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The Design of a Once-Through Cooling System to Meet the Challenge of Strict Thermal Criteria

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ABSTRACT

The site of the Shoreham Nuclear Power Station is a 450 acre tract owned by the Long Island Lighting Company (LILCO), situated on the north shore of Long Island in the Town of Brookhaven, Suffolk County, N.Y. After preliminary investigation of ecological data collected at the site, the New York State Department of Environmental Conservation classified the area as "coastal waters." This meant that the thermal effluent discharged from the Shoreham Station could not 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 equivalent area from the point of discharge. In order to meet these strict criteria, a mathematical model for a submerged multiport diffuser was developed by Stone & Webster Engineering Corporation, Engineer-Constructor for the plant. The model synthesizes the near field dilution of the diffuser and the far field return of heat with changing tides. To obtain the information required by the mathematical model, hydraulic model studies were carried out at the Hydrodynamics Laboratory of the Massachusetts Institute of Technology in addition to dye dispersion studies at the site itself. In conjunction with the latter, extensive measurements of currents and tides were also made. Based on the data generated during the above studies, a proposed diffuser design

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system was developed which will release station effluent from a number of submerged outlets discharging in alternating east and west directions along a 3,800 ft line beginning 1,600 ft off shore and extending northward from the site.

Introduction

Once-through circulating water systems, traditionally selected for steam electric generating stations located on large bodies of water, now require extensive design studies to insure compliance with thermal discharge criteria being set by some state environmental agencies. This paper outlines a unique approach which combined mathematical analysis, field investigations, and hydraulic model studies to generate the data necessary for the design of the once-through discharge system for the Shoreham Nuclear Power Station. A description is also given of the discharge structure finally developed to satisfy the stringent coastal waters thermal criteria of the State of New York.

The site of the Shoreham Nuclear Power Station is a 450 acre tract owned by LILCO, and situated on the north shore of Long Island in the Town of Brookhaven, Suffolk County, N.Y. The site location, with respect to Long Island Sound and adjacent areas, is shown in Figure 1.

The station, with a net generating capacity of about 820 Mw, will require cooling water at a rate of about 590,000 gpm. An intake canal will convey this water from Long Island Sound to a screen well structure where it will be pumped through the station, used for cooling purposes in the main steam condenser and other auxiliary heat exchangers and then returned to the Long Island Sound by means of a discharge conduit. When the station is operating at full load, the circulating water temperature will be raised about 19.7°F as it travels through the condenser.

Discharge System Design Requirements

In mid-1969 the State of New York officially announced thermal discharge criteria which placed strict numerical limits on the amount of temperature rise above ambient which would be permitted in waters of the State. The criteria placed different temperature limits on various classes of waters. According to the criteria, the waters of Long Island Sound may be classified as either estuaries or coastal waters, depending upon local characteristics. The former classification permits a maximum temperature of 90°F, the value initially used for the Shoreham discharge design. The classification for coastal waters, on the other hand, dictates that:

The water temperature at the surface of coastal waters shall not be raised more

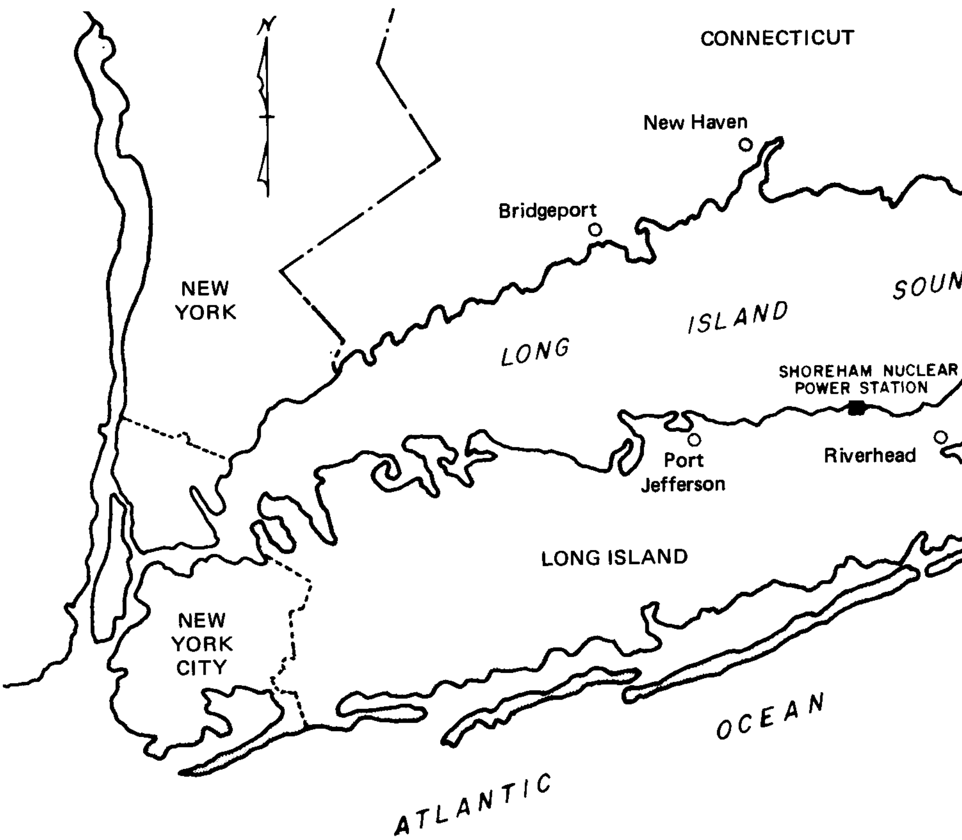

Figure 1. Location of Shoreham nuclear power statio

> than 4°F over the monthly means of maximum daily temperatures from October through June nor more than 1.5°F from July through September except that within a radius of 300 ft or equivalent area from the point of discharge this temperature may be exceeded.[1]

After preliminary evaluation of ecological data collected at the site by LILCO, the New York State Department of Environmental Conservation classified the site area as "coastal waters." This obviously placed very stringent limitations, particularly during the summer, on the type of circulating water system which could be used at Shoreham. As a result it became necessary to reevaluate the feasibility of the once-through cooling system being considered at the time.

Discharge Design Study Program

LILCO authorized Stone & Webster Engineering Corporation, Engineer-Constructor for the plant, to make a design study to develop a discharge system which would satisfy the coastal waters criteria. This work began in the spring of 1970 and was concluded early in 1971. A report outlining the studies and the proposed discharge design[2] was submitted to the State of New York, Department of Environmental Conservation in support of applications for the permits and certificates necessary to construct and operate the Shoreham circulating water discharge system.

Preliminary hydrothermal analysis indicated that a once-through cooling system would still be feasible if a multiport diffuser was employed for the discharge of the heated water. With this concept, dilution is accomplished by jet action of the discharge from the diffuser ports, which through turbulent mixing entrains substantial quantities of the surrounding unheated water. The result is a rapid temperature drop in a relatively short distance. Multiport diffusers have been used successfully for a number of years for the dilution and dispersal of sewage in receiving ocean waters.[3,4] Recently, similar techniques have been applied to the design of power station discharge systems.[5,6]

A conceptual design for the proposed Shoreham diffuser employing a number of jets was developed based on available empirical and theoretical data governing dilution in jet discharges.[4,7-9] However, because available theories and experimental data describing the behavior of jet discharges were based on physical conditions differing from those at Shoreham, additional site information was needed to provide a sound design basis. More specifically, at the site location there is a mean tidal range of about 6 ft, and currents trend generally east-west, reversing in direction about every 6 hr. The water depth at low tide is generally not over 15 ft deep on Herod Point Shoal which extends northward about 1 mile from the site.

Due to these conditions, there were two factors which could not be predicted theoretically with certainty. These were first, the effect of variable current velocity and reversing direction on the dilution ability of an array of jets in shallow water; and second, the amount of heat returned to the discharge area with reversal of the tide.

A program for obtaining the necessary design data was developed and coordinated by Stone & Webster's Environmental Engineering Division. The first phase of the program, which was to investigate various methods to obtain the needed data, resulted in the following conclusions.

A complete mathematical solution to the problem of temperature distribution in the discharge area was ruled out because no general theoretical solution was available. However, it was recognized that hydrothermal analysis could be used with confidence for parts of the problem. Many complex hydraulic problems have been solved directly by the use of physical models. However, there are many difficulties associated with properly simulating in an undistorted model the transient conditions in a segment of Long Island Sound large enough to contain a tidal excursion, and the use of distorted models to simulate turbulent mixing effects is considered questionable. It was, however, considered feasible to model the characteristics of a diffuser discharge in the near field under transient conditions. Also it became obvious that either a mathematical or physical model would require certain field data to define hydraulic and dispersion characteristics of the site.

After considering the above, it was decided that the most efficient approach would be to use a program which combined several engineering techniques. Accordingly, a method of attack was adopted which employed three distinct steps:

1. mathematical analysis
2. field studies
3. hydraulic modeling

The final phase of the program was to combine the results of these steps by means of a mathematical formulation to obtain the required solution to the problem.

Mathematical Analysis

Early in the design study a mathematical model was developed with the objective of showing the generalized analytical relations between the diffuser characteristics and the associated thermal effects in tidal waters. The model predicts the temperature rise at the water surface near the point of discharge as a function of

1. station operating conditions,
2. characteristics of the diffuser,
3. natural flow and temperature conditions in the near field area, and
4. dispersion, heat transfer to atmosphere and recirculation effects from the far field.

