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ENVIRONMENTAL ENGINEERING STUDIES
FOR
THERMAL DISCHARGES AT COASTAL SITES

BY

D. L. MATCHETT
Y. J. TSAI

Stone & Webster Engineering Corporation

Presented at 1972 Joint Power Generation Conference

September 11, 1972 - Boston, Massachusetts

August 17, 1972

Mr. Robert H. Smart
Northeast Utilities Corporation
P. O. Box 270
Hartford, Connecticut 06101

Dear Mr. Smart:

THERMAL EFFECTS OF
CIRCULATING WATER SYSTEMS SESSION
JOINT POWER GENERATION CONFERENCE

As indicated in your letter of August 14, 1972, we will make arrangements with Mr. C. O. Buffington to have five hundred copies of our paper available for distribution at the session on thermal effects on Monday afternoon, September 11.

We would like to show several slides on an overhead projector, if one could be made available.

Yours very truly,

D. L. Hatchett

Copy to: Y.JTsai
COBuffington

DLHatchett/adm

ENVIRONMENTAL ENGINEERING STUDIES FOR THERMAL DISCHARGES AT COASTAL SITES

By D. L. Matchett,(1) A. M. ASCE and Y. J. Tsai(2)

INTRODUCTION

The design of cooling water systems for steam electric power stations presents engineers with a most interesting and challenging task. This is due to the need for carefully evaluating the environmental impact of thermal discharges on the receiving water bodies.

Because of the complexity of the problem and many factors that usually have to be considered, a systematic approach to the control of thermal effects from the power station is required. In general, studies to select the best circulating water system for a power station require a program which coordinates the efforts of a variety of engineering and scientific disciplines ranging from the biologist and the meteorologist to the hydraulic engineer.

This paper deals with the subject of the engineering studies for discharges where once-through cooling systems are appropriate. Analytical techniques are discussed which are applicable to the design of once-through systems where temperature limitations are specified in the discharge area. This is followed by several case histories showing how these techniques have been applied at various specific sites.

(1) Supervisor, Hydrothermal Engineering, Stone & Webster Engineering Corporation, Boston, Massachusetts

(2) Consultant, Environmental Engineering, Stone & Webster Engineering Corporation, Boston, Massachusetts

Historically once-through cooling systems have been selected for stations located on the open coast or on rivers or lakes having large heat-assimilation characteristics. Although sites where this type of system is proposed must be carefully evaluated from the environmental standpoint, it is clear, however, that the ocean still offers in many cases a most satisfactory location for waste heat disposal.

Federal and State water quality standards have been implemented in an attempt to preserve and, if possible, to enhance our water resources. These standards are being augmented by regulations intended to reduce the effects of waste heat discharges to a level where their ecological impact is judged to be minimal. These regulations are often set forth in the form of thermal discharge criteria limiting discharge temperatures or temperature rises above ambient for various classes of waters.

Federal guidelines for water quality were established by the National Technical Advisory Committee, in Water Quality Criteria, dated April 1, 1968.[1] These guidelines are being currently updated. There are wide variations between the Federal guidelines and State water quality standards set pursuant to the Water Quality Act of 1965. It is proper that there should be because of wide variations in natural conditions and life forms in different localities. However, without attempting to pass judgment on the ecological bases for various State criteria, it is fair to say that some of them impose extremely stringent requirements on the design of circulating water systems.

SCOPE OF ENGINEERING STUDIES

A coastal site which is environmentally acceptable for a once-through cooling system must have several basic characteristics. These include:

1. Access to large quantities of water

2. Hydrologic features which permit flushing of station discharges

3. Presence of aquatic ecosystems that would not be seriously affected by construction and operation of the power plant.

The last requirement can be demonstrated only by extensive ecological studies and will not be covered in this paper. However, before a decision can be made on the general ecological question, extensive engineering studies are often needed to predict the physical effects of a proposed system.

The first and probably most important step in any engineering study program for circulating water systems is to establish the existing physical conditions at the site. Although some basic characteristics of a proposed site probably would have been defined during site selection studies, no final judgments of system suitability should be made until all natural factors affecting the water discharge and heat dissipation are thoroughly understood. The required information in some cases may be obtained from existing records, but usually extensive field studies are required.

The second step involves the design of the system which is compatible with the environmental requirements of the site, including compliance with established regulatory criteria regarding thermal discharges. This step also requires predictions of effects resulting from proposed design in order to demonstrate that the system selected is indeed suitable.

Prediction of temperature changes can be made either by use of physical or mathematical models, or by a combination of these. Selection of the proper prediction technique is most important and must be based on a number of factors including an understanding of the limitations of various modeling techniques and the feasibility of applying these techniques to the natural conditions at a particular site. It has been found in a number of cases that both physical and mathematical modeling were required.

Field Studies

Natural physical conditions which must be determined for the water body at a coastal site generally include:

1. Current velocities
2. Tide levels
3. Bottom topography
4. Water temperatures
5. Salinity
6. Thermal stratification and density variation
7. Dispersion characteristics
8. Flushing characteristics
9. Meteorology necessary to determine heat exchange with atmosphere

Consideration must be given to variations in natural characteristics on an annual or other appropriate basis.

The field program to obtain necessary information to successfully carry out the hydrothermal analysis must be carefully tailored to suit the proposed discharge system, the natural site conditions, and the analytical

techniques that will be used in making predictions. This last requirement means that the analytical techniques should be developed before the field studies are undertaken.

Natural current patterns and dispersion characteristics must be clearly understood to provide input for mathematical or hydraulic models used to make predictions of temperature changes from system operation. Techniques used for obtaining the field information required in the hydrothermal analysis include:

1. Long term in-situ current and temperature measurements

2. Vertical profiles of current, temperature, and salinity at various times through the year

3. Infrared surveys to map existing surface temperature patterns

4. Drogue studies

5. Dye dispersion studies

The technique of using fluorescent dye to trace water movement and determine natural dispersion characteristics in tidal estuaries can be very effective. Of particular interest is a method for determining the flushing characteristics and the return of material to the discharge area with tidal reversal. Under certain conditions, measurement of return of dye to the discharge area may be used as a basis for predictions of the amount of artificial heat return with tidal reversal. This factor is important when stringent temperature rise criteria are specified in the discharge area. An example of the application of this technique will be given subsequently.

Hydraulic Model Studies

Hydraulic model studies often provide the only practical way of solving complicated fluid flow problems. In other cases, model studies provide confirmation of a theoretical analysis and present tangible evidence which can be presented to regulatory agencies. A substantial reservoir of general hydraulic model information has been developed in recent years relative to turbulent jet diffusion and two-layer flow, subjects which apply to submerged diffusers and surface discharge, respectively. However, new sites and new discharge configurations continue to require specific model studies in order to solve unique problems.

