Canada Centre for Inland Waters
Department of the Environment
Government of Canada

# Study of Thermal Discharge Diffusion for the Canadian Great Lakes Shoreline

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Acres Consulting Services Limited
Niagara Falls, Ontario

ACRES

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## SUMMARY

A study was undertaken of diffusion in the Great Lakes of waste heat discharge from thermal electric generating stations. For purposes of economic comparison,an estimate was made of the additional cost of using offshore submerged jet diffusers for cooling water discharge for all generating stations on the Canadian shores of the Great Lakes up to the year 2000, rather than the conventional shoreline surface discharge system presently being utilized.

To allow a valid comparison of the physical effect of the two systems, a methodology, verified by model tests, was developed for estimating dilution and surface water temperatures obtained with submerged jet diffusers. This was used to compare their performance with that observed for surface discharge systems.

The study indicated that submerged jet diffusers would require a total increase in construction cost and capitalized operating cost of $210 to $435 million, depending on the temperature criterion adopted. These increases represent 0.5 to 1.1 per cent of total capital cost of the generating plants considered. The corresponding incremental costs for energy are 0.018 and 0.036 mills/kwh.

As a physical measure of environmental impact, the study shows that exclusive use of submerged jet diffusers to limit surface temperature to 1.7 Centigrade degrees (3 Farenheit degrees) or less, at all present and future thermal generating stations, would reduce the lake surface area contained by the 1 Centigrade degree differential isotherm from 98,440 square kilometres to 1,431 square kilometres, a reduction of

98.6 per cent. For higher isotherms the percentage reduction in area would be greater. Offshore submerged jet diffusers provide protection of the biologically productive shoreline area from high temperatures in the discharge plume. On the other hand, surface discharge systems in naturally cold water lakeshore situations can induce greater biological productivity in the surrounding surface waters that might be beneficial in some cases. The choice for a specific site requires assessment of environmental conditions and objectives at that site. The methods for assessing these are not within the scope of this study.

# 1 - INTRODUCTION

## 1.1 - The Waste Heat Question

Once-through cooling by lake water is used by thermal electric generating stations along the shores of the Great Lakes as the most economical means for disposing of the heat rejected at the condensers. The flow of cooling water is warmed as much as 17 Centigrade degrees and in most installations the heated water is returned to the lake through an open channel across the shoreline. The total quantity of heat involved is equivalent to roughly one to two times the energy output of the generating station.

Potentially harmful effects of waste heat in the lakes have been recognized. The effects of the use of the lakes for the disposal of increasing quantities of waste heat and the best means for taking these into account are currently being weighed by the Federal and Provincial Governments in Canada as part of an Environmental Impact Assessment Procedure.

In some jurisdictions, notably, certain states on the southern shores of the Great Lakes, restrictions based on a maximum allowable increase in water surface temperature have been applied uniformly to all heat sources and all sites. The magnitude of the temperature increase permitted is an implied judgment of the importance of the various physical, environmental, and socio-economic factors involved. Where strict standards based on allowable surface temperature increases have been adopted, as in New York State, they have generally led to the design of submerged jet diffusers in order to achieve physical separation from shore facilities and rapid dilution of the warm water into the lake. A number of these diffusers are now being built.

An alternative approach, which would have the merit of accounting for the great diversity of conditions encountered at various sites in Canada, would be to evaluate physical effects against environmental goals and impacts on a site-by-site basis. In one instance, an offshore outfall location could be required primarily to provide protection of ecologically sensitive shore areas that can tolerate only small increases in temperature above those occurring naturally. In another case, if very rapid reduction of temperature rise were required adjacent to the outfall to avoid chaining with nearby thermal plumes, a submerged jet diffuser would be advantageous. Alternatively, for a thermal generating plant which has a low rate of heat rejection, and is situated on a cold water shoreline, a surface discharge might achieve the environmental objectives.

This study examines two facets of the overall problem:

(a) What measurable differences in the spatial distribution of temperature would result from application of thermal discharge regulations based on restricting temperature excess at the surface?

(b) What increased costs to power consumers would be implied?

The answers to these questions will form part of the basis for appraisal of biological effects, leading ultimately to selection of a control strategy for Canada.

## 1.2 - The Basis for Comparisons

The introduction of substantial amounts of waste heat from a large thermal electric generating station into a lake has a measureable physical effect. For surface discharge from the shoreline, the differential in surface water temperatures has been measured by Bernard C. Kenney[1]. However, offshore submerged jet diffusers are a relatively new application and there is only limited experience and information on their performance and cost. The terms of reference for this study therefore emphasized:

(a) Development of a mathematical model, verified by physical model experiments, for predicting water surface temperature differentials and other thermal effects induced by multiport offshore submerged jet diffusers.

(b) Use of the model for conceptual design of submerged jet diffusion outfalls to determine the additional cost involved in meeting a range of excess surface temperature design criteria.

In order to facilitate the eventual use of the study results in interpreting the physical descriptions of thermal plumes in terms of ecological changes and social consequences, guidance was obtained on the forms of plume description which would be most suitable.

## 1.3 - Study Objectives

In specific terms, the objectives of the study are as follows:

(a) To provide descriptions of typical offshore submerged multiport diffusers and the nature of their plumes.

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[1] Kenney, B.C. The Physical Effects of Water Heat Input to the Great Lakes. Canada Centre for Inland Waters, Inland Waters Directorate, Scientific Series No. 28, 1973.

(b) To develop methodology for estimating the differences in capital and operating costs for onshore surface and offshore submerged multiport discharge alternatives.

(c) To estimate, as a limiting case, the additional costs that would be implied by hypothetical thermal discharge regulations requiring the exclusive use of submerged jet diffusers instead of shoreline surface discharges.

(d) To demonstrate the sensitivity of the foregoing additional costs to the severity of the operating criteria required to be satisfied.

## 2 - ANALYTICAL MODELS

To accomplish the objectives of the study, analytical models of both surface discharge plumes and submerged jet discharge plumes were necessary.

For the surface discharge alternative, the study prepared for the Canada Centre for Inland Waters by Bernard C. Kenney[1] was utilized directly. Kenney's empirical analysis was used to give continuity to the CCIW Program of study and because its application in the present study is straightforward. The application of a more complex method of analysis was not considered justified.*

For the submerged jet diffuser, considerable attention was given to developing a semi-empirical analytical model. This model is based on the two-dimensional analytical diffusion model developed by Koh and Fan[2] for the buoyant plume from a row of submerged jets discharging into an infinite body of still, linearly stratified water.

In practice, the diffusion of a buoyant plume is three-dimensional and the assumed simple boundary conditions seldom, if ever, prevail.

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[2] Koh, R.C.Y. and Fan, L.N. Mathematical Models for the Prediction of Temperature Distributions Resulting from the Discharge of Heated Water into Large Bodies of Water, for the Environmental Protection Agency, October, 1970.

*Acres generally uses a modified form of the work by Y. Jen, et al (Surface Discharge of Horizontal Warm Water Jet, Journal of the Power Division, ASCE April 1966, pp. 1-29) for surface discharge plume analysis.