Figure 2 schematically diagrams the essential elements which are considered. The first five equations shown in Figure 2 describe the behavior of the system depicted, assuming uniform vertical mixing. Equation 6 permits consideration of naturally occurring differences between the surface temperature and the mean temperature in a vertical profile. The surface temperature is of principal interest for prediction purposes because the State criteria address themselves to this location. The simultaneous solution to these six equations yields

$$\Delta T_s = [\Delta T_c/S]\,[1 + RSQ_c/\textstyle\int u\,dA] + [T_m - T_s] \qquad (1)$$

shown in the center of Figure 2. Equation 1 is the mathematical relationship used to associate water surface temperature rise (ΔT_s) to the other system parameters.

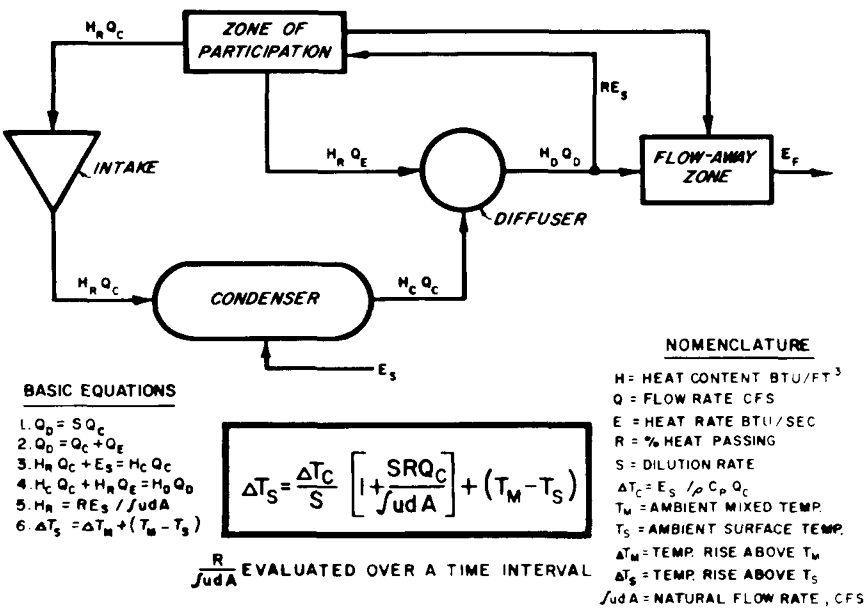

Figure 2. Mathematical model.

By way of brief explanation of the model, the zone of participation in the system diagram given in Figure 2 is that area from which water is supplied to the station intake and to the diffuser for dilution. The factor R is used to indicate that a portion of the condenser waste heat (E_S) which may recirculate to the zone of participation under natural flow conditions. Diluted discharge from the diffuser may return heat to the zone of participation or may pass to the flow-away zone. The flow-away zone is the area which receives the water which does not return to the zone of participation. The physical location of elements in the schematic diagram are shown in Figure 3.

Field Studies

Considerable information was already available on the general oceanography and hydrography of Long Island Sound, and specific data on currents and water temperature had been obtained from surveys by LILCO. However, this data was inadequate for determining the value of the term $R/\int u\,dA$ in Equation 1 which is the measure of the heat concentration in the zone of participation from the far-field return during tide reversals. This factor is time dependent, being influenced by the predictable cyclic nature of the tides and to some extent by more difficult to predict meteorological and hydrological events. One of the most challenging parts of the entire study program was the evaluation of this factor.

Far-field heat return predictions were based on field experiments conducted at the site using dye as a tidal current tracer material. The rationale behind this approach is quite simple. Dye is released in the discharge area in such a manner that a discharge flow field is produced similar to that expected during the discharge of heat. The dye is carried away from the discharge area under natural current conditions and subjected to the natural advective and dispersive characteristics of the receiving waters. At a later time some of the dye may return again to the area of discharge, due to current reversal. The amount of dye returning provides a basis for predicting the amount of heat return.

The dye dispersion study was performed between September 20 and October 1, 1970. Pritchard-Carpenter of Baltimore, Maryland, was responsible for technical aspects of the field program and provided most of the supplies and equipment, including a novel dye release system.

To simulate as nearly as possible the motion of heated discharge from the station, a fluorescent dye was released continuously along a north-south line in the discharge area. The dye release was made from five small dinghies, each equipped with a storage tank, metering pump and battery. A 20 per cent solution of Rhodamine WT, a fluorescent dye, was used as the