The use of hydraulic models for coastal and estuarine sites subjected to reversing tidal flow presents several problems. In order to maintain hydraulic similitudes between the flow regime of the model and prototype, there are limits to the scale factor that can be applied. Accordingly, a very large model may be needed to include the area which might be influenced by some increase in temperature. An even more difficult problem might arise if the model were constructed to simulate only a portion of an estuary due to the difficulty of reproducing natural flow conditions at the artificial boundaries of the model.

Because of these problems, techniques have been developed to combine model studies with field measurements and mathematical analysis. In such a combined approach, the hydraulic model supplies important information on hydrothermal effects in the near-field area, that is, the area near the discharge structure. Typical information provided would be the dilution capability and resulting temperature rise of a particular type of diffuser discharging into simulated ambient conditions in the discharge area. If return of heat from the far

field due to tide reversal is a consideration, hydraulic model results would be adjusted by mathematical analysis based on field studies.

Mathematical Analysis

Hydrothermal mathematical modeling, that is, the analytical prediction of the extent of thermal plumes from power stations and of temperatures within such plumes, is an active and developing area of applied science. Incorporation of the effects of the density difference between heated water and ambient receiving water, the heat exchange between air and water and hydrodynamic phenomena opened a new era in the field of applied fluid mechanics.

Numerical simulation of the thermal plume gives a powerful tool for predicting the effects of the discharged heat on the environment. However, prototype behavior is often too complicated to be exactly described, and must be simulated by introducing some simplifications and assumptions in the mathematical model.

The development of a mathematical model follows three distinct phases:[2] conceptual, functional, and computational. Analyzing the fundamental physical elements to be incorporated in the model is the conceptual phase. The second stage is to convert the proposed physical phenomena into mathematical terms. The numerical solution is the final step in the development of the mathematical model. The predictive capability of the mathematical model should then be tested in the field by comparison with observed data if possible.

The thermal plume resulting from the discharge of power station cooling water can be physically characterized as two regions. In the first region, the near-field area in the immediate vicinity of the discharge, the temperature rise

above ambient is controlled mainly by the type of discharge structure and by the characteristics of the discharge flow. In the near-field, the temperature of the discharge is reduced predominantly by dilution caused by the mixing processes. The second region is the far-field which is dominated by natural heat transfer processes. In this region the thermal plume moves with the prevailing currents, essentially as a part of the ambient velocity field. The heat transfer mechanisms in the far-field are advection, dispersion, and surface heat loss. The atmosphere is the ultimate heat sink for all power plant rejected heat, and the heat exchange between air and water plays the dominant role in the far-field region.

Once the physical mechanisms of the thermal discharge behavior are understood, the formulation of descriptive equations, either theoretical or semiempirical, is required. In general, two basic approaches exist in the derivation of plume models. One is based on a differential analysis, and the other on an integral analysis.(3) The differential method involves solving the general partial differential equations of motion and heat diffusion to arrive at velocity and temperature distributions. The integral analysis involves several simplifying assumptions on the flow and temperature fields to obtain a solution for the desired physical quantities. In coastal water areas, such as an estuary, it is necessary to couple the conservation of heat equation with the momentum and continuity describing the tidal hydrodynamics. The reversal of the natural current due to tidal effects complicates the solution. Because the flow and temperature fields are transient in nature, the solution should also be time dependent.

The computational solution of the mathematical formulations is the final step in the development of the mathematical simulation model. A closed

form solution may be obtained for both semiempirical equations and steady state theoretical equations with simplified boundary conditions. In most cases, either in the near-field or far-field, numerical solutions are required. The finite control volume analysis is perhaps the most widely used technique for modeling of flow patterns and temperature distribution. The water body is divided into segments of finite size and mean values of the physical properties are assigned to each element. The system of differential equations is then replaced by its finite difference approximation yielding a system of algebraic equations which are then solved using a high-speed digital computer.

In most environmental engineering studies for thermal discharges, mathematical analysis is required to integrate the data obtained from field surveys and hydraulic model studies for the near-field thermal effects. The mathematical model also provides the most effective technique available to predict the far-field thermal effects, especially for areas limited by the hydraulic model scale.

CASE STUDIES

Four case studies have been selected to demonstrate techniques that have been used successfully in engineering studies for once-through circulating water systems.

The first case presented is for the James A. FitzPatrick Nuclear Power Plant, located on Lake Ontario. Although this is not an ocean site, it is located on the coast of a large body of water subject to wind induced currents. Also, this station is one of the first to employ a submerged multiport diffuser for heat discharge.

The second case is the Shoreham Nuclear Power Station on Long Island Sound where a multiport diffuser is again applied, this time to a tidal situation.

The last two cases are for stations employing surface discharge systems. These are Big Bend Station on Tampa Bay in Florida and the Maine Yankee Atomic Power Station on Montsweag Bay, a tidal estuary on the coast of Maine.

<u>James A. FitzPatrick Nuclear Power Plant, Power Authority of the State of New York</u>

This plant, located on the shore of Lake Ontario and scheduled for completion in 1973, will require 825 cfs of cooling water. Temperature rise through the condenser is 31.5 F.

To provide a sound basis for developing and predicting the effect of the plant cooling water discharge, field surveys were conducted to measure lake temperatures and lake currents. Data obtained from these surveys were used in analytic and hydraulic model studies to develop the hydraulic design of the structures and to ensure that the temperature patterns to be produced by plant operation will comply with the thermal discharge criteria of the State of New York. The criteria require that the water temperature at the surface may not be raised more than 3 F over the natural surface water temperature outside a radius of 300 ft, or equivalent area.

The basic concept of the plant discharge structure is to achieve rapid dilution of condenser water with the colder lake water and corresponding decrease in temperature at the surface by means of a number of submerged high velocity jets.

The following is a list of the environmental studies which lead to the final design of the plant cooling water circulating system:

A. <u>Field Studies</u>

1. Continuous recording of currents and temperatures at various depths for six months from late spring to fall.

2. Two overall lake current pattern surveys using drogues.

3. Two overall surface temperature pattern surveys using airborne infrared radiometry.

4. Four temperature profiles in deep water by traversing with single thermistor.

B. <u>Meteorological Studies</u>

Collection of wind speed and direction data from four weather stations and the adjacent Nine Mile Point Station anemometer to correlate with lake currents.

C. <u>Hydraulic Model Studies</u>

1. Basic study of submerged jet dilution to determine characteristics of surface layer (1/26 scale).

2. Lake model. To select optimum orientation and direction of discharge (1/50 vertical, 1/200 horizontal scales).

3. Details of discharge structure. Selection of design characteristics of discharge nozzles (1/50 scale).

4. Complete discharge and intake model. Location and design of intake; temperature patterns with lake currents (1/81 scale).