Also, the Koh and Fan model represents only the first phase of plume dispersion in which the plume momentum and buoyancy govern the flow. The later phases of unsteady buoyant spread on the surface of the receiving body of water, turbulent diffusion within the receiving body, and surface heat exchange to the atmosphere are not represented.

As an expedient to at least partly overcome the foregoing limitations of the model and to yield more realistic plume descriptions, both an empirical calibration and means of adjusting the results of the analytical model were obtained.

The analytical model was modified slightly and calibrated on the basis of experimental results from physical models for the basic condition of a horizontal discharge into unstratified, still water adjacent to a lake bed.

The modification provides prediction of mean temperature at the lake surface along a diffuser of finite length. This important feature permits the magnitude (or intensity) of the heat rejection to be accounted for.

The calibration of the analytical model allows for such things as:

(a) Inaccuracies in the approximations used in the analysis (e.g. two-dimensional flow field, length of flow establishment zone, negligible internal friction, criteria for point of transition from behavior as a row of independent circular jets to behavior as a slot jet, and assumed Gaussian form for the transverse distributions of velocity, density and temperature).

(b) Effect of the proximate lake bed on the intermediate three-dimensional field of dilution water flow.

This calibration with experimental data has given the mathematical model a capability to recognize the important effects of proximity and boundary conditions on the magnitudes of induced flows. An overall entrainment coefficient for a group of jets in this context is typically 0.040 compared with values of from 0.057 to 0.080 for a single round jet discharging into a semi-infinite body of unstratified still water.

From additional physical model data, non-dimensional relationships based on the analytical model predictions for the basic discharge conditions were derived to account for:

(a) Buoyant surface spread of the plume.

(b) Turbulent diffusion in the receiving water.

(c) The effects of drift currents on plume trajectory and form, surface isotherm areas, and rate of dilution.

(d) The effects of lake bed slope on plume length and rate of dilution.

(e) The effect of the discharge induced three-dimensional dilution water flow field on temperature distribution within the plume.

The experimental data used for the foregoing analytical model enhancement was obtained from two independent physical model studies.* These studies were carried out by Acres to derive conceptual design details for submerged jet diffusers at two

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*As no submerged jet diffusers of the type considered herein are in actual operation, no field data are available.

quite different lake sites, thereby providing a broad range of lake current velocities of 0 to 0.76 m/s (0 to 2.5 fps), bottom topography (1:12.5 and 1:220 slopes), and ambient temperature (1.7 degrees Centigrade to 26.7 degrees Centigrade). The optimization nature of the studies also provided parametric data for discharges of from 22.65 to 73.61 $m^3/s$ (800 to 2,600 cfs), initial jet temperature excess from 5.6 degrees Centigrade to 16.7 degrees Centigrade, initial jet velocities from 4.57 to 15.24 m/s (15 to 50 fps), port diameters of from 0.30 to 1.22 metres (1 to 4 feet), port spacings of from 3.05 to 304.8 metres (10 to 1,000 feet) and number of ports from 1 to 59.

Although one study represented onshore currents, the data obtained were too limited to be useful in developing a generalized empirical function.

The models from which the empirical data were obtained were carefully scaled and sized in accordance with criteria developed on the basis of experience in five model basins for two other design studies. These criteria consider the relative importance of the six mechanisms[3] of heat dispersion, which operate for both the surface or submerged jet discharge alternatives. Each of the model studies required several hundred thousand point temperature measurements at various depths in the model to define the thermal plumes under the various lake ambient and operating conditions. The physical models have been verified by comparison with field data for surface discharge where such data have been available in the particular project area.

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[3] These are momentum entrainment, buoyant plume rise, ambient current transport, ambient turbulence, densimetric spread and surface cooling as described by P. Ackers, edited by F. L. Parker and P. A. Krenkel, Modelling of Heated Water Discharges, Chapter 6, Engineering Aspects of Thermal Pollution, Vanderbilt University Press. 1969.

In spite of the foregoing experimental justification of the analytical model, it is readily acknowledged that certain limitations make this semi-empirical approach fall short of properly satisfying existing needs for comprehensive analytical modelling of thermal discharges. Nevertheless, the model is considered to be an improvement over Koh's basic analytical model and, as such, a valid, practical engineering expedient for preliminary design of submerged jet diffusers until an improved form of model can be developed.

Comparisons of the temperatures predicted by the analytical model with the physical model results are shown in Figures 1 and 2.

Figure 1 illustrates verification of the mean surface temperature rise over the diffuser length predicted by the analytical model.

Figure 2 shows comparisons of the maximum point surface temperature rise, and the value of the isotherm of temperature rise enclosing areas of 4,047 square metres and 20,235 square metres (1.0 acres and 5.0 acres) predicted by the analytical model with those of the physical model test results.

