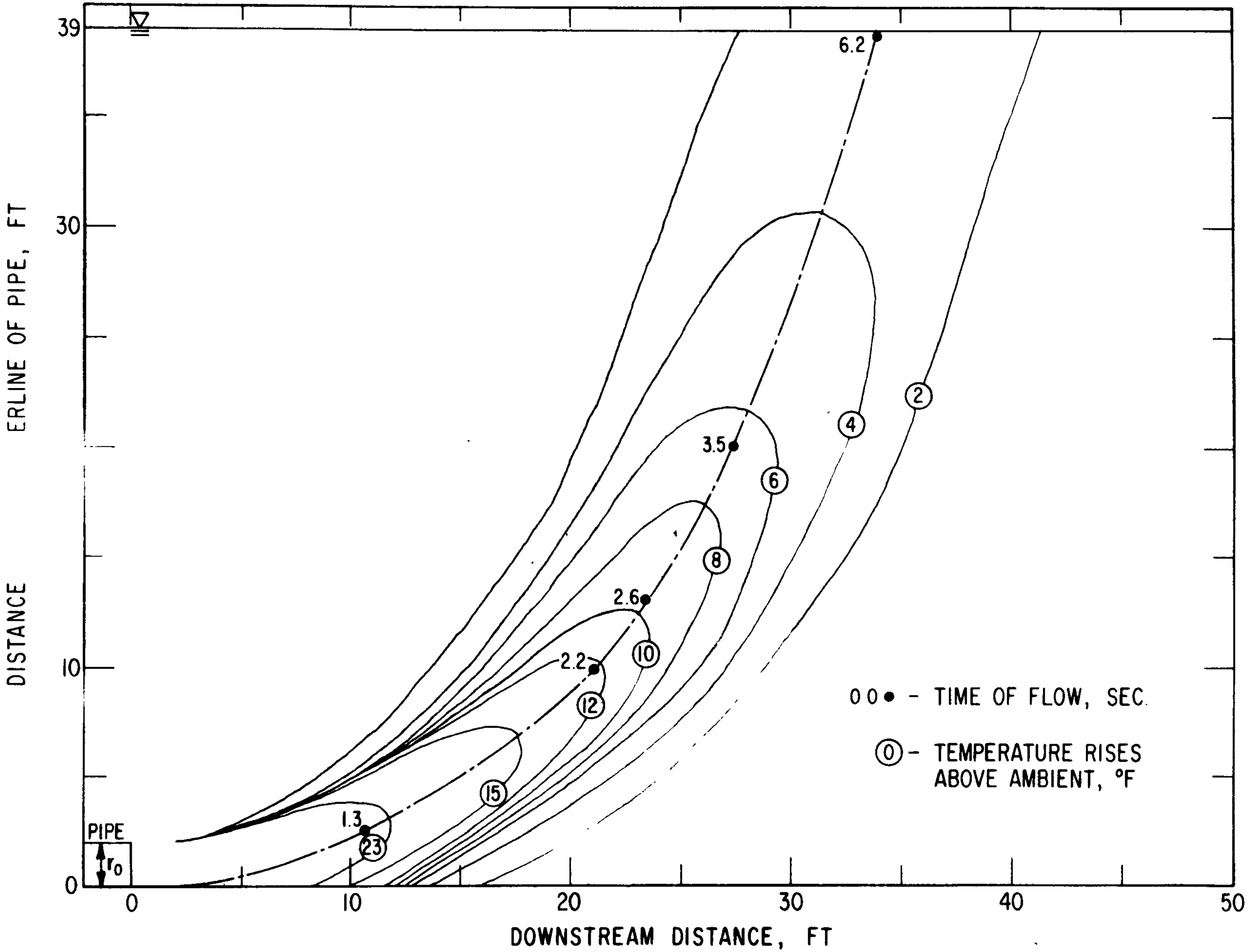

Figure 8.45:

WAPORA Application of Hirst Model to J. M. Stuart Plant, Case 9 (3 units non-stratified ambient, critical river

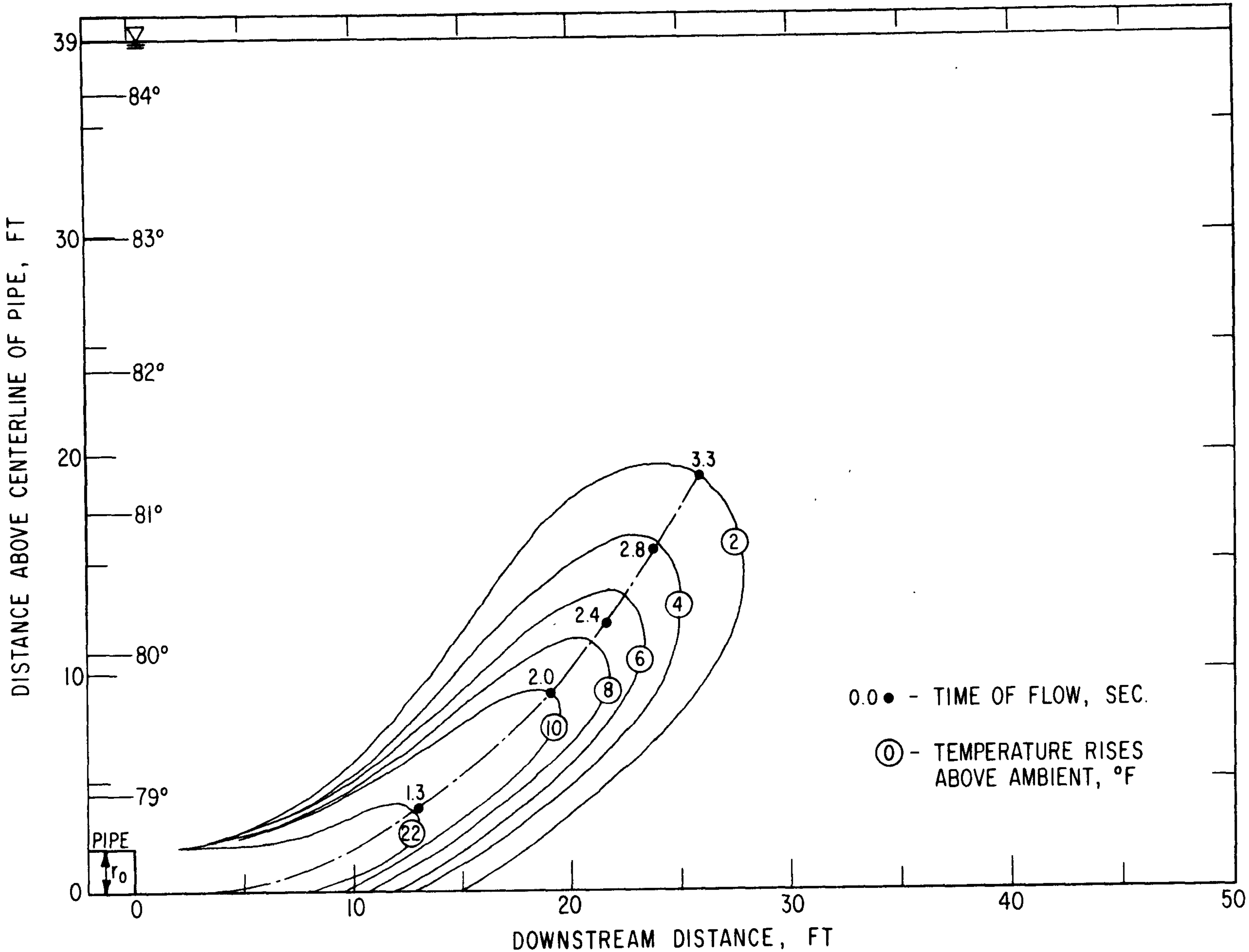

Figure 8.46:

WAPORA Application of Hirst Model to J. M. Stuart Plant, Case 10 (3 units, stratified ambient, critical river flow)[20b]

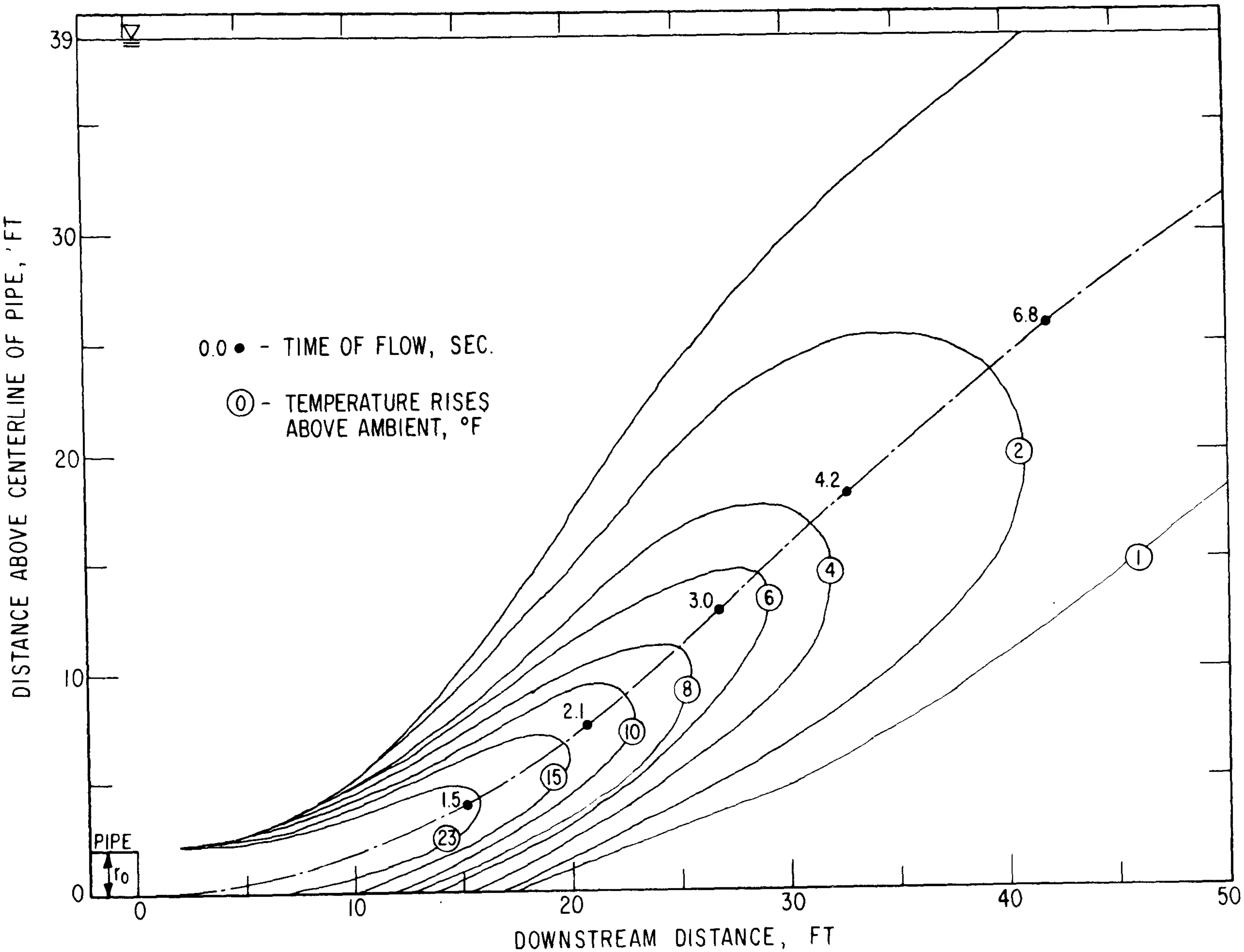

Figure 8.47:

WAPORA Application of Hirst Model to J. M. Stuart Plant, Case 11 (3 units, non-stratified ambient, normal river flow)[20b]