D. Analytic Studies

1. Develop basic concept and design features of structures.

2. Predict overall hydrothermal patterns of cooling water discharge.

Lake current and temperature measurements provided detailed information on the physical lake environment at the James A. FitzPatrick site. Lake currents at the site are primarily wind induced and low in magnitude, usually only a few tenths of a foot per second. The current flow lines generally follow the lake topography. Temperatures of the lake water vary according to atmospheric conditions, and thermal stratification exists in water 60 ft or more in depth during late summer. At this time, the thermocline is at 40 to 50 ft below the surface. The proposed lake structures will be in the epilimnion during times of stratification. In the vicinity of the future lake structures, significant natural upwellings have been recorded, with colder hypolimnetic water replacing epilimnetic water.

The extensive hydraulic model testing program, in conjunction with analytic studies, was used to develop the hydraulic design of the intake and discharge structures. A submerged diffuser structure discharging high velocity jets which will produce rapid decrease in condenser cooling water temperature was selected as the final discharge structure of the power plant. A total of

12 jets will be discharged in pairs from six diffuser heads at an initial velocity of 14 fps at 5 to 6 ft above lake bottom. The direction of the discharge will be lakeward and essentially perpendicular to the bottom contours.

For all lake current conditions, i.e., no current, eastward and westward currents ranged from 0.2 fps to 0.8 fps, the model test results showed the surface water temperature will not be raised more than 3 F outside the permissible zone, thus satisfying the New York State criteria. It was also shown that the concept and location of the intake structure are satisfactory. No recirculation of warm water was detected with or without lake currents. Basic results from the model tests of the flow pattern and temperature distribution along a section perpendicular to the shoreline through the James A. FitzPatrick lake structures are shown on Fig. 1.

A more detailed description of the field study and hydraulic model test programs with the adopted design of intake and discharge structures can be found elsewhere.[4]

Because of physical size limitations which precluded determining the overall site temperature patterns from the hydraulic models, the overall thermal patterns at the site were predicted analytically using the hydrothermal conditions determined from the model tests in the vicinity of the discharge structure. Analytic solutions of heat dispersion from the discharge were obtained for the condition of a static lake and for the condition of lake currents of different speeds.

For a static lake, analytic solutions for the discharge plume were obtained by analogy to a hypothetical surface jet. This hypothetical jet is defined such that it simulates the velocity and temperature distribution found in the

model approximately 300 ft downstream from the diffuser structure. The predicted temperature pattern is shown in Fig. 2. It is evident that a symmetrical plume is formed lakeward of the diffuser, with a relatively rapid drop in temperature due to dispersion.

To analyze overall temperature patterns with lake currents, it was necessary to establish the center line of the discharge plume. The cooling water discharge is deflected in the direction of the prevailing current as the velocity of the jets decreases. Using the entire flow field as a single jet, available data on deflection of jets in moving environments were used to establish the flow center line. Lateral spread of the flow field along the center line was computed by considering the dispersion of a continuous line source. Fig. 2 shows the predicted temperature patterns for eastward curent of 0.2 fps. In general, low current speeds produce a broader plume with less total area within the 0.5 F temperature rise isotherm than is the case for high currents. Analyses of heat loss to the atmosphere indicate only a small decrease in plume temperature at any point.

The above-described analytical methods have been compiled by Argonne National Laboratory in the report "State-of-the-Art of Analytical Modeling."(5)

In summary, the adopted design of intake and discharge structures for the James A. FitzPatrick Nuclear Power Plant is based on a sound knowledge of the site environment and was developed by a combination of hydraulic models and analyses.

Shoreham Nuclear Power Station, Long Island Lighting Company

The Shoreham Nuclear Power Station, to be located on the south shore of Long Island Sound, is designed for a once-through cooling system requiring

about 1,280 cfs of cooling water which is raised about 20 F as it passes through the condenser. The New York State Department of Environmental Conservation has classified this area as "coastal waters." This means that, in order to satisfy the State's thermal discharge criteria, the station discharge cannot raise the surface water temperature at the site more than 4 F over the monthly means of maximum daily temperature from October through June, nor more than 1.5 F from July through September, except within a radius of 300 ft, or an equivalent area, from the point of discharge.

These stringent thermal criteria presented an unusual challenge for the designers. Preliminary analysis indicated that the criteria probably could be satisfied by using a submerged multiport diffuser. However, there was no theoretical basis for accurately predicting such small temperature changes for a diffuser placed in water only 15 to 20 ft deep and subject to the tidal conditions prevailing at the site.

A. Mathematical Analysis

After considering various possible analytical techniques that might be used to make temperature predictions, it was decided that a program combining field studies, hydraulic model studies, and mathematical analyses would yield the most efficient and reliable solution. A concise description of the enginering studies is given in Reference 6. Fig. 3 shows the system model that was developed to synthesize the significant physical parameters. This model predicts water surface temperature rise as a function of:

1. Station operating conditions

2. Characteristics of the diffuser

3. Natural flow and temperature in the near-field area

4. Dispersion, heat transfer to the atmosphere, and recirculation effects from the far-field

The model was used to make predictions at various times throughout the tidal cycle in order to recognize variations in natural flow and dispersion characteristics.

B. <u>Field Studies</u>

The field study programs supplied model input for Items 3 and 4, above. The principal elements in the field studies which extended over a three year period were:

1. Continuous in-situ water temperature and current measurements during the summer months.

2. Water temperature measurements for all seasons at the surface and bottom, as part of the ecological monitoring program.

3. Dye dispersion and current measurements in a summer month.

The dye dispersion studies provided information needed to determine the effect of heated water returning to the discharge area where it might become mixed again with the diffuser discharge. The factor "R" in the mathematical model is a measure of this return.

Dye was released continuously for about ten days from five points located along the line of the proposed diffuser, and measurements were made upstream of the release points to determine how much dye was being returned by tidal reversal.

Because of the shallow water and turbulence at the site, neither the dye in the field test nor the heated water in the hydraulic model exhibited significant stratification. Accordingly, the dye could be used to simulate, after correcting for heat transfer with atmosphere, the movement of heated water.

C. Hydraulic Model Studies

The basic purpose for the hydraulic model studies was to determine the factor "S" in the mathematical model. This factor represents the dilution capability of a diffuser under varying conditions of tidal currents.

The model studies were divided into two phases[7]; in Phase I, a two-dimensional generalized model measured the ability of jets to induce mixing as a function of discharge velocity, water depth, port diameter, and spacing. These tests were conducted at undistorted scales of 1/20 and 1/40.

In Phase II, a three-dimensional undistorted site model with a scale of 1/100 was used to determine the capability of the diffuser, taking into account intake flow, site topography, diffuser length, and unsteady tidal currents. The diffuser arrangement was ultimately developed which provided the dilution capability required by the mathematical model to satisfy the thermal criteria.

D. Diffuser Design

The diffuser arrangement finally selected is shown in Fig. 4. The analysis upon which the design is based has been reviewed by the New York State Department of Environmental Conservation and, subsequent to a public hearing, the Department issued a construction permit for the discharge system and a Certificate of Reasonable Assurance that water quality standards will be satisfied. The Atomic Energy Commission and the Environmental Protection Agency also concur that applicable standards will be satisfied.