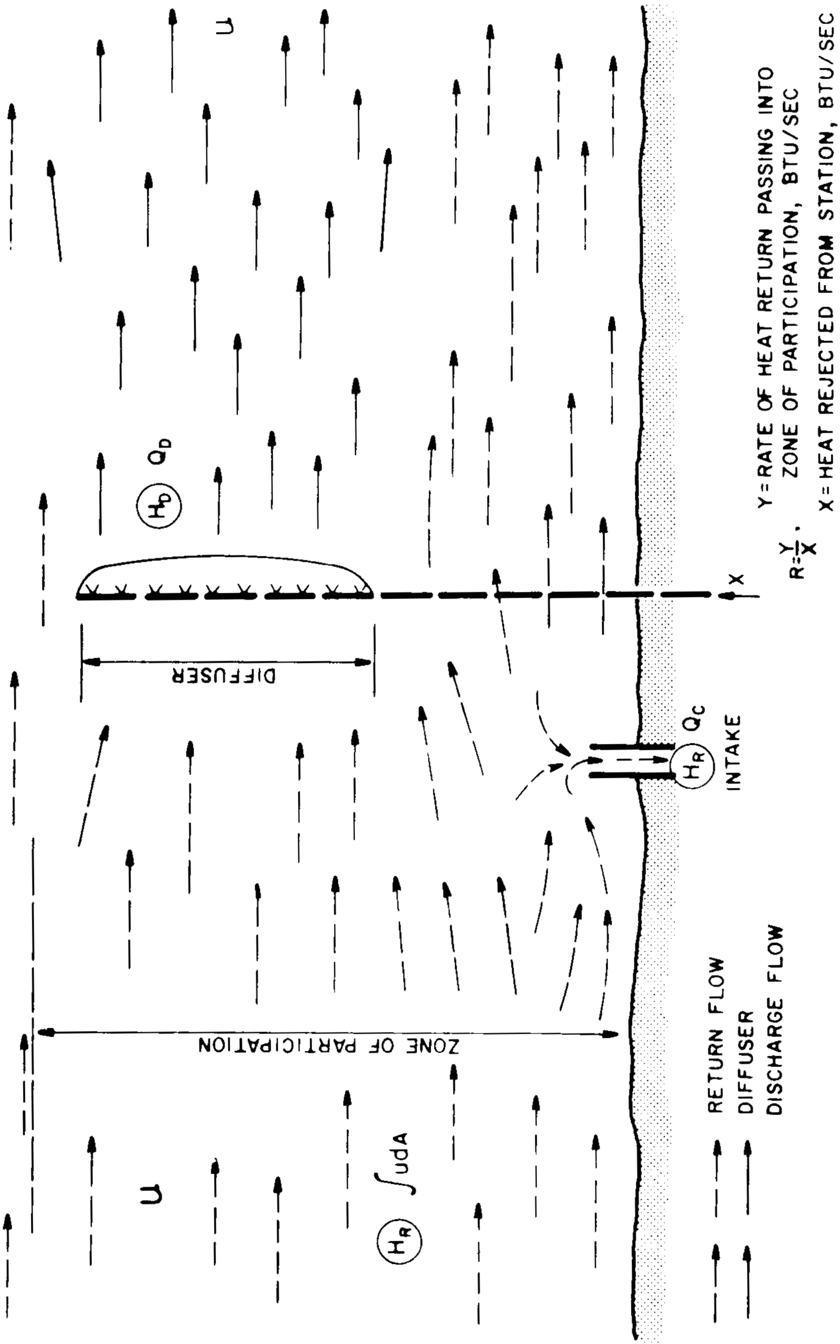

Figure 3. Heat and flow patterns.

tracer. The dye was pumped at a predetermined rate through a small tube which terminated about 1.5 ft below the water surface to promote initial mixing.

The distribution of the dye was measured over a period of nine days along a number of predetermined transects. During the study period, current meters were located permanently at mid-depth about 1,600 ft and 3,000 ft offshore. Locations of the dye release points, the transects, and the current meter installations are shown in Figure 4.

Tracer concentrations were measured by means of an under way sampling system mounted on the survey boat. While the boat maintained a constant course and speed along a particular transect, water from a selected depth was pumped through a fluorometer equipped with a recorder which provided a continuous trace of changes in dye concentration.

To simulate station discharge effects, a requirement of the study program was to inject dye continuously until a steady state condition was obtained. Since concentrations were found to vary considerably in the near field area depending on tide stage, steady state conditions were assumed to exist along a transect when average concentrations were similar for the same time in the tide cycle on successive days. In general, steady state as thus defined was reached after several tidal reversals in the western study area and after about 6 days of dye release. This condition existed generally throughout the zone within one tidal excursion. A dye decay experiment under controlled conditions indicated that the dye was essentially a conservative material when exposed to the Long Island Sound environment.

The factor initially determined from dye concentration and current measurement was the dye concentration returning to the zone of participation. This factor was adjusted to account for the nonconservative nature of the heat content of the protype discharge. Methods outlined by Edinger & Geyer[10] were used to account for heat decay by transfer with atmosphere.

Values of $R/\int u\, dA$, calculated using data from the dye concentration measurements for the three transects east and west of the discharge line, are shown in Figure 5. These curves present the data as a function of distance offshore for various times during the tide cycle to facilitate later use in predicting time dependent temperature rises for diffusers with various lengths.

For a period of about one to two hours after the beginning of slack water, it was impossible to obtain accurate dye return measurements because of the confused dye plume situation and because the discharge released in the period just prior to slack water was not uniformly mixed from top to bottom. Heat return during this period was determined later from the hydraulic model.