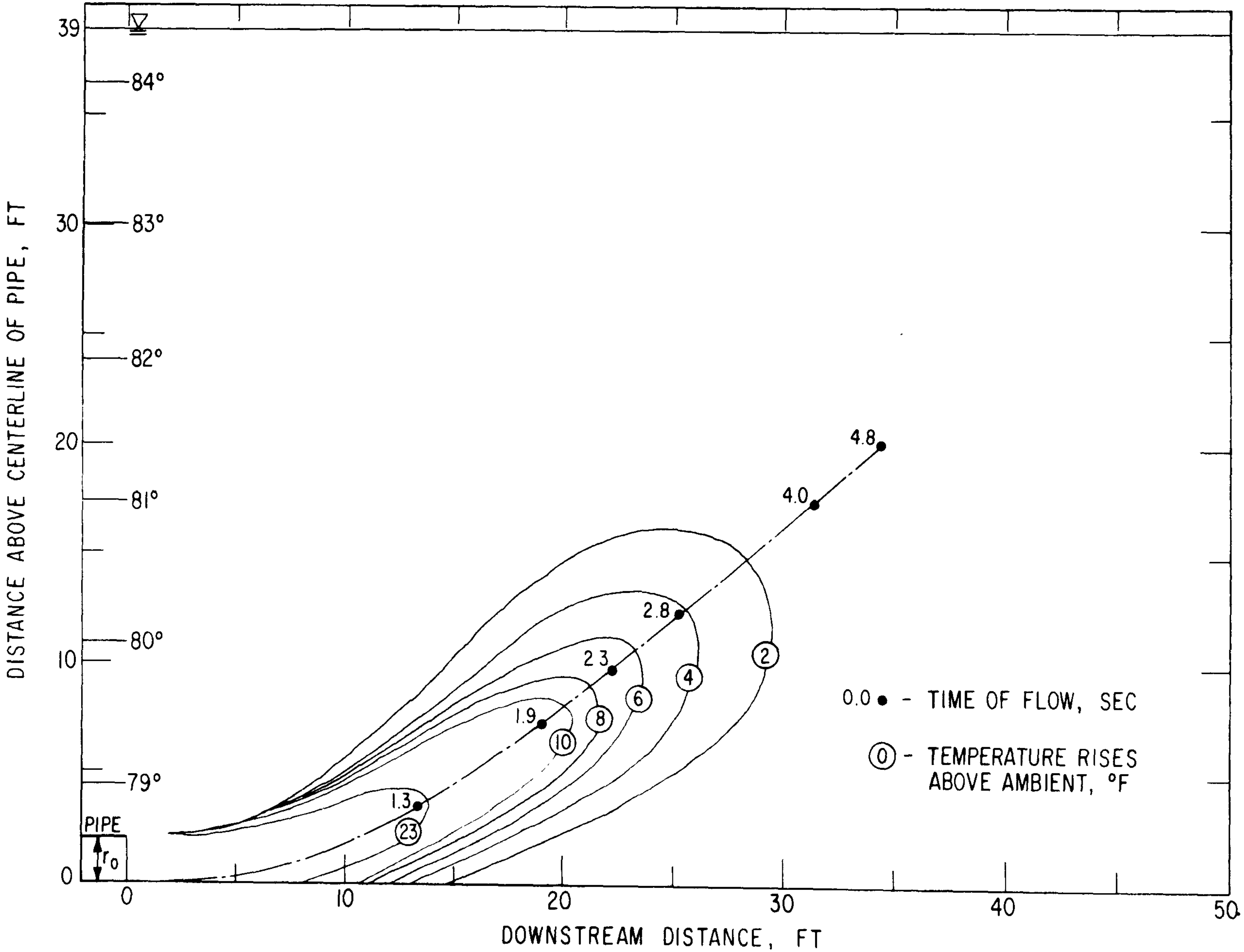

Figure 8.48: WAPORA Application of Hirst Model to J. M. Stuart Plant, Case 12 (3 units, stratified ambient, normal river flow)20b

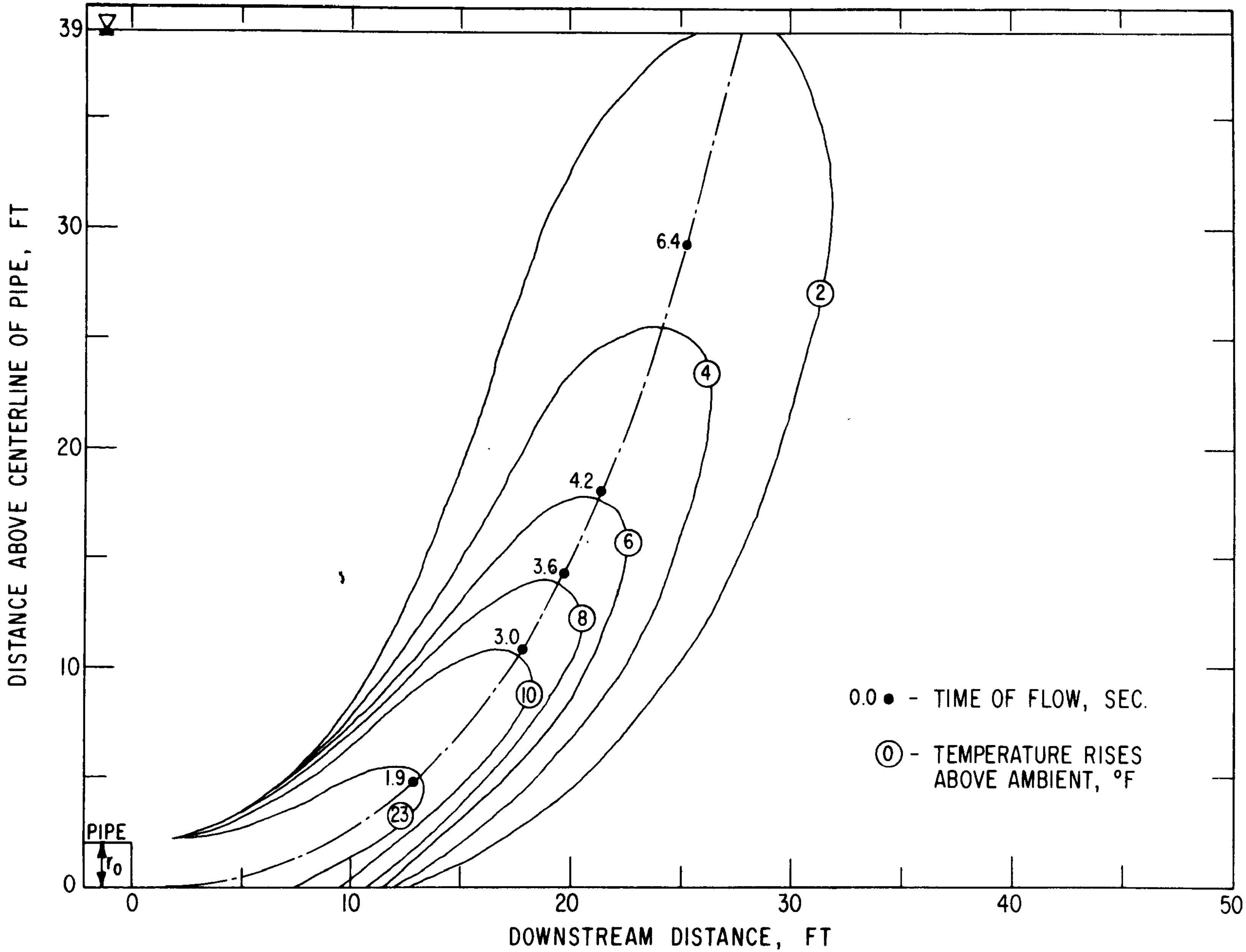

Figure 8.49: WAPORA Application of Hirst Model to J. M. Stuart Plant, Case 13 (2 units, non-stratified ambient, critical river flow)[20b]