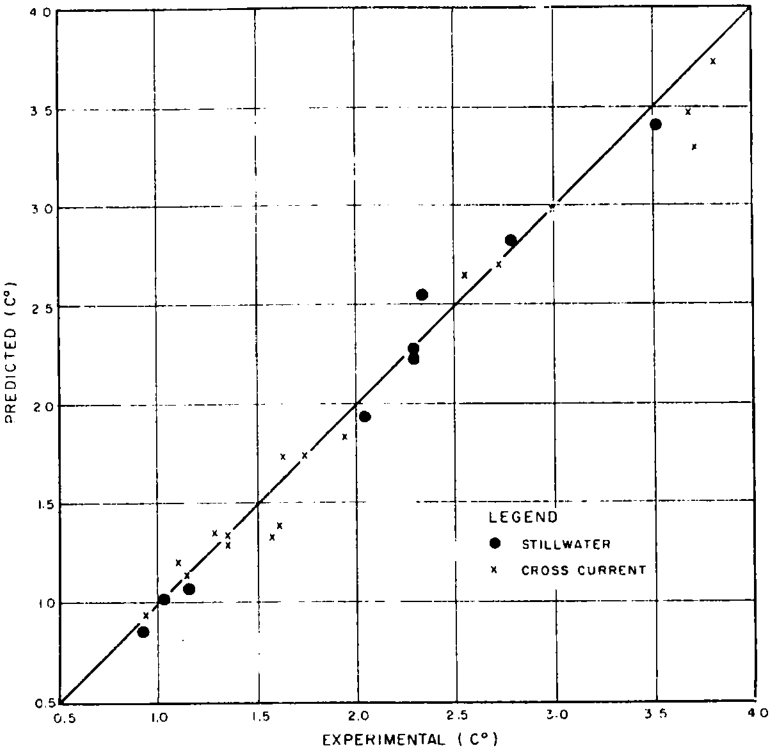


FIGURE 1

COMPARISON OF RESULTS
MEAN SURFACE TEMPERATURE RISE

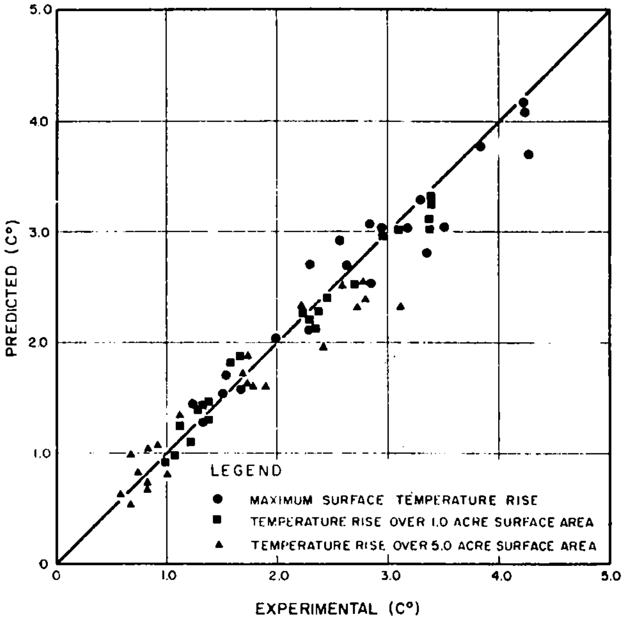


FIGURE 2
COMPARISON OF RESULTS
SURFACE TEMPERATURE RISE,
MAXIMUM, OVER 1 ACRE AND 5 ACRES

ACRES

## 3 - SUBMERGED MULTIPORT DIFFUSERS

The submerged multiport diffuser is a recent innovation designed to provide rapid rates of temperature dilution for condenser cooling water discharges from thermal electric generating plants to receiving bodies of water. Its use has been necessitated in the United States by concern with the potential environmental changes that might result from concentrated releases of the large quantities of waste heat characteristic of thermal electric generating plants. This concern has been expressed in terms of "near field", or mixing zone temperature criteria with which thermal discharge arrangements must comply.

As yet, no submerged multiport diffusers are in operation in the Great Lakes, although several are planned and in construction in the United States. None are presently planned for the Canadian shoreline of the Great Lakes.

There are several possible configurations for the arrangement of the ports in a submerged multiport diffuser. Of these variations, only one has received appreciable consideration for use in the Great Lakes. This arrangement was adopted for consideration in this study and is described as follows:

### 3.1 - Description of Diffuser

The submerged jet diffuser considered herein comprises a row of ports on a line located offshore and essentially parallel to the shoreline to discharge horizontally into a receiving body of water, near its bed and away from the shoreline.

The ports may be an array of either equally spaced single ports or equally spaced pairs of ports on bifurcated elbows (double ports). A 1:20 scale physical model study has indicated an optimum bifurcation angle of about 20 degrees.

The double-port arrangement is generally found to be more economical if the manifold supplying the nozzles is a subsurface tunnel under the lake bed, because of the cost of underwater drilling of "risers" to connect the nozzles and the manifold. The single-port array is generally more economical if the manifold is a steel conduit, located in a surface excavation in the lake bed, because of the saving in cost of manufacture of the complex bifurcations.

Comparative performance tests undertaken in two different physical model studies have shown the dilution performance of a bifurcated arrangement under critical lake current conditions to be practically identical to that for an equal number of identical single ports spaced over the same total distance.

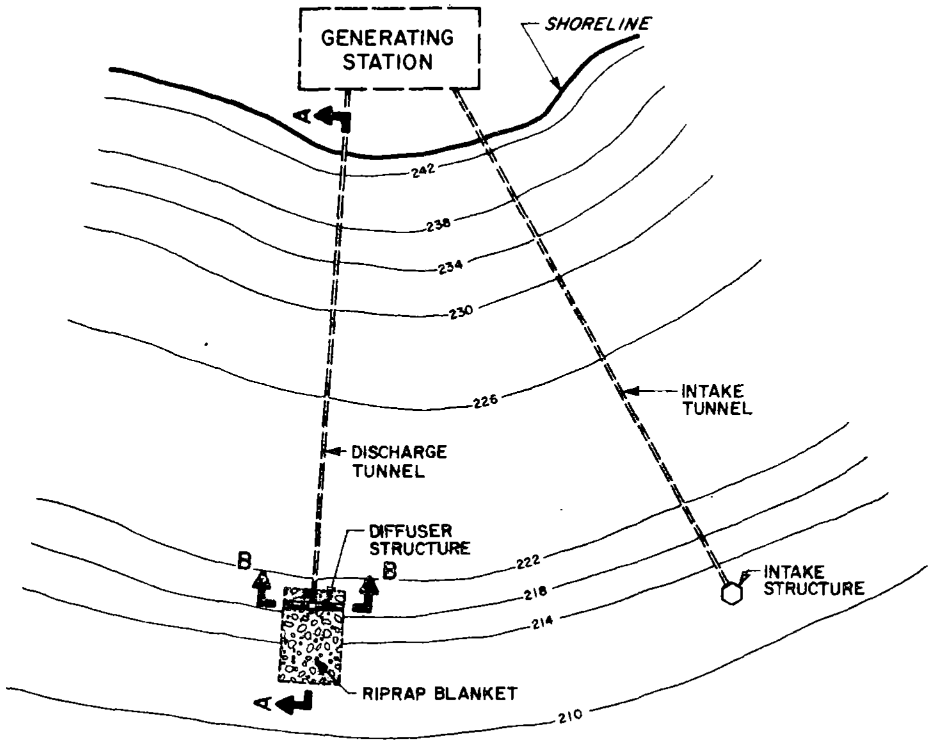
The conduit carrying the condenser cooling water from a wet well onshore to the point of discharge in the lake may also be, regardless of type of manifold, either a conduit excavated in rock well below the surface of the lake bed or a conduit laid in an excavation in the lake bed. The choice of type and details is generally based on considerations of:

- safety in the event of seismic activity
- economy of construction and operation
- potential environmental effects both during construction and over a long term.