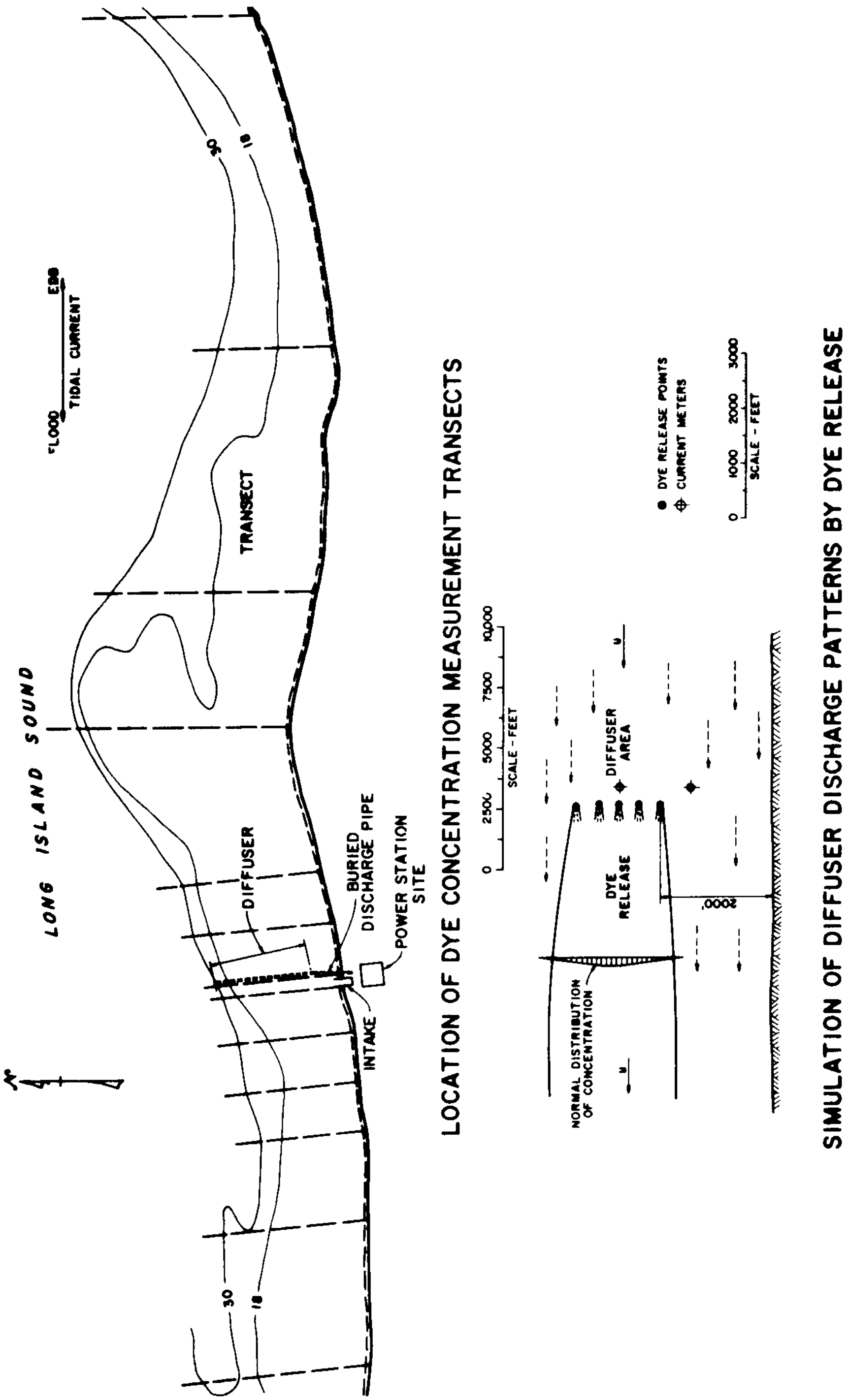

Figure 4. Dye dispersion study.

In additon to providing necessary input for the mathematical model, the dye studies provided other useful information on the large scale current patterns in the general vicinity of the site. As time permitted during the field program, concentration measurements were made at some distance from the site in order to learn where the dye was going. It was learned that there was a continuous traceable flow offshore along the coast to the east, but on the contrary, the flow to the west never extended beyond the distance it could travel during a single flood tide excursion. In fact, near low slack water on the ebb tide during most of the study period there was only a small residual left anywhere west of the dye discharge line. This fact is evident from the low return rates shown in Figure 5 at this time. Current measurements during the study confirmed the net transport to the east.

On the day before ending dye releases, a series of transects were run working to the east to determine how far the dye could be traced. The dye was detected in very small concentrations about 10 miles east of the site, within 1 mile of the shore. At this location, the concentrations were so low that the analogous temperature rise would be insignificant. During these tests, dye was not detected more than two miles north of the Long Island shoreline. Table 1 gives predicted temperature rises along the center line of the discharge plume which will generally follow the shoreline to the east. These temperature rises were derived from the concentration measurements corrected for heat transfer to the atmosphere.