Big Bend Station, Tampa Electric Company

The Big Bend Station site is located on east shore of Hillsborough Bay which is a northeasterly extension of Tampa Bay about 25 miles from Egmont Key at the entrance to Tampa Bay at the Gulf of Mexico. The station has currently one unit in operation, a second unit is under construction, and the third unit is in the licensing stage.

All three units are identical in size with a generating capacity of 446 Mw and a circulating water flow of 535 cfs per unit. The temperature rise in the condensers is approximately 17 F at full load.

A surface discharge cooling system was designed for Unit 1. The system provided a dredged discharge channel for better mixing within the site boundary before discharging into Hillsborough Bay. A half mile long dividing dike minimizes heat recirculation.

The hydrographical and hydrothermal conditions prevailing at the vicinity of the site before and after the operation of Unit 1 were obtained by a

series of field investigations. The field programs included all the items listed in the previous general discussion under field studies except dye diffusion studies.

The information obtained from these comprehensive studies provided a basis for conceptual design of the cooling water system and also fulfilled a provision of the construction permit for Unit 1. The natural variations in temperature at the bay surface, as influenced by the tidal currents, and as influenced by the thermal discharge and pumping of the station, were well documented.

The criterion for the design of a second unit discharge system is that the impact of combined thermal discharge, or the zone of thermal influence, as defined by the administratively established area of the first unit, will not be enlarged. Among all alternatives studied, the dilution pumping system which gives the least environmental impact is the most practical solution, and still complies with the design criterion.

The arrangement of the dilution pumping system is shown in Fig. 5. A dilution channel is required to divert the pumped dilution flow and to facilitate good mixing with the warm water discharge from the station. The system was approved by the Department of Air and Water Pollution Control of the State of Florida.

The operation of Unit 1 alone represents a unique hydraulic situation compared to conditions which will exist with the addition of Units 2 and 3 and their accompanying dilution flows. The volume rate of flow from Unit 1 allows a stratified two-layer flow condition in the discharge channel. Entrainment of the lower cool water layer into the upper warm water layer significantly

reduces the temperature of the upper layer along the length of the discharge channel. This phenomenon could occur to a lesser degree with Unit 2 added. However, with the addition of dilution water flow, the cooler bottom layer penetrating the discharge channel as a wedge is repelled.

A mathematical model describing the two-layer flow system in the discharge channel and Hillsborough Bay was solved numerically to predict the hydrothermal patterns for various station generating conditions.(8) The model takes into account the effects of geometry, buoyancy forces, surface cooling, energy losses due to interfacial shearing stresses, and entrainment of ambient water into the surface layer flow.

Cooling by entrainment in the discharge channel as a two-layer flow system has been observed in surveys conducted at the station with Unit 1 in operation. The mathematical predictions of temperature decay recognize the elimination of this means of cooling in computing the combined effects of Unit 1 and Unit 2 with dilution pumping. The results of these predictions are summarized in Fig. 6. A noteworthy characteristic of the curves is that, with the addition of units, the decay curve becomes flatter. This is due to the fact that the smaller initial temperature rise above ambient would result in lower rates of heat loss to the atmosphere and the increase in flow rate would substantially decrease the reduction in temperature due to mixing or entrainment.

<u>Maine Yankee Atomic Power Station, Maine Yankee Atomic Power Company</u>

The station, expected for commercial operation in the fall of 1972, is located on tidal water in the Town of Wiscasset, Maine. The plant site is approximately 13 miles inland from the open ocean, with several bays and narrows linked between the site and open ocean.

In order to define natural conditions in this complicated estuarial system, and to evaluate the station heat discharge effect, comprehensive field surveys were started in 1967. These included flow measurements of several control sections in the estuary, continuous water temperature recording at surface and bottom at nine stations, periodic measurement of temperature and salinity at 14 stations covering the entire estuary, drogue surveys to determine flow patterns, infrared imagery of temperature at the water surface, and dye tracer surveys to investigate flushing characteristics.

The Montsweag Bay-Back River area, in which the station heat is discharged, can be considered as a semienclosed tidal estuary. Water enters and leaves the area from both ends of the estuary with a causeway restricting tidal flow at one end. Surface heat loss and heat advection at the boundaries are the two major heat dissipation mechanisms in the area under consideration. A heat balance concept was therefore employed in the overall area, and the temperature distribution was determined based on the characteristics of natural tidal flow and station heat discharge conditions.

The most important parameters considered in the overall heat budget are the heat exchange between water and air and the flushing rates at the boundaries. Twenty years of meteorological data from a nearby weather station and 5 yr of water temperatures recorded at the site were analyzed to establish the adverse summer condition and also the normal summer condition for the basis of analytical analysis. A typical winter condition was also chosen for the analysis.

To investigate the flushing characteristics of the area, two dye tracer surveys were carried out at different seasons of the year. The surveys consisted of a continuous release of Rhodamine WT dye at the plant site and

measurement of the resulting dye concentrations at many transects in the estuary. Flow measurements were conducted simultaneously with the dye tests in order to compute the total amount of dye advected through a particular section. A specific boundary condition of the heat balance equation was obtained from the test, that is, the percentage of the station heat permanently carried away by tidal action at the boundaries of the area and not returned into the area.

The station cooling water is discharged into a wide shallow cove before entering the main estuary. Small initial mixing or entrainment of ambient water is expected because of the buoyancy and low velocity of the warm water issuing from the cove. The station discharge will spread as a stratified surface layer in the estuary. The temperature distribution or temperature decay along the estuary is primarily a function of the natural flow pattern and velocity in the estuary and the behavior of the stratified surface layer.

A series of equations which describe the heat transfer between air and water, boundary conditions, heat budget of the area with constant heat rejection from the power station, cooling water flow system, recirculation, stratified flow behavior, geometry of the estuary, and natural flow and temperature conditions were written for one-dimensional quasi steady state condition. The temperature rise above natural ambient at any point in the estuary was determined by solving the equations simultaneously. For normal summer conditions, the results of the analysis which yields the surface temperature pattern are shown in Fig. 7.

CONCLUSION

Systematic engineering studies are required for the final design of power plant cooling water systems and for the assessment of their thermal effects

on the environment. To be most effective, this effort may employ the combination of field studies, hydraulic model studies, and mathematical analyses.

Field survey activities may span a number of years prior to adoption of the final scheme. Temperature, salinity, and current measurements are usually needed on a continuous basis. Drogue and dye tracer studies, if necessary, should be conducted during a time which represents the typical conditions for the critical period or season.

The mathematical modeling activity should also begin in the early stage of the total study program. Conceptual design of the mathematical model can be started without any precise and definite field and discharge data. This first phase of the mathematical modeling helps in scoping the field studies and in overall development of the hydraulic model studies.