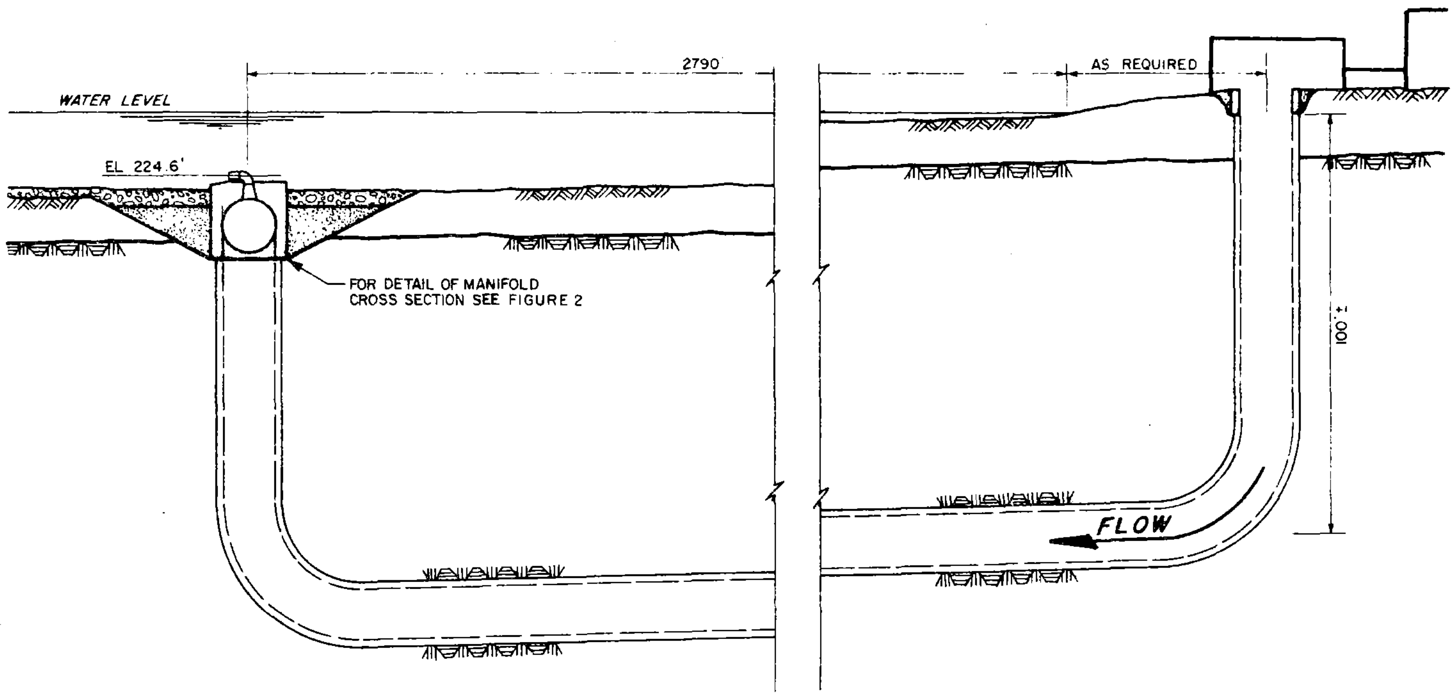
The selection of a general arrangement for the diffuser and intake structures relative to the shoreline and local hydrographic features requires consideration of the possibility and extent of recirculation of the heated discharge to the intake. Such circulation, dependent upon the direction, frequency, duration and magnitude of the local lake currents, is undesirable from the point of view of both fish attraction to the intake and efficiency of plant operation. In some cases the diffuser location and general arrangement is also influenced in some measure by a preference to minimize construction activity in important areas of bed-fixed benthos.

It is evident, even without consideration of the factors affecting the detailed design and performance of submerged diffusers, that each diffuser and intake arrangement must be "tailored" to suit a particular site. The analyses carried out in this study were based on arrangements chosen according to conditions determined on a site-by-site basis. For illustration, the typical arrangement shown in Figure 3 for a 2,056-Mw nuclear site is used.

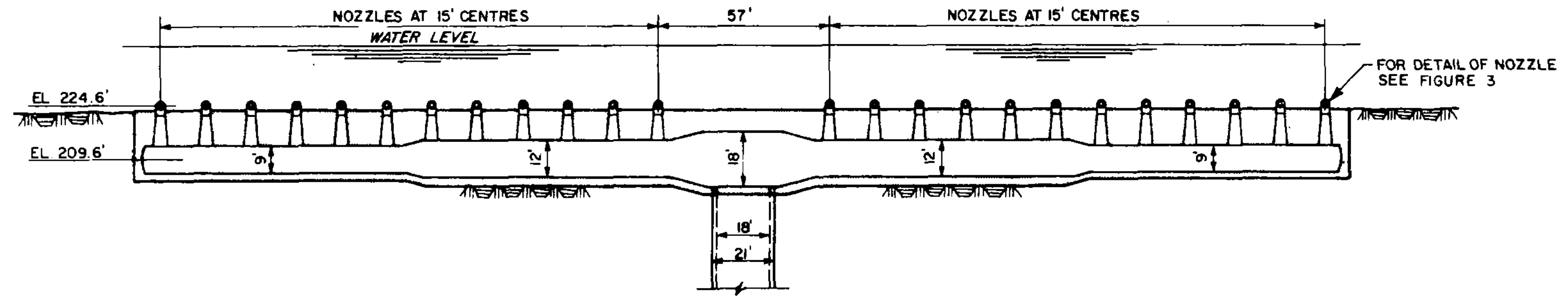
The typical arrangement shown in Figure 3 comprises twenty-four 0.61-metre (2.0-foot) diameter ports spaced at 4.57-metre (15-foot) intervals to discharge 81.67 $m^3/s$ (2,885 cfs) of cooling water flow at 12.19 m/s (40 fps) with an initial temperature excess of 13.9 Centigrade degrees. The centre line of the ports are located 6.10 metres (20 feet) below the mean low water level of the lake and 1.52 metres (5 feet) above the original lake bed, about 914.4 metres (3,000 feet) offshore. The manifold and nozzles are secured in place in a lake-bed excavation by means of a continuous tremie concrete anchor block and sand and gravel backfill. Although lake-bed scour protection comprising a 0.46-metre (1.5-foot) deep rock-fill blanket of 15.24-centimetre (6-inch) diameter, or less, stone for a distance of 152.4 metres (500 feet)



PLAN



SECTION A-A



SECTION B-B

FIGURE 3

## TYPICAL SUBMERGED THERMAL DIFFUSER LAYOUT

NOTE

THIS IS A TYPICAL LAYOUT OF A NUCLEAR GENERATING STATION FOR THE FOLLOWING PLANT CHARACTERISTICS:

CAPACITY : 2056 MW
DISCHARGE : 81.67 $m^3/s$ (2885 cfs)
TEMPERATURE RISE ACROSS CONDENSER : 13.9 C°

downstream of the nozzles is shown, such extensive protection is generally not required.

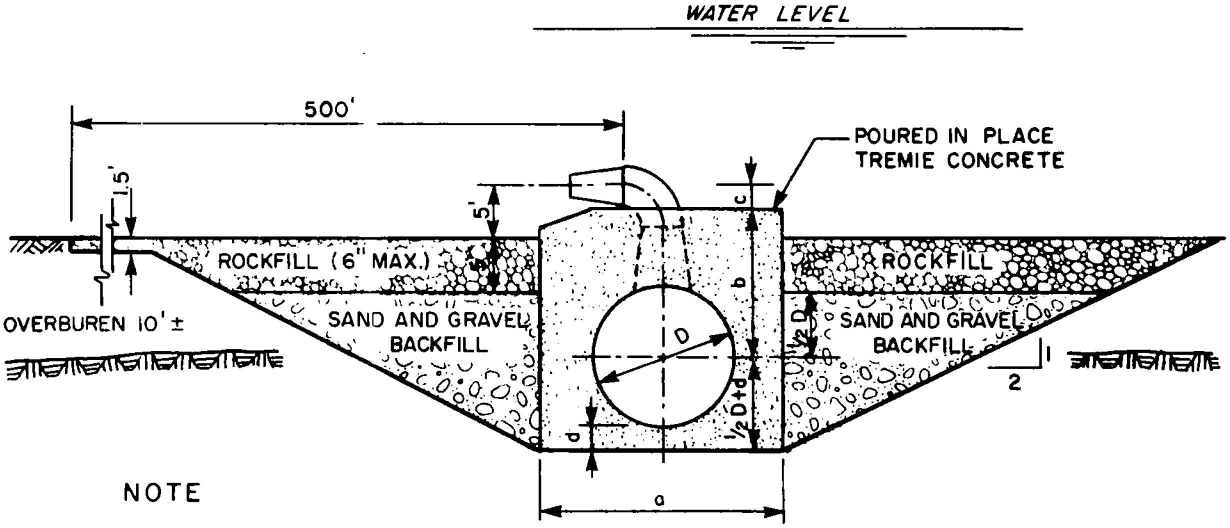
The arrangement in Figure 3 provides a 762.0-metre (2,500-foot) separation of the intake and diffuser, with the intake located 1,036.3 metres (3,400 feet) from shore in 5.64 metres (18.5 feet) of water below the mean low water level.