Hydraulic Model Studies

The final major step in the three-part approach to the design study was to determine S in Equation 1 which defines the dilution capability of the diffuser. To determine this factor for various diffuser arrangements, extensive hydraulic model studies were conducted at the Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, a division of the Department of Civil Engineering at the Massachusetts Institute of Technology. These studies are reported in Reference 11.

Table 1. Predicted Temperature in the Far Field

Distance from discharge (ft)	*Surface temperature rise above ambient (°F)*
20,000	0.65
30,000	0.45
40,000	0.20
50,000	0.10

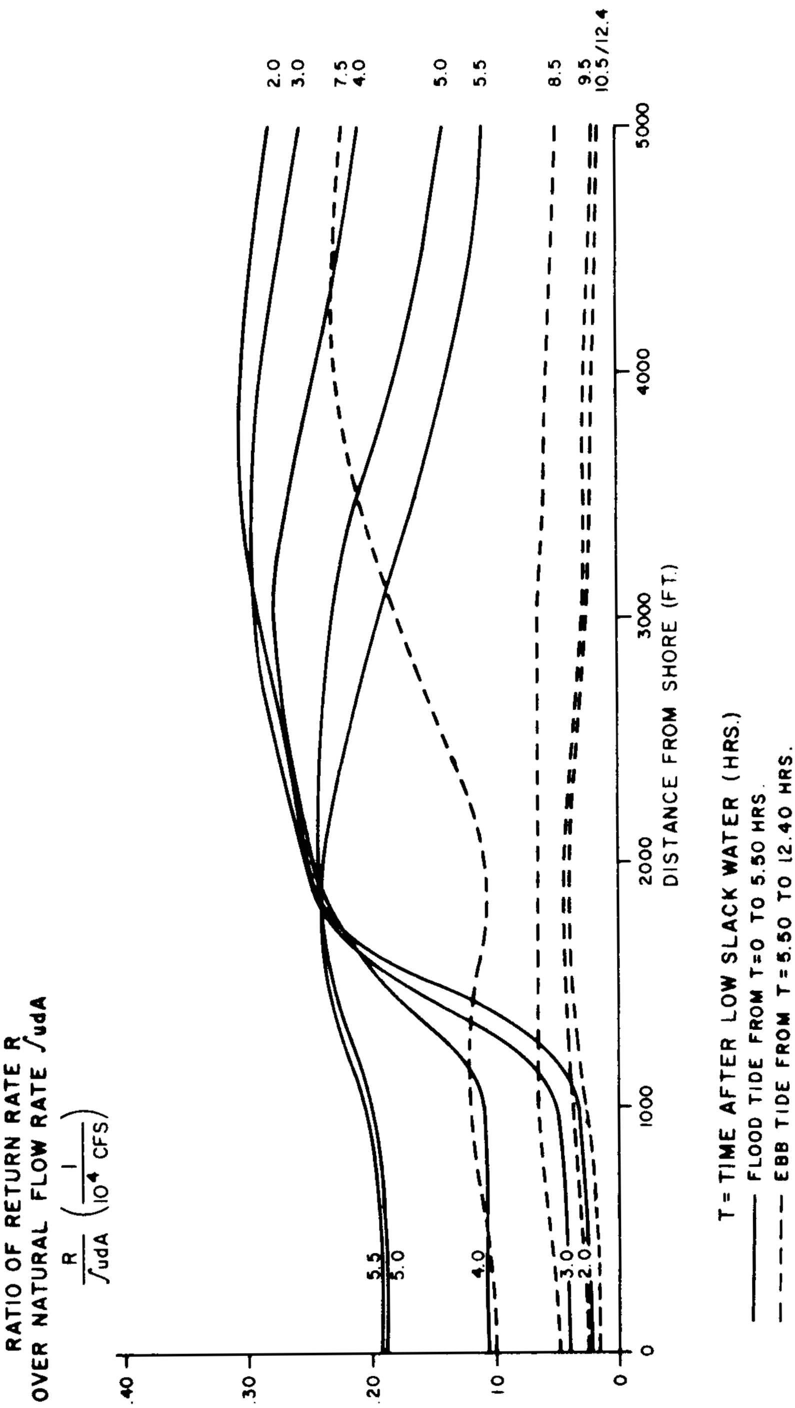

Figure 5. R/∫ ud A vs. distance from shore.

The work completed at MIT was divided into two phases. In Phase I, a study was made of a two-dimensional model which isolated the effects of the variables associated with the diffuser design rather than its location. Three adjacent ports were investigated at an undistorted scale of 1/20 and 1/40. The ability of the jets to induce mixing was measured as a function of discharge velocity, water depth, port diameter, depth above bottom, spacing between ports and angle with the horizontal. The dilution ratio was determined and compared with a theoretical model. As a result a simple predictive formula was developed for a row of jets in shallow water.