Hydraulic model study is an indispensable step toward the design of discharge and intake structures when the cooling water system is unique and no previous design data are available.

The case studies presented show how these various techniques have been successfully combined to produce environmentally acceptable designs for once-through circulating water systems at coastal sites.

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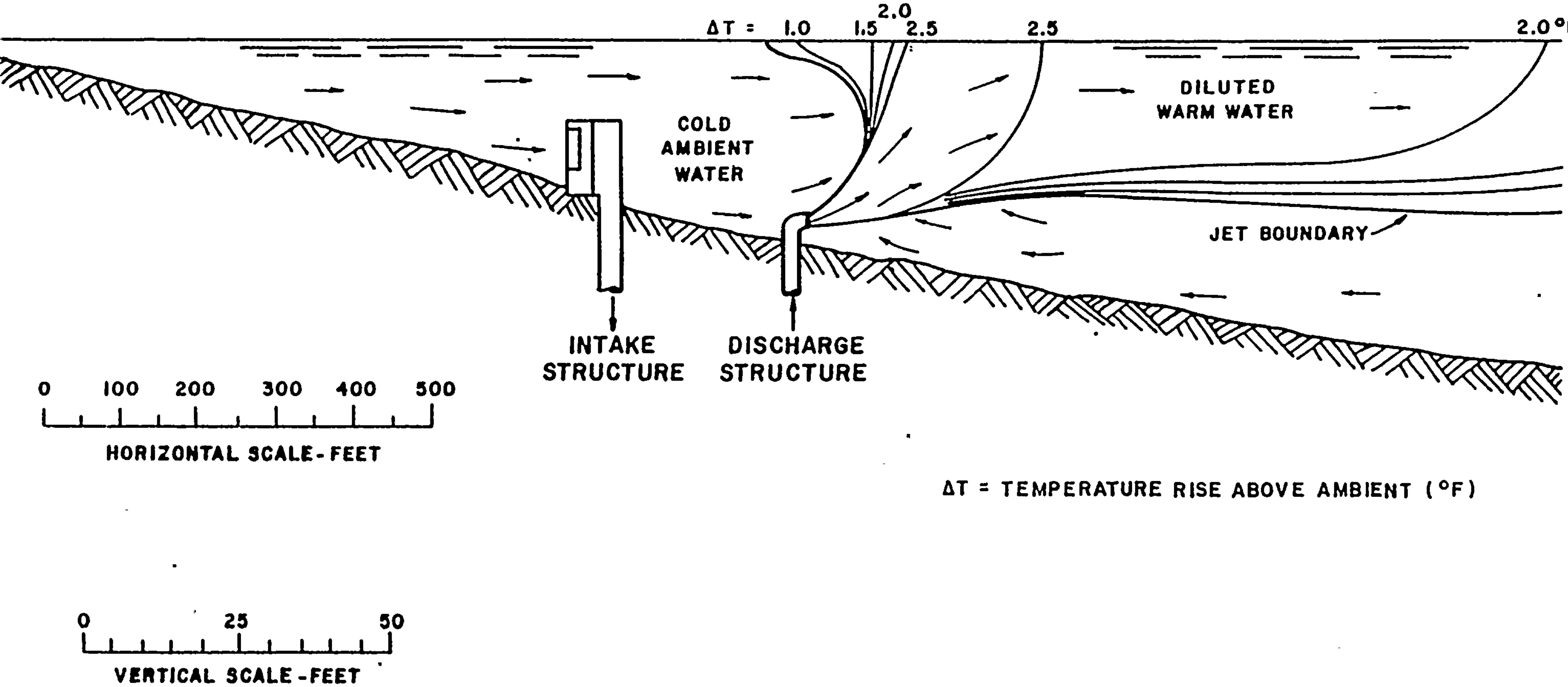