The diffuser supply conduit is a concrete-lined tunnel some 30.48 metres (100 feet) below the lake bed, thereby by-passing the major zone of fixed benthos and providing some additional measure of security in the event of seismic activity at the site. Details of the diffuser placement and the steel diffuser nozzles are shown in Figures 4 and 5. These latter figures also provide some dimensional details for other diffuser sizes considered in Section 4 herein.

## 3.2 - Present Design Practice

Submerged multiport diffusers are designed to satisfy a specified near-field lake surface temperature dilution criterion at minimum cost and with minimum secondary environmental effects. The design and performance are dependent upon and involve a number of factors and variables which can be generally considered as climatic factors, lake factors, generating station factors and diffuser geometry.

Climatic factors control the rate of heat exchange between the plume and the atmosphere, the ultimate "sink" for all rejected heat. The lowest rate of exchange, and therefore the greatest plume temperature, occurs with still, humid air at nearly the same temperature as the ambient lake temperature. This condition is normally assumed for diffuser



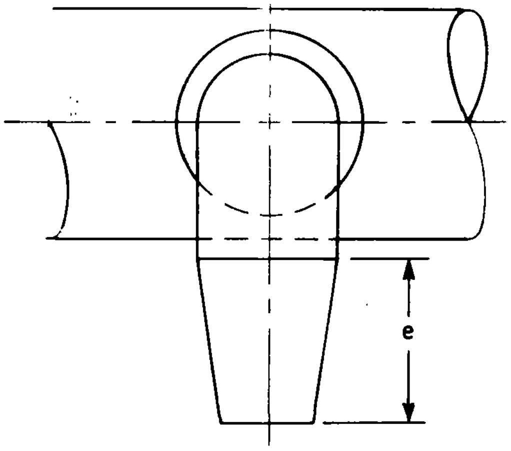
NOTE

a = MAX OF ( $b + \frac{1}{2}D + d$ ) OR 1.5 D

| (ft) D(ft) | 2.0 FOOT NOZZLE | | | | | 2.5 FOOT NOZZLE | | | | | 3.0 FOOT NOZZLE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | a | b | c | d | e | a | b | c | d | e | a | b | c | d | e |
| 15 | 23.0 | 13.5 | 1.5 | 2.0 | 19.5 | 22.625 | 13.125 | 1.875 | 2.0 | 19.5 | 22.25 | 12.75 | 2.25 | 2.0 | 19.5 |
| 12 | 21.5 | 13.5 | 1.5 | 2.0 | 18.0 | 21.125 | 13.125 | 1.875 | 2.0 | 18.0 | 20.75 | 12.75 | 2.25 | 2.0 | 18.0 |
| 10 | 20.5 | 13.5 | 1.5 | 2.0 | 17.0 | 20.125 | 13.125 | 1.875 | 2.0 | 17.0 | 19.75 | 12.75 | 2.25 | 2.0 | 17.0 |
| 8 | 19.0 | 13.5 | 1.5 | 1.5 | 15.5 | 18.625 | 13.125 | 1.875 | 1.5 | 15.5 | 18.25 | 12.75 | 2.25 | 1.5 | 15.5 |
| 6 | 18.0 | 13.5 | 1.5 | 1.5 | 14.5 | 17.625 | 13.125 | 1.875 | 1.5 | 14.5 | 17.25 | 12.75 | 2.25 | 1.5 | 14.5 |

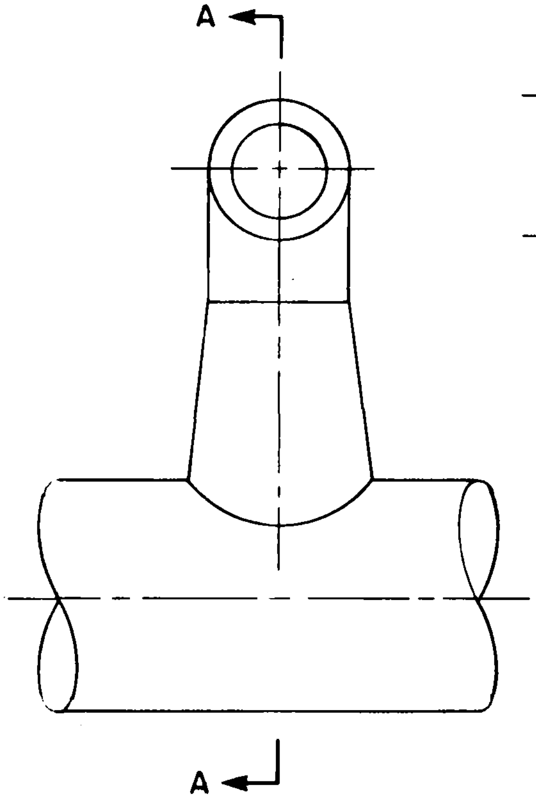
FIGURE 4

MANIFOLD CROSS SECTION

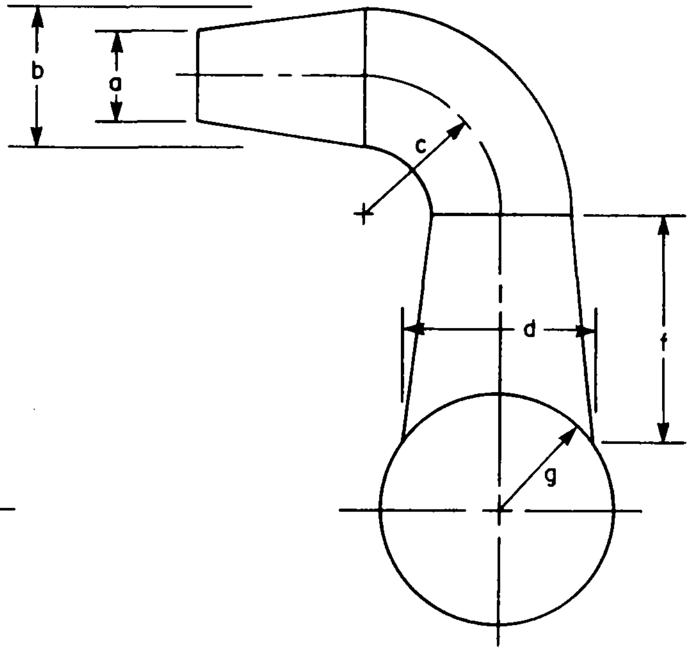


TOP VIEW

| (ft) / a (ft) | a | b | c | d | e | f | g |
|---|---|---|---|---|---|---|---|
| 1.5 | 1.5 | 2.25 | 2.25 | 3.0 | 2.625 | 3.75 | VARIES |
| 2.0 | 2.0 | 3.0 | 3.0 | 4.0 | 3.5 | 5.0 | VARIES |
| 2.5 | 2.5 | 3.75 | 3.75 | 5.0 | 4.375 | 6.25 | VARIES |
| 3.0 | 3.0 | 4.5 | 4.5 | 6.0 | 5.25 | 7.5 | VARIES |
| 3.5 | 3.5 | 5.25 | 5.25 | 7.0 | 6.125 | 8.75 | VARIES |