In Phase II, a three-dimensional, undistorted site model with a scale of 1/100 was used to investigate the influence on the dilution capability of the diffuser of interactions such as intake flow, bottom contour, diffuser length, and unsteady tidal currents. The initial choices of port spacing, diameter, and height were determined using the results of Phase I. In short, the main objective of Phase II was to evaluate the effect of overall dimensions, location, and orientation of the diffuser on the near-field temperature distribution.

The various diffuser arrangements shown in Figure 6 were tested during Phase II with steady state ambient currents. The tests in which the diffuser was placed along a line perpendicular to the ambient tidal current (arrangements 5, 6, and 7) showed the greatest dilution capability. The three outlet orientations for the perpendicular arrangement were then tested under conditions of time varying currents. This was done to determine which orientation would perform best during tide reversal after slack water, since during this period temperature rises were the highest due to near field heat recirculation. Tests on arrangement 7 produced the lowest maximum temperature rise. Therefore, this arrangement was selected as the one to be used in the protype, and the data collected for these tests were used as a basis for predicting the dilution capability of the Shoreham diffuser.

Diffuser Design

Obviously the 1.5°F temperature rise criteria for the summer months controls the diffuser design. Also by examination of Equation 1, it is seen that the smaller the difference between the natural mean temperature, T_m, and the surface temperature, T_s, the larger ΔT_s will be. Measurements made at the site over several years showed that for the summer months this value is smallest in September when $(T_m - T_s)$ averages -0.5°F.

If Equation 1 is solved for S, the dilution factor, it can be rewritten as

$$S = \Delta T_c / [\Delta T_s - (\Delta T_c Q_c R / \int u \, dA) - (T_m - T_s)] \qquad (2)$$

For given values of ΔT_c, ΔT_s, Q_c and $(T_m - T_s)$, the required values of S can then be calculated for different $R/\int u\,dA$ over the complete tide cycle. This was done for hourly intervals throughout the tide cycle. Model tests were then made to determine the outlet spacing and sizes to produce the necessary dilution rates required by Equation 2 during the complete cycle.

The critical period, controlling the dilution rate required to meet the State criteria of 1.5°F above ambient at the water surface, occurred one hour after slack water. During most of the tidal cycle, the temperature rise was considerably less than the required value.

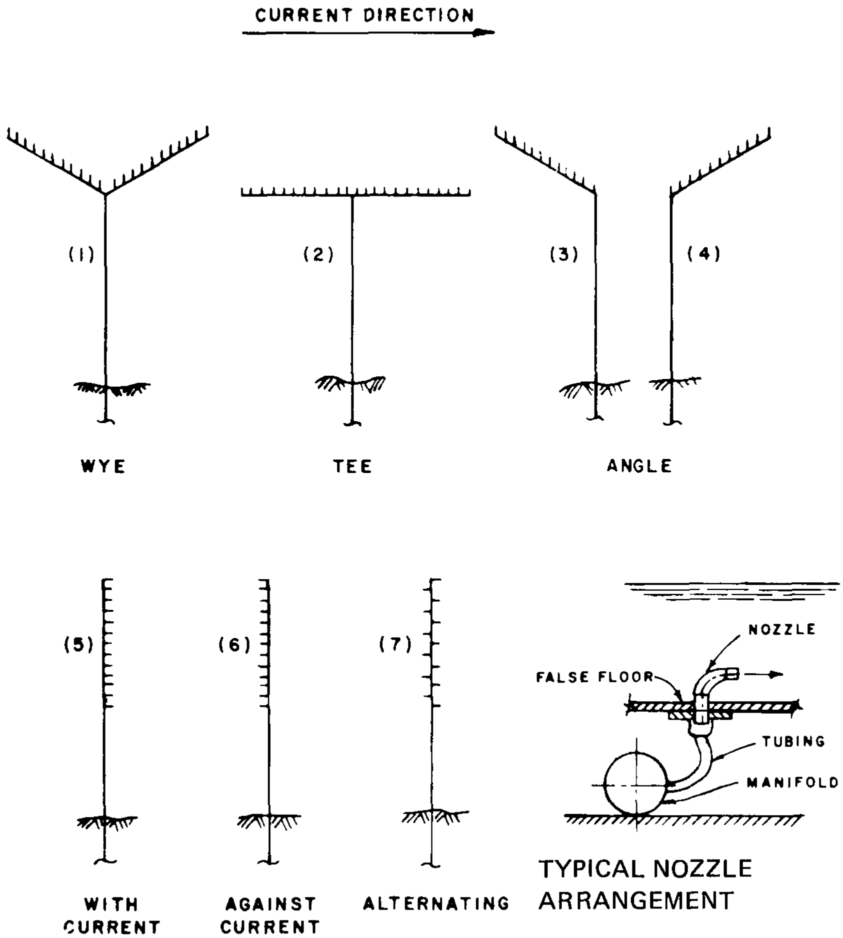

Figure 6. Schematic arrangement of diffuser for phase II model tests.