FIG. 1

TYPICAL FLOW PATTERN AND TEMPERATURE DISTRIBUTION

JAMES A. FITZPATRICK POWER PLANT

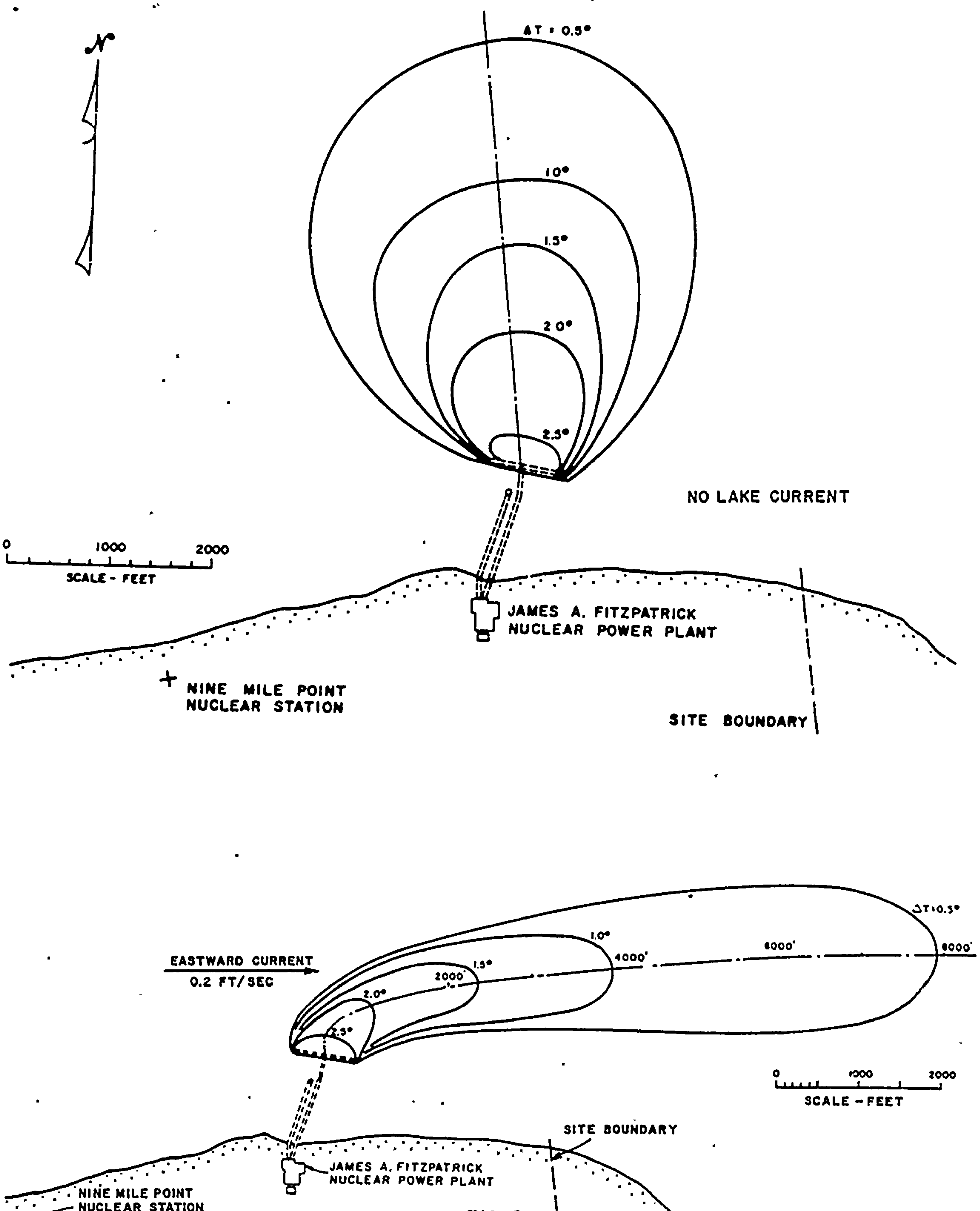
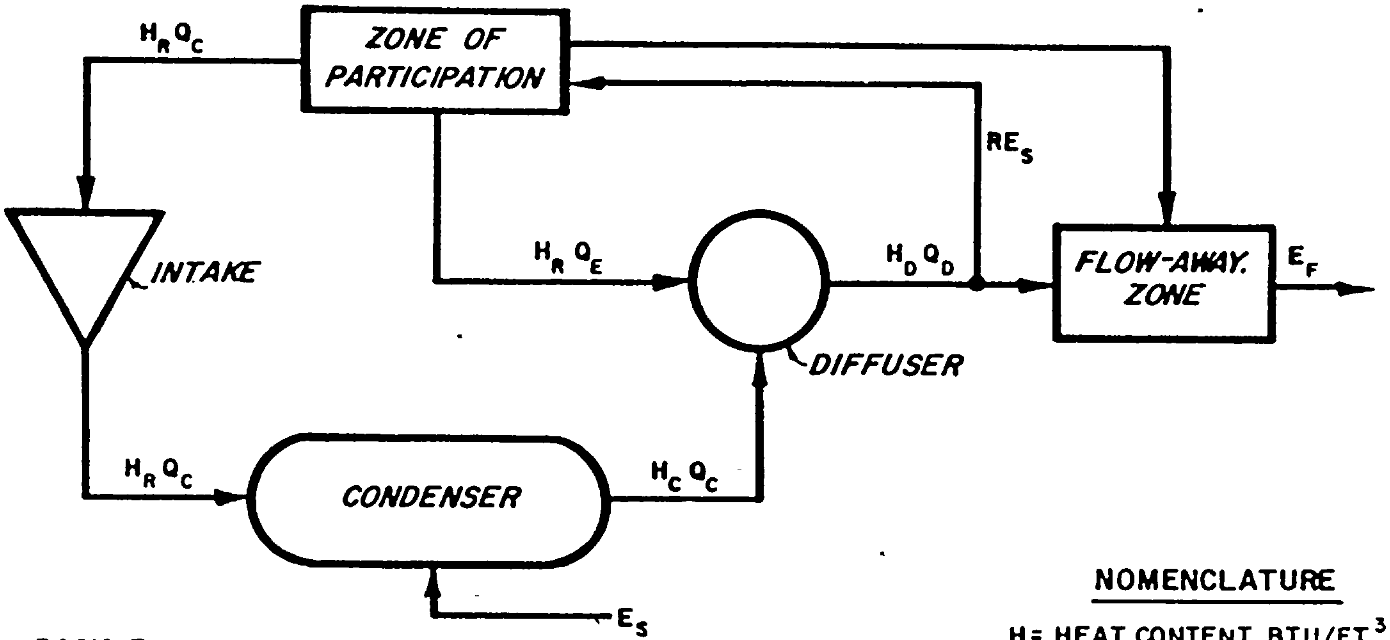


FIG. 2
PREDICTED SURFACE TEMPERATURE PATTERNS
JAMES A. FITZPATRICK POWER PLANT



BASIC EQUATIONS

1. $Q_D = S Q_C$
2. $Q_D = Q_C + Q_E$
3. $H_R Q_C + E_S = H_C Q_C$
4. $H_C Q_C + H_R Q_E = H_D Q_D$
5. $H_R = RE_S / \int u dA$
6. $\Delta T_S = \Delta T_M + (T_M - T_S)$

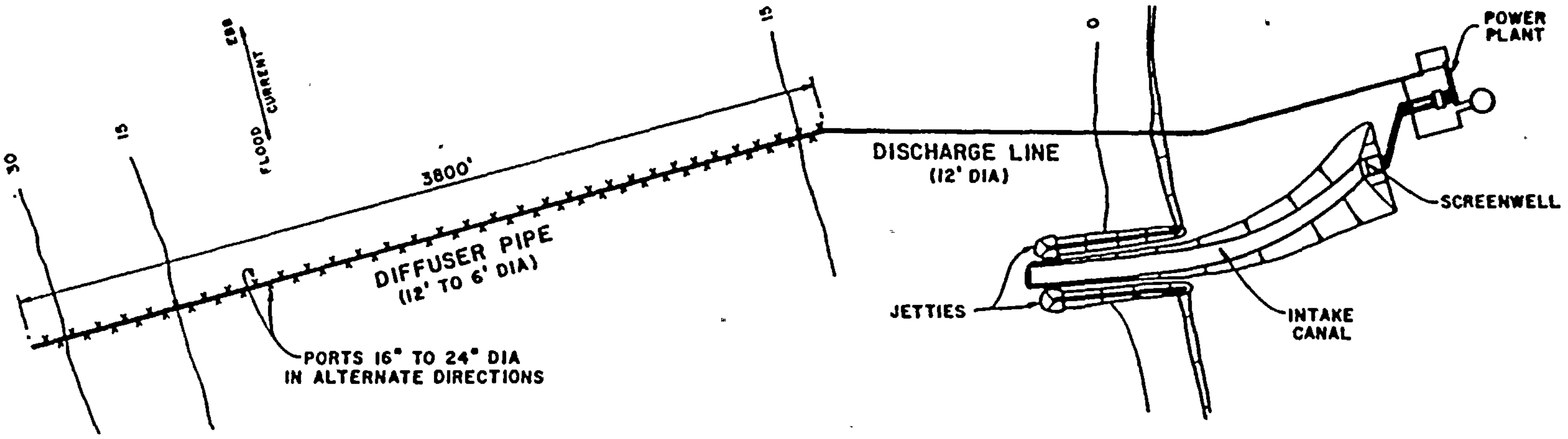
$$\boxed{\Delta T_S = \frac{\Delta T_C}{S}\left[1 + \frac{SRQ_C}{\int u dA}\right] + (T_M - T_S)}$$