FRONT VIEW



SECTION A - A

FIGURE 5

PORT DIMENSIONS

NOTE
PLATE THICKNESS EQUAL 1/2"
INTERNAL DIMENSIONS SHOWN

design to ensure adequate diffusion under all climatic conditions. The climatic factors do not, however, affect the diffuser design to any great extent,as the diffuser is designed on the basis of a near-field temperature criterion. The amount of lake surface/atmospheric heat exchange that takes place over the small near-field areas usually specified in such criteria is generally too small to affect the near-field isotherms notably.

The assumption of still air is conservative with respect to both heat exchange with the atmosphere and dispersion of the plume by wind-generated lake surface turbulence. However, it is not conservative with respect to the effect of lake currents, which are generally wind generated.

Lake factors have a very significant effect on the design and performance of a submerged jet diffuser and are, therefore, of paramount importance.

The hydrography of the site has a twofold effect on diffuser performance. With a gentle lake-bed slope, a thermal plume in shallow or nearshore areas tends to "cling" to the lake bed (Coanda effect), thereby inhibiting dilution flow to the underside of the plume and altering the trajectory length of the plume. The general form of the lake bed in the area of the discharge contributes to the form of the current patterns at the diffuser location. Physical model studies are used to properly represent these effects in final design studies.

The local geology and lake-bed materials are significant in diffuser design with respect to selection of type of conduit and potential environmental effects, due to disturbances of bottom sediments both during construction and by high jet velocities after construction. The arrangement shown in Figure 3 is generally favored in this regard, if feasible, as it minimizes the disturbance of the more prolific nearshore benthic zone. Also, the lake bed to jet centre line height of 1.52 metres (5 feet) shown in Figure 4 has been found in various physical model studies to produce minimal lake-bed scour, even for highly erodible materials, because of the buoyancy of the plume and the rapid rate of initial entrainment and, therefore, rapid rate of velocity reduction. Evidently, these factors require specific consideration at each site.

The ambient lake surface temperature and stratification affect the buoyancy of the plume and the rate of lateral spread. The critical condition used for design on the basis of a surface temperature criterion is generally a high ambient temperature and no stratification. Other ambient temperature conditions are usually considered in the design study to ensure adequacy of performance for the entire possible range of temperature.

Various lake current directions and velocities are considered in the design study to determine that combination which results in the poorest diffuser performance. A combination of a critical direction and an infrequently occurring velocity is then chosen for design purposes. It is generally accepted that the diffuser will fail to meet the specified surface temperature criterion, by a small amount, on infrequent occasions, and for short periods of time. Again, physical model studies are used to properly represent the lake current effects for various directions and velocities in final design studies. The effect on the plume of a lake current direction reversal is also usually studied.

Generating station factors. The heat rejection rate used for design purposes is the maximum that can occur with the plant operating at full load,as the difficulty of complying with a surface temperature criterion increases with heat rejection.

Unusual operating conditions such as occur during sudden load rejection (full discharge and no heat rejection) or during pump breakdown (partial discharge and full heat rejection) are also considered. Loss of pumping capability generally requires partial load operation to keep within the lake surface temperature criterion,since the diffuser design is fixed to perform adequately for the predominant full-load and full-pumping conditions. Part of the diffuser design procedure thus consists of determining the required load reduction for various percentage losses of cooling water flow. Study of the transient plume condition requires a physical model as present analytical models are limited to steady-state conditions.

The combination of cooling water flow and temperature rise used may be determined entirely by the economics of condenser design as related to the efficiency of the thermal cycle for the generating station steam plant. In some cases, however, these are considered as variables in the jet diffuser design and provide a link between the engineering economics of the plant and the diffuser. It is generally considered desirable from the environmental point of view to use lower condenser flow rates in order to reduce both the rate of nutrient pumping and exposure of organisms to the higher temperature excesses. The correspondingly higher temperature rises require greater dilution ratios from the diffuser in order to meet a fixed surface temperature rise criterion. The higher dilution ratios generally mean higher diffuser costs.

The diffuser geometry provides, in combination with the cooling water discharge and temperature rise, the independent variables for design. The complete list of variables is thus:

- discharge rate, $Q_o$
- temperature rise, $\Delta T_o$
- port diameter, D
- number of ports, N (which, with discharge rate and port diameter, defines the jet velocity, $V_o$)
- depth of water over port centre line (submergence), $Y_o$
- height of port centre line off lake bed, $Y_b$,
- port spacing, S.

In practice, the dependent design variable, temperature dilution ($S_o$), can be adequately represented as an empirical function of the densimetric Froude number, $F_\Delta$, the relative velocity, $V_o/V_a$ and the relative submergence, $Y_o/D$ for each set of values of heat rejection rate, ambient lake stratification, hydrography, lake current direction, port centre line height from the bed, and port spacing. The densimetric Froude number, relative velocity and relative submergence together represent five of the foregoing independent variables ($Q_o$, $\Delta T_o$, D, N, and $Y_o$) as well as the lake ambient temperature, $T_a$, and ambient lake velocity, $V_a$.

Characterization of the dilution performance of the diffuser in this way permits a systematic engineering economic analysis of various geometric arrangements which will meet a specified temperature dilution criterion for an assumed severe combination of meteorologic, lake and plant conditions. The variables of centre line height from the bed, $Y_b$, and port spacing, S, are not included in the foregoing approach and therefore require special consideration.

Physical model studies indicate dilution performance to be insensitive to minor variations in the port centre line height from the bed, particularly in shallow water and/or when the lake-bed slope is gentle and the plume has a tendency to "cling" to the lake bed. It is generally desirable to locate a diffuser in shallow water as near shore as possible,both to minimize the length of conduit and to keep the discharge in the epilimnion, for cases of ambient temperature stratification. The discharge conduit generally represents a significant portion of diffuser costs. Placing both the cooling water intake and discharge in the epilimnion minimizes nutrient pumping from the hypolimnion to the epilimnion as well as disturbance of the thermocline.

A minimum submergence is required, however, to provide adequate clearance for smaller craft which might cruise the nearshore locations of diffuser structures. This minimum is generally set at 3.66 metres (12 feet) of clearance over intake and diffuser structures at mean low water level, in accordance with recommendations by the U.S. Coast Guard and the U.S. Corps of Engineers.