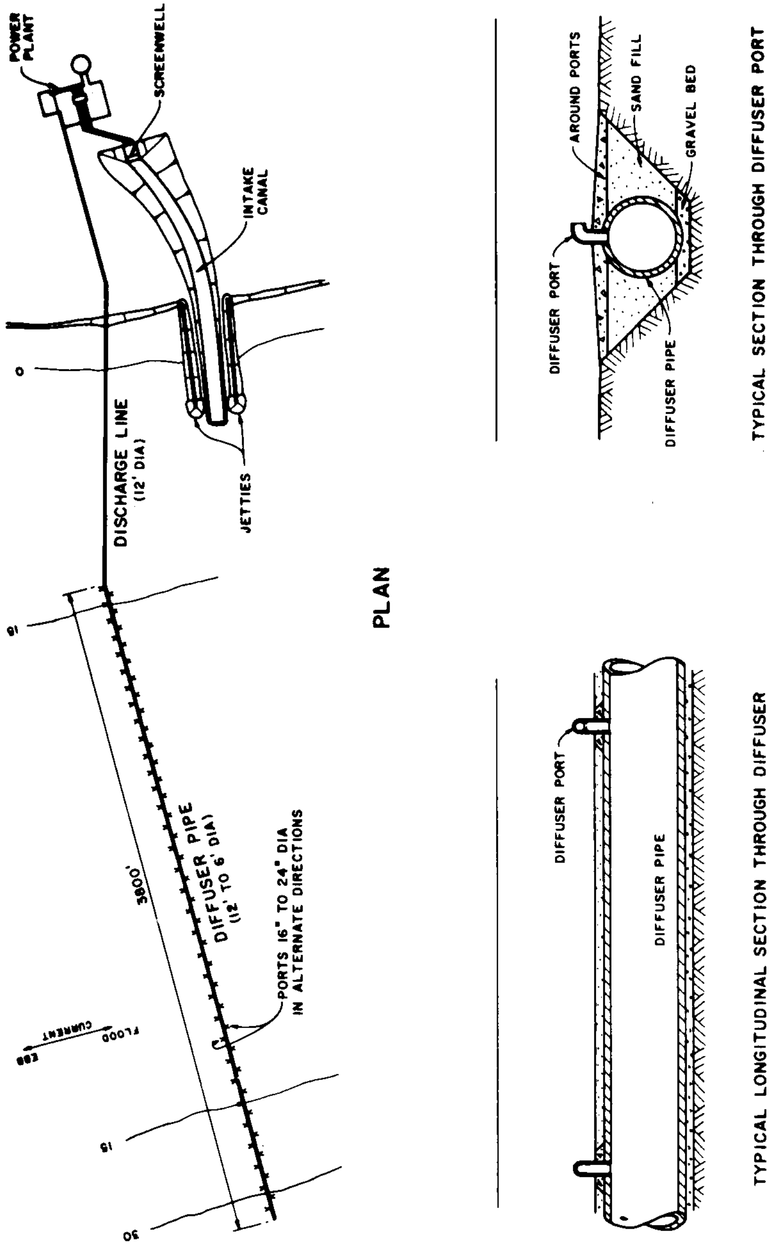

Figure 7. Intake and discharge arrangement.

After nozzle spacing was determined, a hydraulic analysis was made to check the discharge along the entire length of the diffuser to ensure a uniformly distributed flow. In this analysis pipe sizes were varied to balance the discharges as much as practical and keep velocities within the limits of from 10 to 14 fps. This technique is similar to that described in Reference 4.

Figure 7 shows the final arrangement of the diffuser which was developed as a result of the design studies. Discharges begin about 1,600 ft offshore where the water first reaches a depth of 15 ft below mean low water. The diffuser then extends northward for about 3,800 ft in a direction perpendicular to the principal tidal currents. The station discharge of 1,320 cfs is released from 65 outlets extending upward through the bottom from a buried pipe and discharging horizontally, except for the end outlet, in alternating east and west directions.

Summary and Conclusions

The design study for the Shoreham circulating water discharge system employed a unique combination of mathematical analysis, field studies, and hydraulic model studies to develop a once-through cooling system to satisfy the stringent coastal waters thermal criteria of the State of New York. The system developed uses a multiport diffuser with 65 submerged outlets which discharge horizontally along a 3,800 ft line perpendicular to the principal current direction, starting about 1,600 ft offshore.

In developing the design, one of the most difficult problems was the determination of far-field heat return to the discharge area resulting from reversing tidal currents. This factor was determined by means of a dye study. Hydraulic model studies provided essential information on the dilution capability of a diffuser system in the shallow water and under the influence of transient currents. The model studies also defined the near-field temperature buildup at the time of tidal current reversal. The results of the dye studies and the hydraulic model studies were combined by use of a simple mathematical relationship which provides the water temperature rise at the surface in the discharge area.

This study shows how a complex problem may be synthesized into several less complex steps which then can be solved by readily available techniques.

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