$\frac{R}{\int u dA}$ EVALUATED OVER A TIME INTERVAL

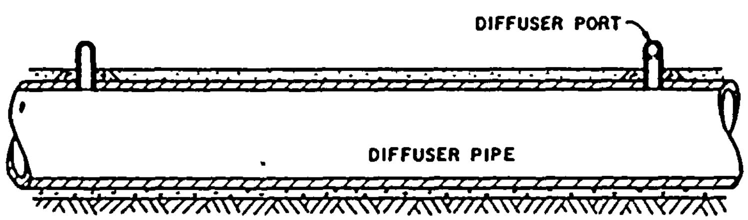
NOMENCLATURE

H = HEAT CONTENT BTU/FT^3
Q = FLOW RATE CFS
E = HEAT RATE BTU/SEC
R = % HEAT PASSING
S = DILUTION RATE
$\Delta T_C = E_S / \rho C_P Q_C$
T_M = AMBIENT MIXED TEMP.
T_S = AMBIENT SURFACE TEMP.
ΔT_M = TEMP. RISE ABOVE T_M
ΔT_S = TEMP. RISE ABOVE T_S
$\int u dA$ = NATURAL FLOW RATE, CFS

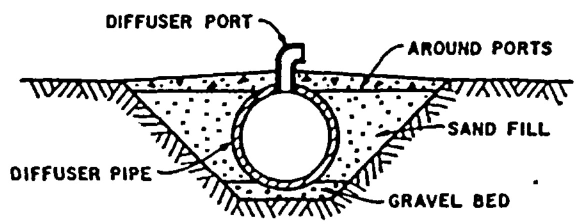
FIG. 3
MATHEMATICAL MODEL
SHOREHAM NUCLEAR POWER STATION



PLAN