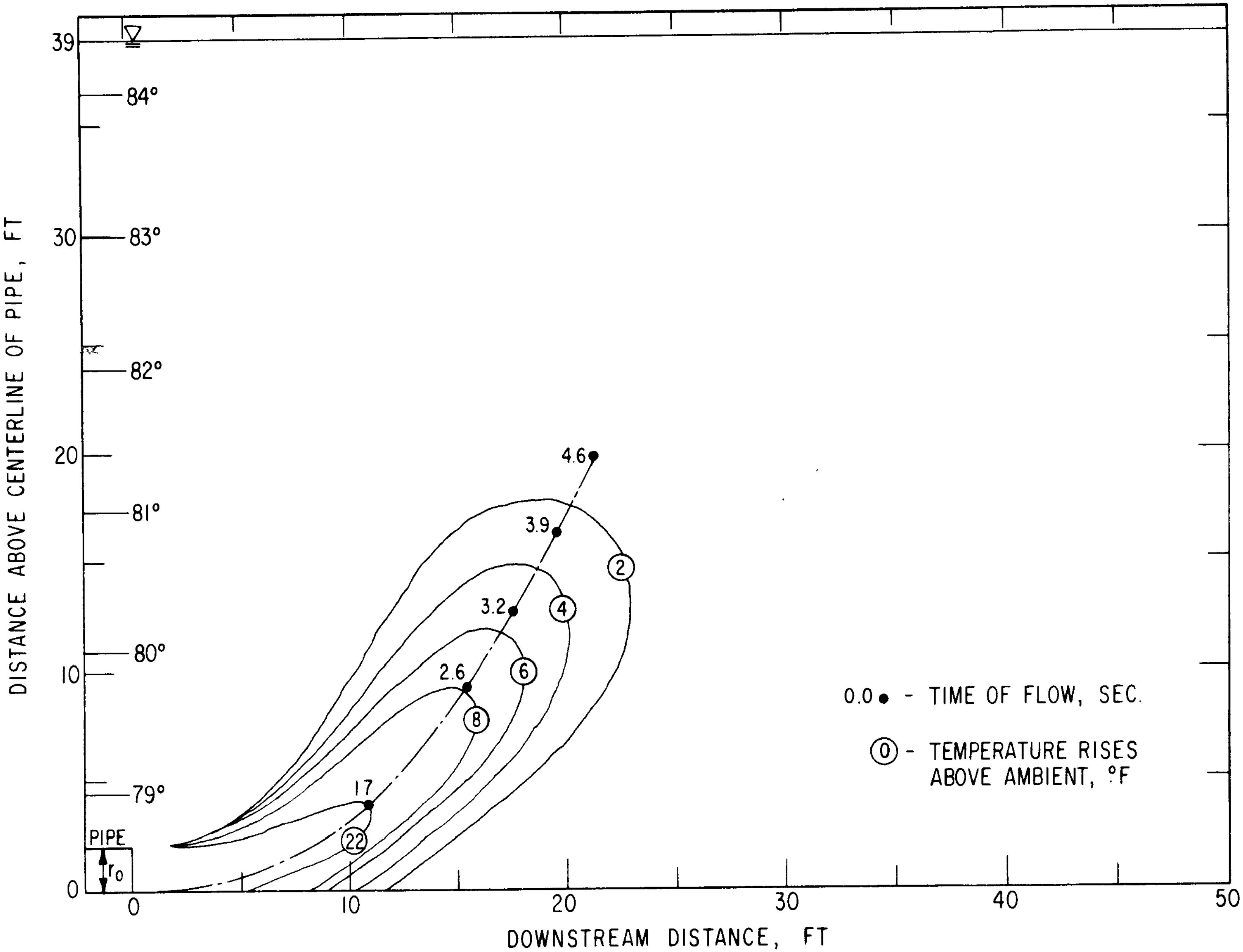

Figure 8.50:

WAPORA Application of Hirst Model to J. M. Stuart Plant, Case 14 (2 units, stratified ambient, critical river

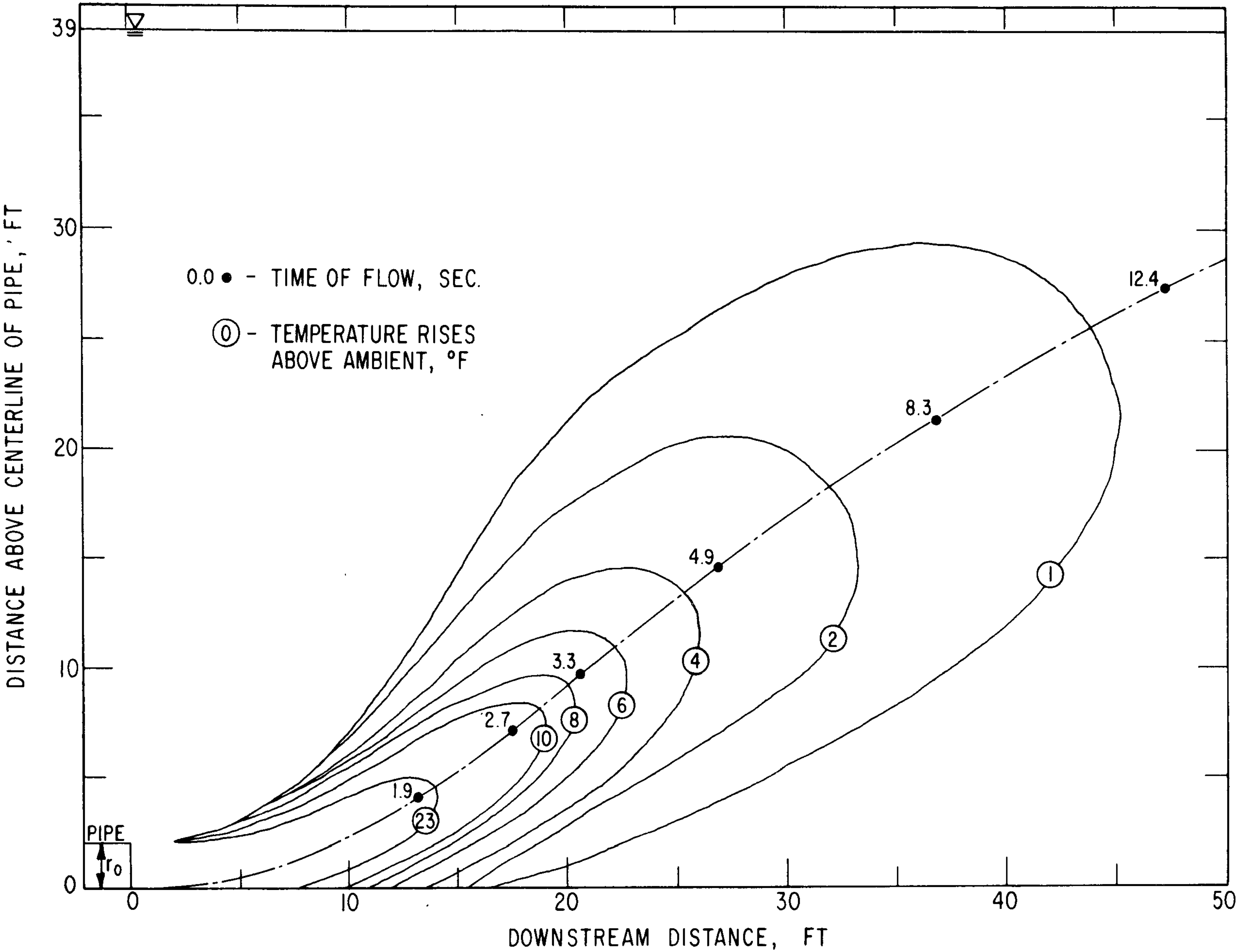

Figure 8.51:

WAPORA Application of Hirst Model to J. M. Stuart Plant, Case 15 (2 units, non-stratified ambient, normal river flow)[20b]