The minimum clearance of 3.66 metres (12 feet) is generally considered acceptable for satisfactory intake operation in view of the requirement for covered structures which provide horizontal entrance velocities of less than 0.15 to 0.30 m/s (0.5 to 1.0 fps) to avoid severe fish impingement.

Model studies indicate an optimum port spacing in still water. However, the still-water optimum is ill defined and has been shown in physical model studies to be irrelevant for the more severe case of lake currents parallel to the line of nozzles (i.e., a "crosscurrent" essentially parallel to the shore and at or near right angles to the direction of jet discharge). The best spacing is then the minimum that is practical for construction and to minimize cost. This is considered to be between 3.05 and 6.10 metres (10 and 20 feet) for the manifold arrangement of Figure 3; hence, the adopted spacing of 4.57 metres (15 feet). A larger spacing of, say, 12.19 to 13.72 metres (40 to 45 feet) would likely be required, for structural reasons, with drilled risers to a tunnelled manifold beneath the lake bed.

Although lower jet velocities are preferable, there is no apparent objection to free jet velocities as high as 12.19 to 15.24 m/s (40 to 50 fps), provided that lake-bed scour is minimal and that lake surface velocities are not excessive. In the absence of satisfactory criteria or guidelines, a maximum point surface velocity of 1.52 m/s (5 fps) for an adverse combination of lake and operating conditions has been arbitrarily adopted for two of the projects in which Acres have participated. This maximum velocity compares favorably with the surface velocities typical of shoreline surface discharges.

## 3.3 - Nature of Plumes

A typical 3,000-Mw station has been adopted as the basis for illustrating the general structure of plumes from submerged jet discharges. The selected station discharges at 152.9 $m^3/s$ (5,400 cfs) with an initial temperature rise of 11.1 Centigrade degrees. The diffuser comprises thirty-eight 0.76-metre (2.5-foot) diameter ports discharging with 5.21 metres (17.1 feet) of centre-line submergence (mean low water) at about 9.14 m/s (30 fps).

Where appropriate, a summation of prominent plume characteristics for the thirty generating sites considered in the costing analysis of Section 4 herein is also provided. These sites are based on existing generation and generation projections to the year 2000.[4,5]

Typical surface isotherms for the 3,000-Mw station operating at full load in both still water and a 0.30 m/s (1.0 fps) crosscurrent are illustrated in Figures 6 and 7. These isotherms are based on observed patterns from a physical model study and isotherm areas calculated by the semi-empirical analytical model described in Section 2.

The notable features of the plumes are:

- the low maximum surface temperature excesses (about 1.6 Centigrade degrees as compared to the initial jet excess of 11.1 Centigrade degrees)
- the small area of the 1-Centigrade degree temperature excess isotherm
- the considerable spreading of the 0.5-Centigrade degree isotherm
- the lateral bending of the plume in the crosscurrent
- the absence of temperature excess behind (i.e., shoreward of) the diffuser.

As the analytical model cannot account for the effects of onshore currents, as noted in Section 2, it has not been possible to illustrate the isotherm patterns for that current condition. However, experience in a thermal model basin which simulated steady-state onshore currents provides an indication of the effect of such currents.

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[4] H. G. Acres Limited. Thermal Inputs to the Great Lakes (1968-2000). Canada Centre for Inland Waters, Inland Water Directorate, February 1970.

[5] Correspondence to the Canada Centre for Inland Waters from Ontario Hydro. July 30, 1973.