TYPICAL LONGITUDINAL SECTION THROUGH DIFFUSER



TYPICAL SECTION THROUGH DIFFUSER PORT

FIG. 4
INTAKE AND DISCHARGE ARRANGEMENT
SHOREHAM NUCLEAR POWER STATION

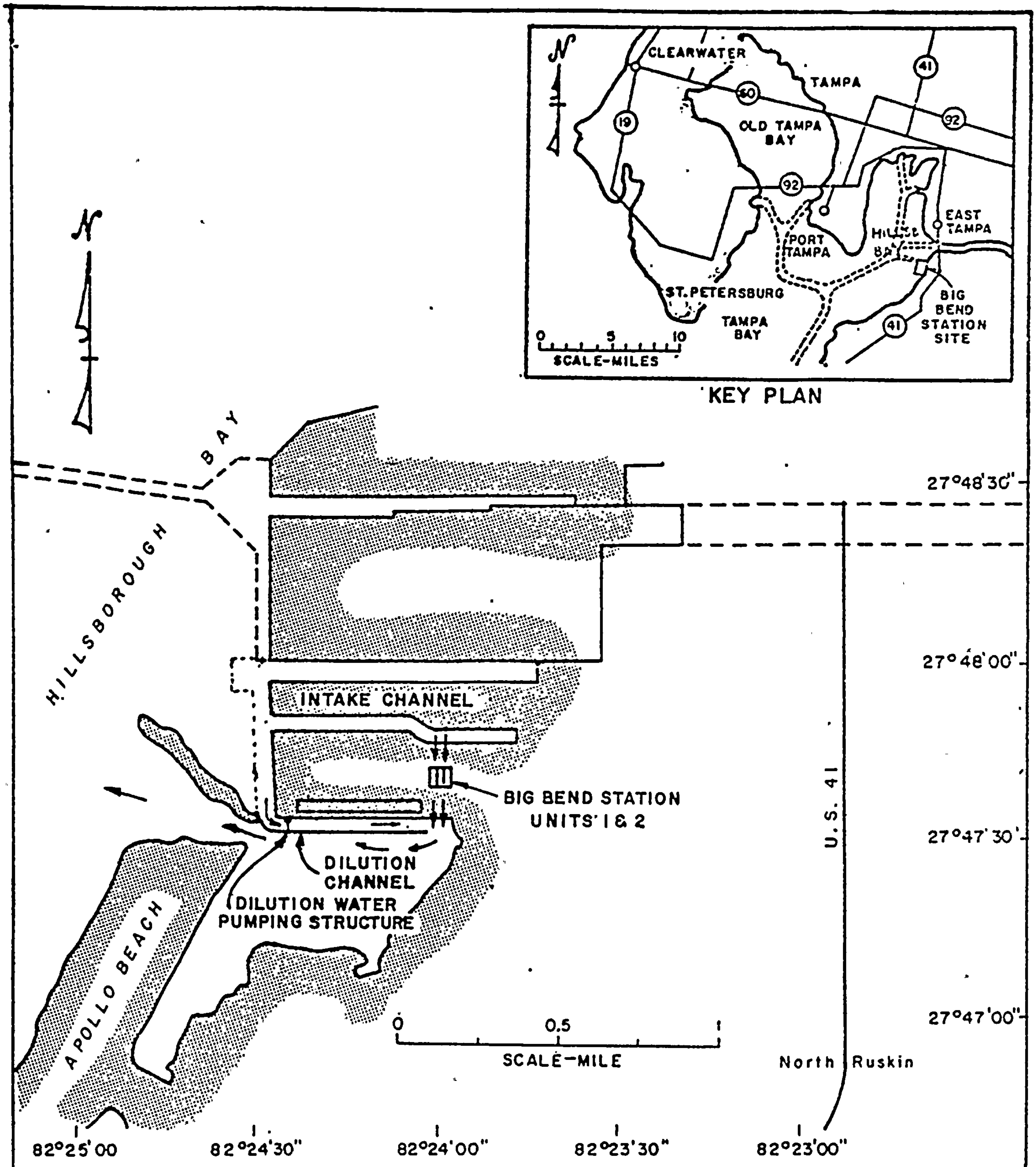


FIG. 5
ON-SITE DILUTION PUMPING SYSTEM
BIG BEND STATION

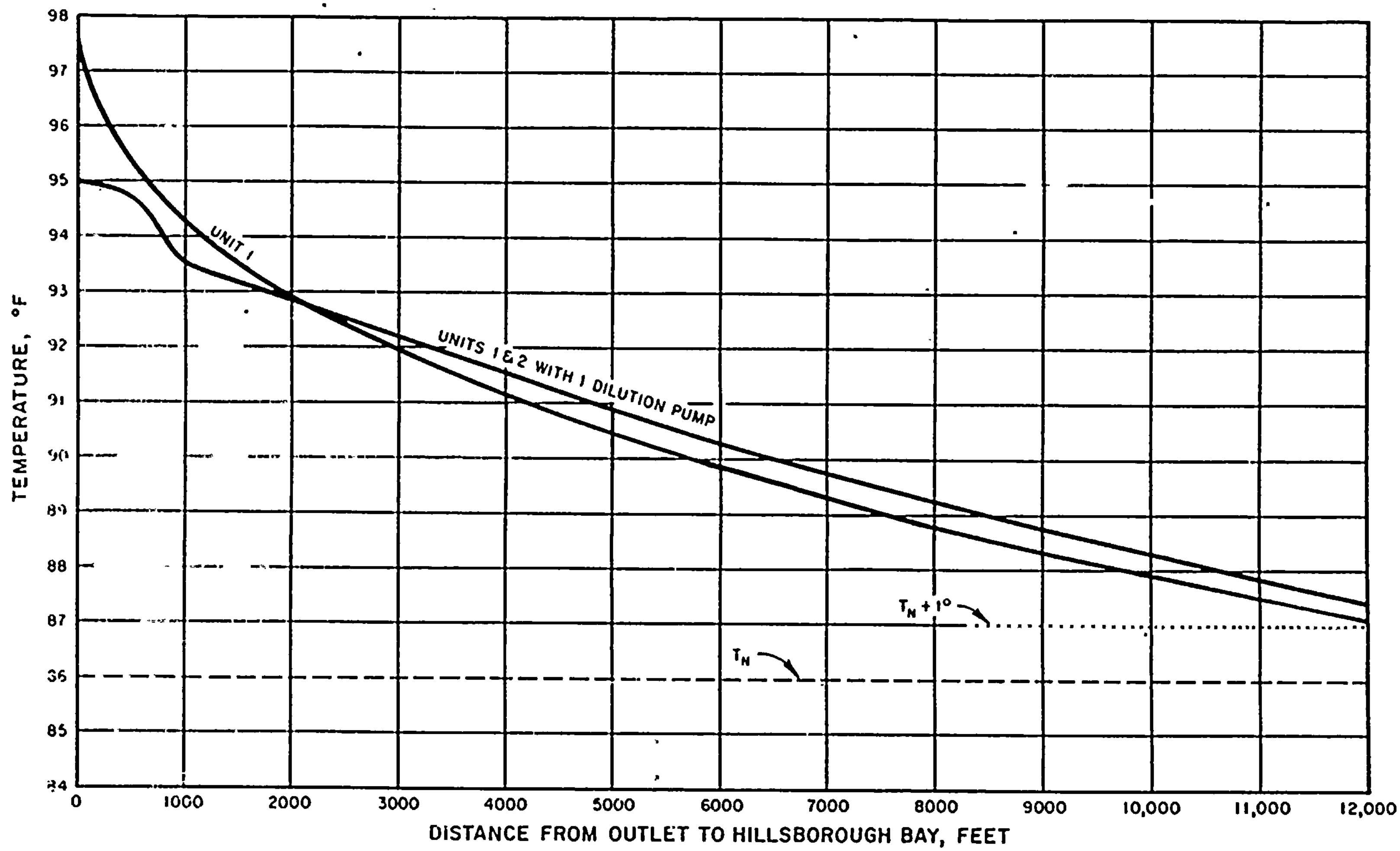


FIG. 6
SURFACE TEMPERATURE DECAY IN HILLSBOROUGH BAY
BIG BEND STATION

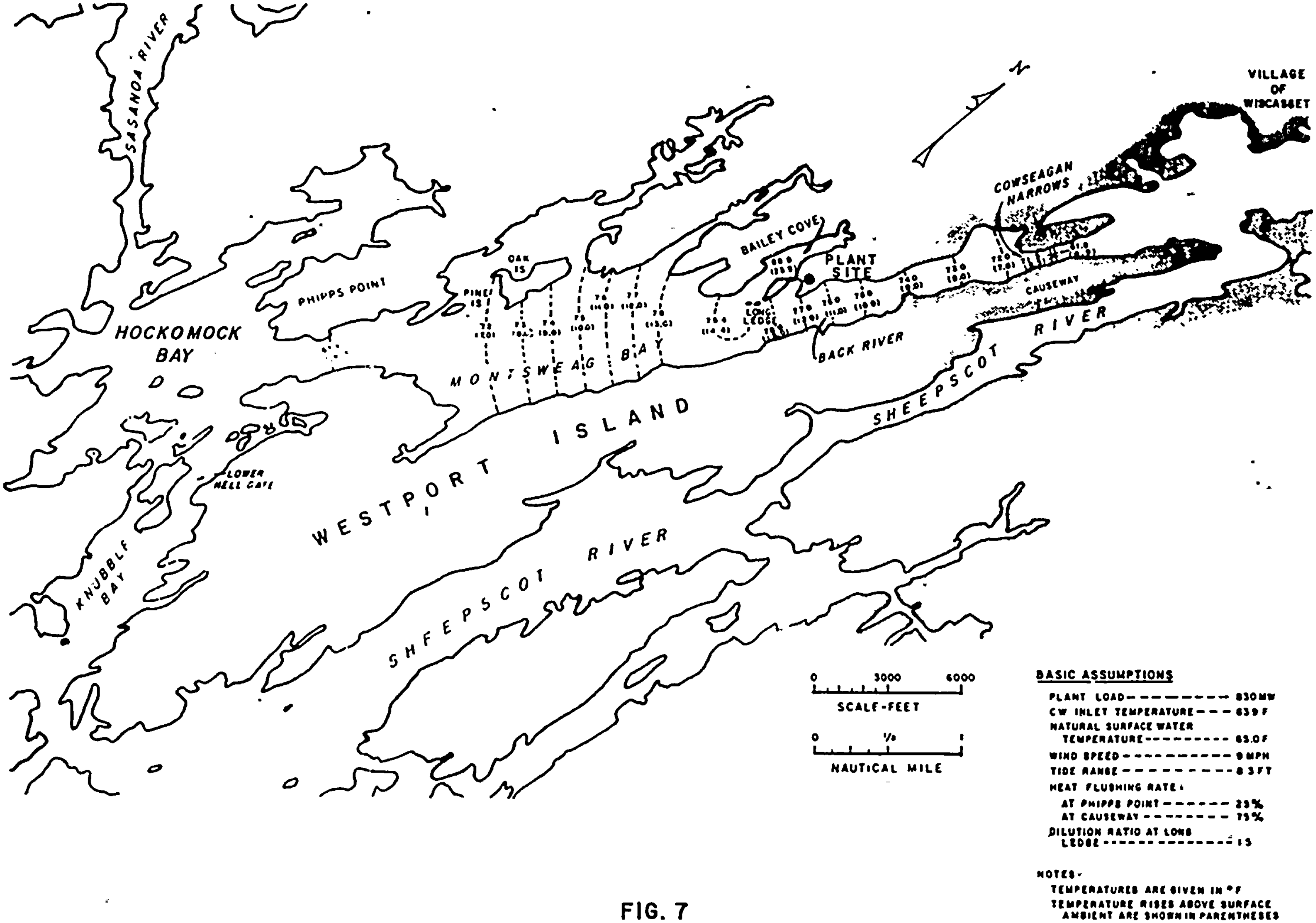


FIG. 7

PREDICTED MEAN SURFACE TEMPERATURES
NORMAL SUMMER CONDITIONS

MAINE YANKEE ATOMIC POWER STATION