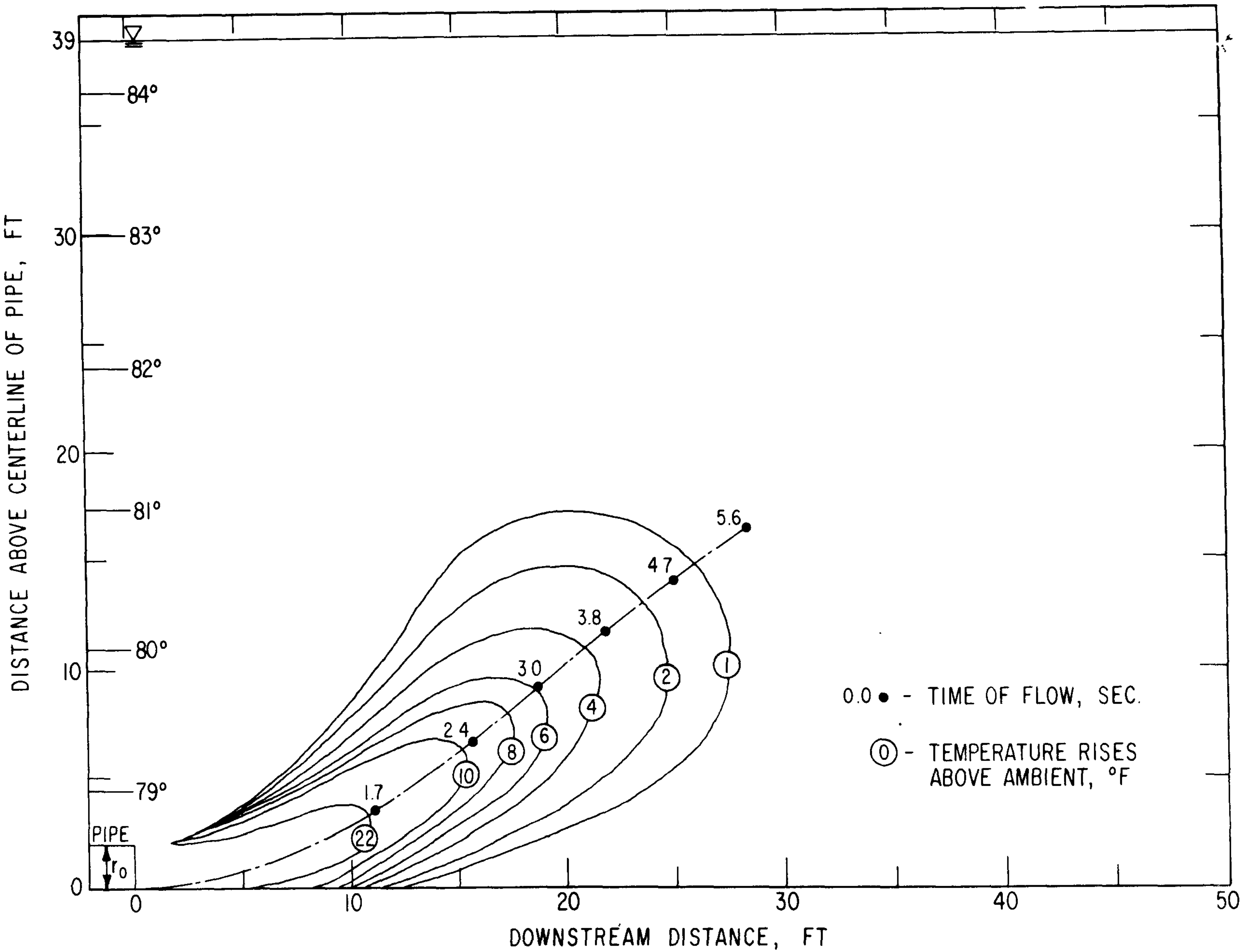

Figure 8.52:

WAPORA Application of Hirst Model to J. M. Stuart Plant, Case 16 (2 units, stratified ambient, normal river flow)[20b]

Table 8.19: Percentage of River Cross-Sectional Area Occupied by the 5°F Isotherm for the Diffuser Proposed by WAPORA[20b]

Case	Percent of Cross-sectional Area Greater than 5°F Temperature Excess
9	5.5
10	3.1
11	4.4
12	2.2
13	4.7
14	2.4
15	2.9
16	1.8

that is above 5°F rise (the mixing zone criterion). The areas indicated are substantially less than 25% of the river cross section. It is stated[29a] that this design will meet the maximum temperature rise criteria but not the maximum absolute temperature on those days when the ambient water temperature is close to the permissible maximum temperature as given in Table 8.16. WAPORA indicates that the above results show feasibility of a diffuser system to satisfy state and federal requirements but that design optimization is required before construction is authorized.

The results of the WAPORA calculation seem reasonable; however, the Hirst model is not strictly valid in this case. First, the Hirst analysis assumes no boundary interference either from a river bottom or the river surface. As seen in Figs. 8.45-8.52, the discharge is directed from the bottom and consequently a cutoff of dilution water will occur and alter the mixing and trajectory of the plume. Surface temperatures calculated also assume an infinite ambient water body with dilution water coming from above the river surface. The predictions of the Hirst model are not conservative but optimistic in the light of boundary interferences.

Secondly, the Hirst model has been improved upon by Shirazi, Davis and Byram[25a,b] in which the effects of ambient turbulence were added to the model. Hydraulic model studies by McQuivey, Keefer, and Shirazi[26] showed that the effects of ambient turbulence in a coflow discharge increased mixing in an important way. The Hirst model used by WAPORA did not include ambient turbulence in the differential equations. Moreover, the Hirst model gave an opposite trend in centerline temperature decay than was indicated by the data in coflow cases like the J. M. Stuart problem (centerline temperature increased with increasing densimetric Froude number of discharge for coflow cases instead of decreasing as was indicated by the data). The two difficulties with the Hirst model (in coflow situations) were remedied in the improved version of the model published by Shirazi, Davis, and Byram. The above difficulties with the Hirst model add additional uncertainties to WAPORA's predictions.

Thirdly, WAPORA applies the Hirst model for cases of current and stratification. There is presently almost no experimental data with current and stratification to verify Hirst's model. Consequently, the results of the model for those cases (cases 10, 12, 14, and 16) are open to question.

In the face of these uncertainties to WAPORA's use of the Hirst model, it would be useful to recalculate model predictions based upon the improved Hirst simulation done by Shirazi, Davis, and Byram. More importantly, however, the undertaking of hydraulic model tests to verify the feasibility of a diffuser discharge in satisfying mixing zone and zone of passage criteria would be useful. This model study would eradicate many of the doubts in the application of the Hirst model. If feasibility is demonstrated in the hydraulic model, optimality would be easier to establish. All this assumes that the frequency of violation of the maximum monthly temperatures, which will occur, is satisfactory to the EPA.

Concerning the temperatures occurring at the Beckjord Plant 47.3 miles downstream, three methods have been used for that calculation. The first and most correct is the energy budget approach in which a one-dimensional fully-mixed heated discharge is assumed. The heat is lost to the atmosphere by surface cooling and is determined from meteorological parameters. WAPORA used Thackston and Parker[27] for the heat transfer coefficient, K, and employed a steady-state heat budget model[20a] to determine temperatures at Beckjord. Based upon K values of 145 in July, 98 in November, 131 in July for extreme conditions, this results in corresponding 1.4°F, 1.6°F, and 1.9°F temperature increase at Beckjord. More precise results might have been obtained using a more dynamic model like COLHEAT or the transient version of the Edinger-Geyer approach due to the large travel-time from the J. M. Stuart to the Beckjord Plant. Also, use of the equilibrium temperature instead of the natural temperature as a base for heat losses is more accurate.

The second approach recommended by WAPORA is the Le Bosquet method[28] for determination of K. Tichenor and Shirazi criticize[22b] this method since the Le Bosquet's K values are determined from field data in which the difference in temperature between water and air is assumed to be the driving force for surface cooling. They state that Le Bosquet's equation for K is not applicable to the standard exponential temperature decay model (used by WAPORA) which uses equilibrium temperature. Thus the higher values of K recommended by Le Bosquet (since air temperature is usually lower than equilibrium temperature) cannot be used to predict a lower excess temperature at the Beckjord Plant.

The third approach is that employed by ORSANCO in which they use[23a] their own exponential decay formula for temperature excesses applied to the river reach between the J. M. Stuart to the Beckjord Plant. Manipulating their exponential decay formula into the more standard heat budget formulation one can see[20c] that an unrealistically high value of surface heat transfer coefficient was being used by ORSANCO, which would underpredict temperature rises downstream. Also, the ORSANCO model uses a formula which is independent of meteorological conditions which cannot be correct.

At the present time, all three units of the J. M. Stuart Plant are discharging into Little Three Mile Creek. Since the heat input into the Creek and, therefore, into the Ohio River is the same as if a diffuser were installed in the Ohio, boat measurements at the Beckjord site can presently determine the effect on river temperature there due to the upstream Stuart site. Taking temperature measurements at Beckjord when one, two, and three units are operating at Stuart would clearly be the best approach. Verifying or improving one of the above models for downstream temperature prediction would then allow the prediction of temperature at arbitrary power levels and river flows.

The best of the above model formulations is the first one although improvements on that could be affected. An increase in temperature on the order of 2°F needs to be judged by EPA as satisfactory if the three unit J. M. Stuart Plant is to be given a permit for once-through cooling.

In summary our recommendations are as follows:

(1) Although the application of the Hirst model by WAPORA is reasonable, predictions should be recalculated based upon the improved version of the Hirst model developed by Shirazi, Davis, and Byram.

(2) Hydraulic model studies should be undertaken to properly ascertain the effects of the free surface and bottom. Recirculation of heated water due to constraining boundaries can then be better assessed. Hydraulic model studies can better test feasibility of the WAPORA design in meeting state and federal standards as well as provide a tool for optimization of that design.

(3) A more dynamic model could be applied over the 47.3 mile reach between the Stuart and Beckjord Plants to better assess the effects of the Stuart Plant on the downstream Beckjord Plant. More directly, boat measurements at the Beckjord site can presently determine the effect of the upstream J. M. Stuart Plant; one, two, and three units; since all three units are in operation at this time. A verified model can predict the frequency of excess temperatures at the Beckjord sites under different plant and river flow conditions.

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Appendix A

Statistical Analysis

The river temperatures computed by each of the models were compared with the river temperatures measured at the four temperature measurement stations used in this study (see Section 6). Figures A.1 and A.2 show the frequency distributions of the difference between observed and computed temperatures for each model at each station. These figures also show the mean and the standard deviation of the distribution as well as the number of sample points compared at each station.

The computational procedure used to obtain these statistical parameters was as follows:

For the mean, μ

$$\mu = \frac{\sum_{\alpha=1}^{N} d_\alpha}{N} \tag{A.1}$$

where

N = Number of sample points

$d_\alpha = T_C - T_M$, the temperature difference

and

T_C = Computed temperature

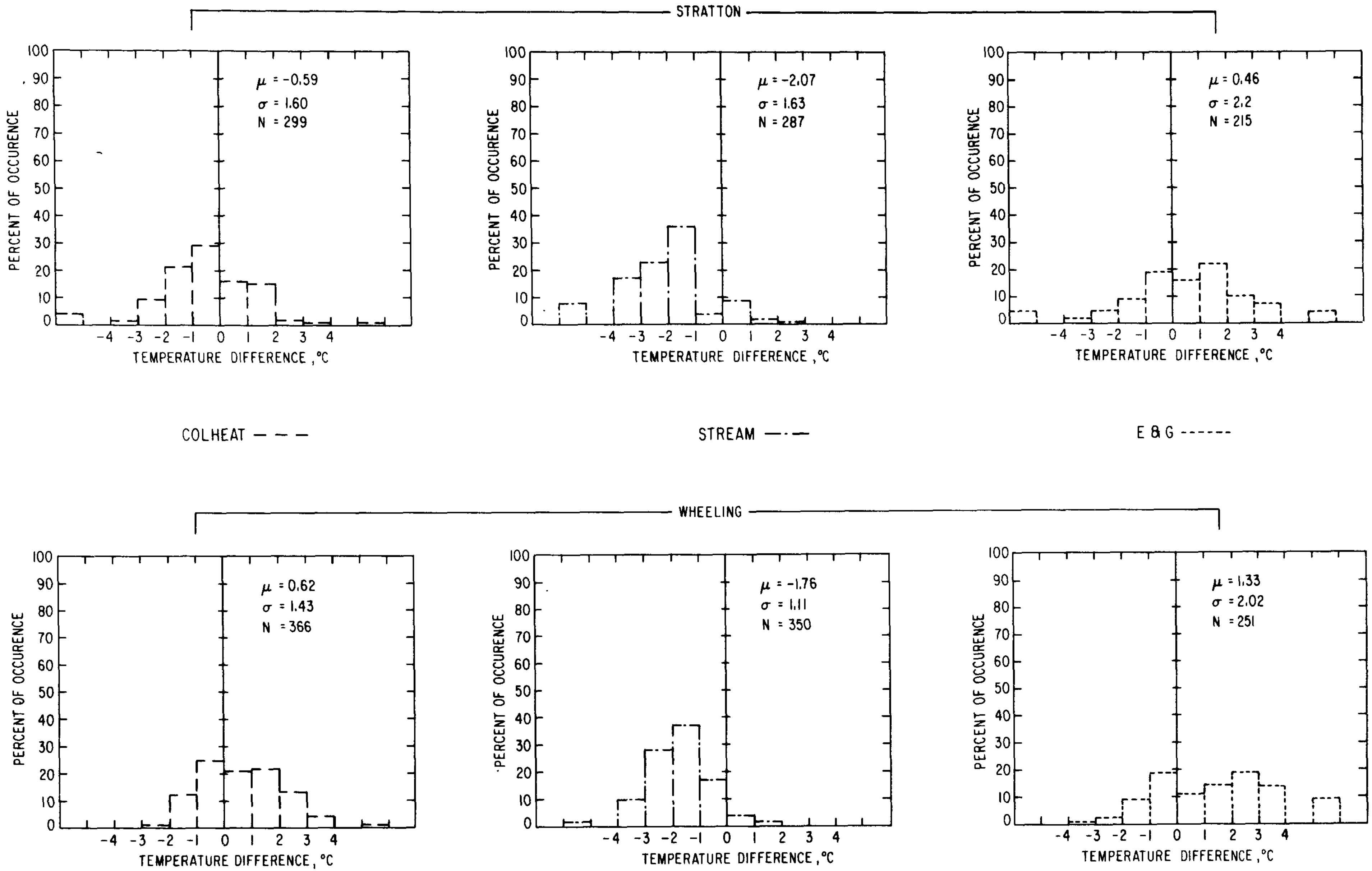
T_m = Measured temperature

The standard deviation, σ, is given by

$$\sigma = \sqrt{\frac{S}{N-1}} \tag{A.2}$$

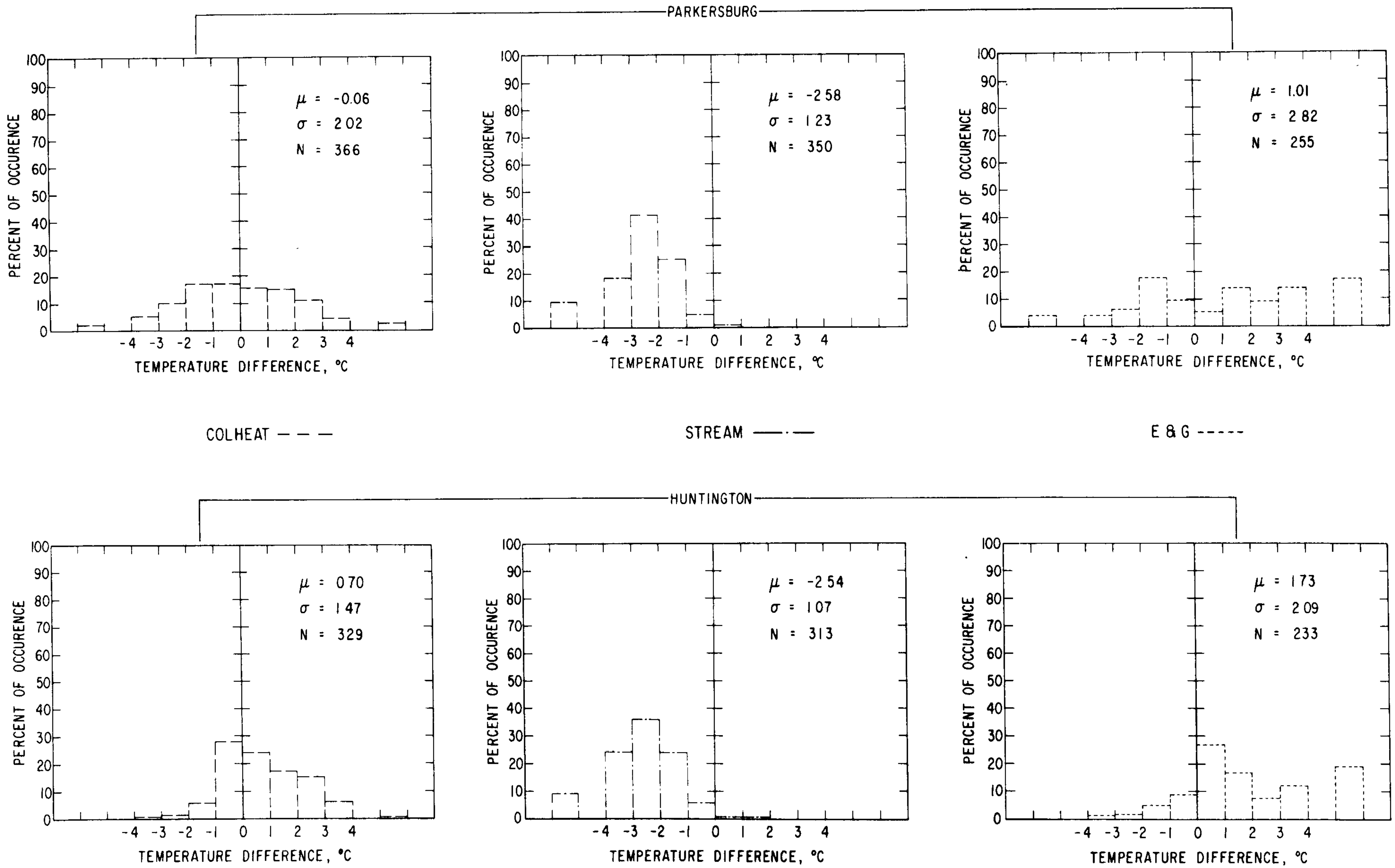
where

$$S = \sum_{\alpha=1}^{N} (d_\alpha - \mu)^2 - \frac{\left[\sum_{\alpha=1}^{N} (d_\alpha - \mu)\right]^2}{N} \tag{A.3}$$



STRATTON
WHEELING
μ = -0.59
σ = 1.60
N = 299
μ = -2.07
σ = 1.63
N = 287
μ = 0.46
σ = 2.2
N = 215
μ = 0.62
σ = 1.43
N = 366
μ = -1.76
σ = 1.11
N = 350
μ = 1.33
σ = 2.02
N = 251
PERCENT OF OCCURENCE
TEMPERATURE DIFFERENCE, °C
COLHEAT — — —
STREAM —·—
E & G ------

Figure A.1



PARKERSBURG
HUNTINGTON
PERCENT OF OCCURENCE
TEMPERATURE DIFFERENCE, °C
μ = -0.06
σ = 2.02
N = 366
μ = -2.58
σ = 1.23
N = 350
μ = 1.01
σ = 2.82
N = 255
COLHEAT
STREAM
E & G
μ = 0.70
σ = 1.47
N = 329
μ = -2.54
σ = 1.07
N = 313
μ = 1.73
σ = 2.09
N = 233

Figure A.2

A linear regression analysis was performed on the data of each scatter diagram shown in Section 6. These scatter diagrams plot measured temperatures on the horizontal axis and computed temperatures on the vertical axis for each model at each temperature measurement station. The linear regression analysis determines a line that best fits* the data and which represents a functional relationship between the measured and computed temperature.

The regression coefficients, intercepts and correlation coefficients are computed as follows: First the sum of the cross products of the deviations from the mean, S_{mc}, is computed from

$$S_{mc} = \sum_{\alpha=1}^{N} (T_{c\alpha} - \bar{T}_c)(T_{m\alpha} - \bar{T}_m) - \frac{\sum_{\alpha=1}^{N} (T_{c\alpha} - T_c) \sum_{\alpha=1}^{N} (T_{m\alpha} - \bar{T}_m)}{N} \quad \text{(A.4)}$$

where

$\bar{T}_m$ denotes the mean of the measured temperatures at a station.

T_c denotes the mean of the computed temperatures at a station for a model

Next, S_{mm} is found by substituting T_m for T_c in (A.4). The slope, G_{mc}, of the regression line is given by

$$G_{mc} = \frac{S_{mc}}{S_{mm}} \quad \text{(A.5)}$$

---

*By "best fit" is meant the line that has the property that the sum of the squares of vertical deviations of observations from this line is smaller than the corresponding sum of squares of deviations from any other line. See R. L. Wine, Statistics for Scientists and Engineers. Prentice-Hall, Englewood Cliffs, N.J., 1964, for further amplification.

and the intercept, a_{mc} by

$$a_{mc} = \overline{T}_c - G_{mc} \overline{T}_m \tag{A.6}$$

Finally, the correlation coefficient is calculated

$$r_{mc}^2 = \frac{S_{mc}^2}{S_{mm} S_{cc}} \tag{A.7}$$

where S_{cc} is found in (A.4) by substituting T_c for T_m.

The regression line for each model at each temperature measurement station and its correlation coefficient are shown in Fig. A.3.

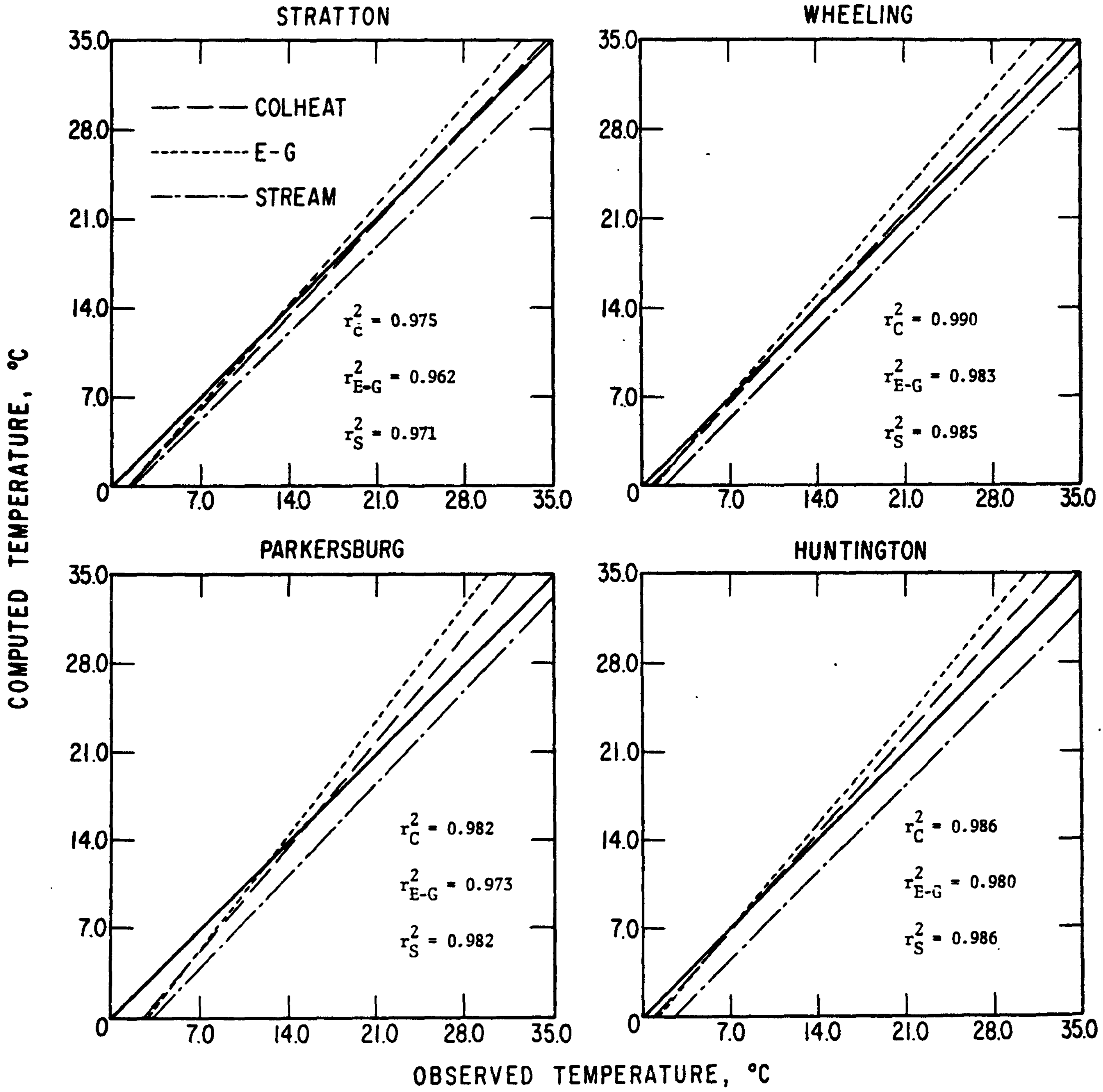

STRATTON
COLHEAT
E-G
STREAM
r_C^2 = 0.975
r_{E-G}^2 = 0.962
r_S^2 = 0.971
WHEELING
r_C^2 = 0.990
r_{E-G}^2 = 0.983
r_S^2 = 0.985
PARKERSBURG
r_C^2 = 0.982
r_{E-G}^2 = 0.973
r_S^2 = 0.982
HUNTINGTON
r_C^2 = 0.986
r_{E-G}^2 = 0.980
r_S^2 = 0.986
0
7.0
14.0
21.0
28.0
35.0
COMPUTED TEMPERATURE, °C
OBSERVED TEMPERATURE, °C

FIGURE A.3

Appendix B
Fish Names

Common Name	Scientific Name
Bigeye chub	*Hybopsis amblops*
Black bass	*Micropterus* sp.
Black bullhead	*Ictalurus melas*
Blue catfish	*Ictalurus furcatus*
Blue sucker	*Cycleptus elongatus*
Bluegill sunfish	*Lepomis macrochirus*
Brown bullhead	*Ictalurus nebulosus*
Brook trout	*Salvelinus fontinalis*
Buffalofish	*Ictiobus* sp.
Bullhead	*Ictalurus* sp.
Carp	*Cyprinus carpio*
Catfish	*Ictalurus catus*
Channel catfish	*Ictalurus punctatus*
Chinook salmon	*Oncorhyncus tshawytscha*
Coho salmon	*Oncorhyncus kisutch*
Common sucker	*Catostomus commersoni*
Crappie	*Poxomis* sp.
Creek chub	*Semotilus atromaculatus*
Emerald shiner	*Notropis atherionoides*
Flathead catfish	*Pylodictis olivaris*
Freshwater drum	*Aplodinotus grunniens*
Gar pike	*Lepisosteus osseus*

Common Name	Scientific Name
Gizzard shad	*Dorosoma cepedianum*
Golden redhorse	*Moxostoma erythrurum*
Goldeye	*Hiodon alosoides*
Lake sturgeon	*Acipenser fulvescens*
Largemouth bass	*Micropterus salmoides*
Longear sunfish	*Lepomis megalotis*
Mooneye	*Hiodon tergisus*
Mudpuppy	*Necturus moculosus*
Muskellunge	*Esox masquinongy ohioensis*
Rainbow trout	*Salmo gairdneri*
Sauger	*Stizostedion canadense*
Shiners	*Notropis* sp.
Skipjack herring	*Alosa chrysochloris*
Smallmouth bass	*Micropterus dolomieui*
Sockeye salmon	*Oncorhyncus nerka*
Spoon-bill cat	*Polyodon spathula*
Spotted bass	*Micropterus punctulatus*
Stoneroller	*Campostoma anomalum*
Striped bass	*Morone saxatilis*
Sunfishes	*Lepomis* sp.
Walleye	*Stizostedion vitreum vitreum*
White bass	*Morone chrysops*
White perch	*Morone americana*
Yellow perch	*Perca flavescens*

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7. Author(s) Anthony Policastro, James J. Reisa, Jr., Brian P. Butz, Donald R. Schregardus, Barbara-Ann Lewis

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16. Abstracts This study presents a review and critique of existing technical information relevant to the environmental effects of the use of the Ohio River main stem for cooling. In order to evaluate the effect of heat discharges on the indigenous aquatic life of the Ohio River, an extensive review and critique of past and existing studies dealing with the biological aspects of cooling water was undertaken. In order to judge the effect of heat discharges on the thermal regime of the river, three one-dimensional river temperature prediction models - COLHEAT, STREAM and Edinger-Geyer were evaluated, and the most appropriate model was selected to analyze changes in temperature distribution along the river. The effects of heat discharges on the thermal regime of the river near the points of discharge were evaluated by analyzing and critiquing available thermal plume study results.

17. Key Words and Document Analysis. 17a. Descriptors

Aquatic biology, Cooling water, temperature discharges

17b. Identifiers/Open-Ended Terms

Ohio River, heat discharges, temperature prediction, COLHEAT, STREAM, Edinger-Geyer

17c. COSATI Field/Group 13B, 6F

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20. Security Class (This Page UNCLASSIFIED

21. No. of Pages

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