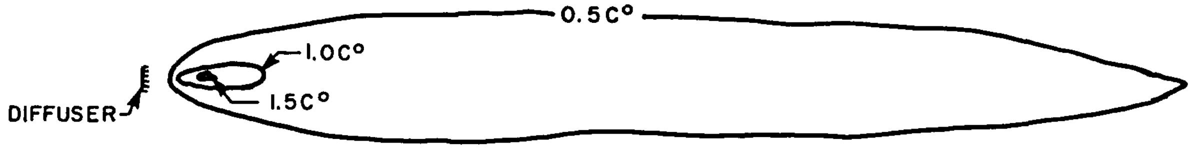

FIGURE 6

TYPICAL STILLWATER SURFACE ISOTHERMS

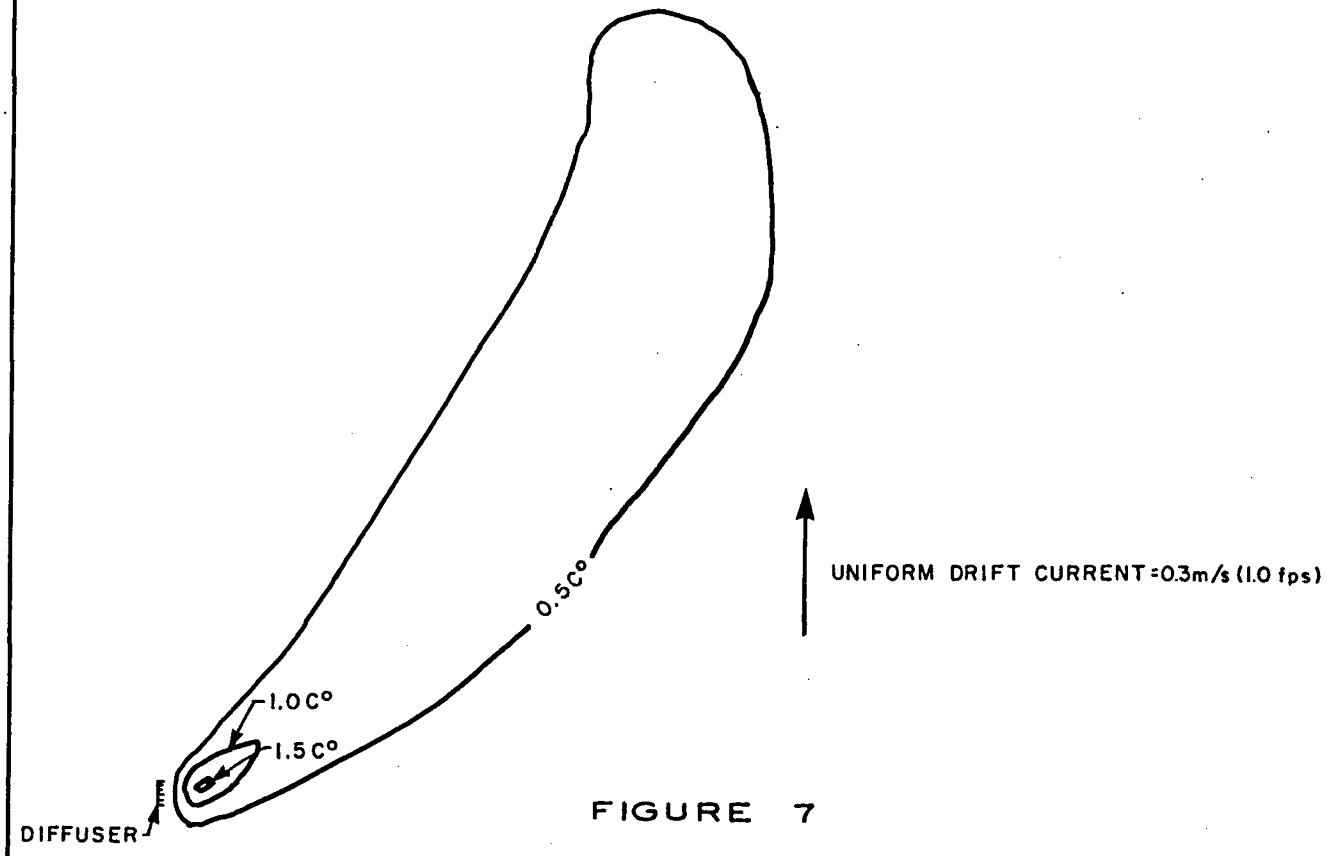

FIGURE 7

TYPICAL DRIFT CURRENT SURFACE ISOTHERMS

NOTE

ISOTHERM SHAPES FOR BOTH FIGURES ARE DERIVED FROM PLANT I AND EXTRAPOLATED FOR A 3000 MW NUCLEAR STATION

1.7 C° (3F°) CRITERION IS SATISFIED

In general, the core, or very near-field portion, of the plume increases slightly in area and is displaced shoreward so that the shoreward boundary of, say, the 1-Centigrade degree isotherm lies behind the diffuser line. The amount of displacement is dependent upon the velocity of the onshore ambient currents, but tends to be small because of the relative magnitude of the jet discharge velocity.

The 0.3 to 0.5-Centigrade degree temperature excess isotherm can be expected to reach the shore area. The residual momentum from the initial jet discharge is small at this point in the plume, relative to the momentum of the ambient lake current.

Because of the relative weakness of onshore currents, their short duration and relative infrequency as a transient state in the reversal of a predominantly bilateral current regime, and the relatively low shoreline temperature excesses experienced with 304.8 to 914.4- metre (1,000 to 3,000-foot) diffuser and shoreline separations, the onshore current condition is generally not considered critical. However, should an evaluation of this premise at a specific site on the basis of environmental and lake conditions reveal the premise to be wrong, departure from the "typical" diffuser arrangement can be considered as an alternative to, say, cooling towers, as a means of avoiding the environmental problem.

Typical subsurface isotherms and isovels for the 3,000-Mw station are presented in Figures 8 and 9. These sections were prepared from analytical calculations on the plume centre line for a still-water condition and three ambient lake temperature conditions, namely:

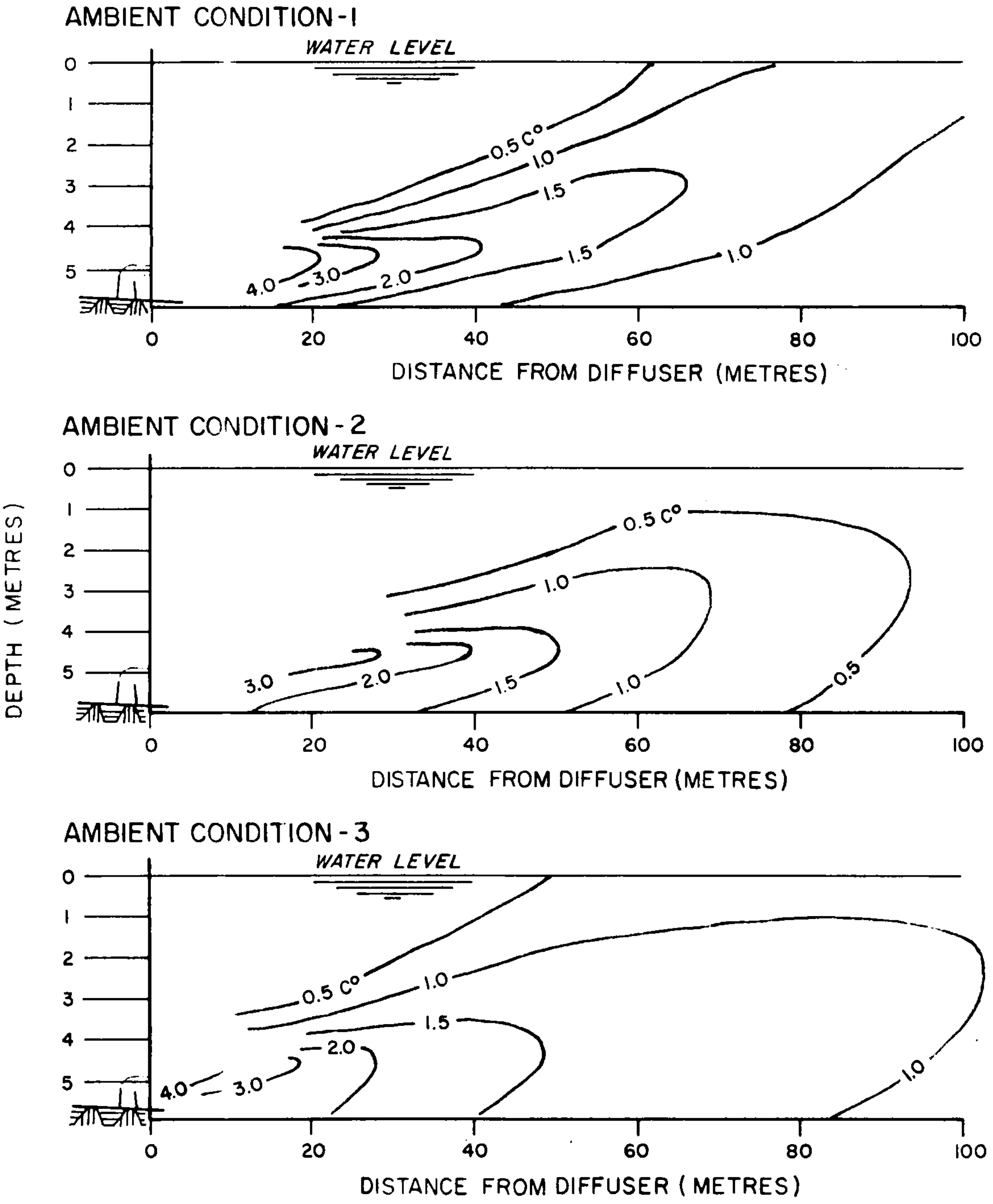

FIGURE 8

TYPICAL SUBSURFACE ISOTHERMS

NOTE

AMBIENT CONDITION 1 - STILLWATER, UNIFORM TEMPERATURE AND WARM WATER (18.6°C)

AMBIENT CONDITION 2 - STILLWATER, LINEARLY STRATIFIED TEMPERATURE (0.182 C°/m) AND WARM WATER (18.6°C AT DIFFUSER LEVEL)

AMBIENT CONDITION 3 - STILLWATER, UNIFORM TEMPERATURE AND COLD WATER (1.9°C)

THE ISOTHERMS ARE BASED ON A NUCLEAR PLANT OF 3000 MW

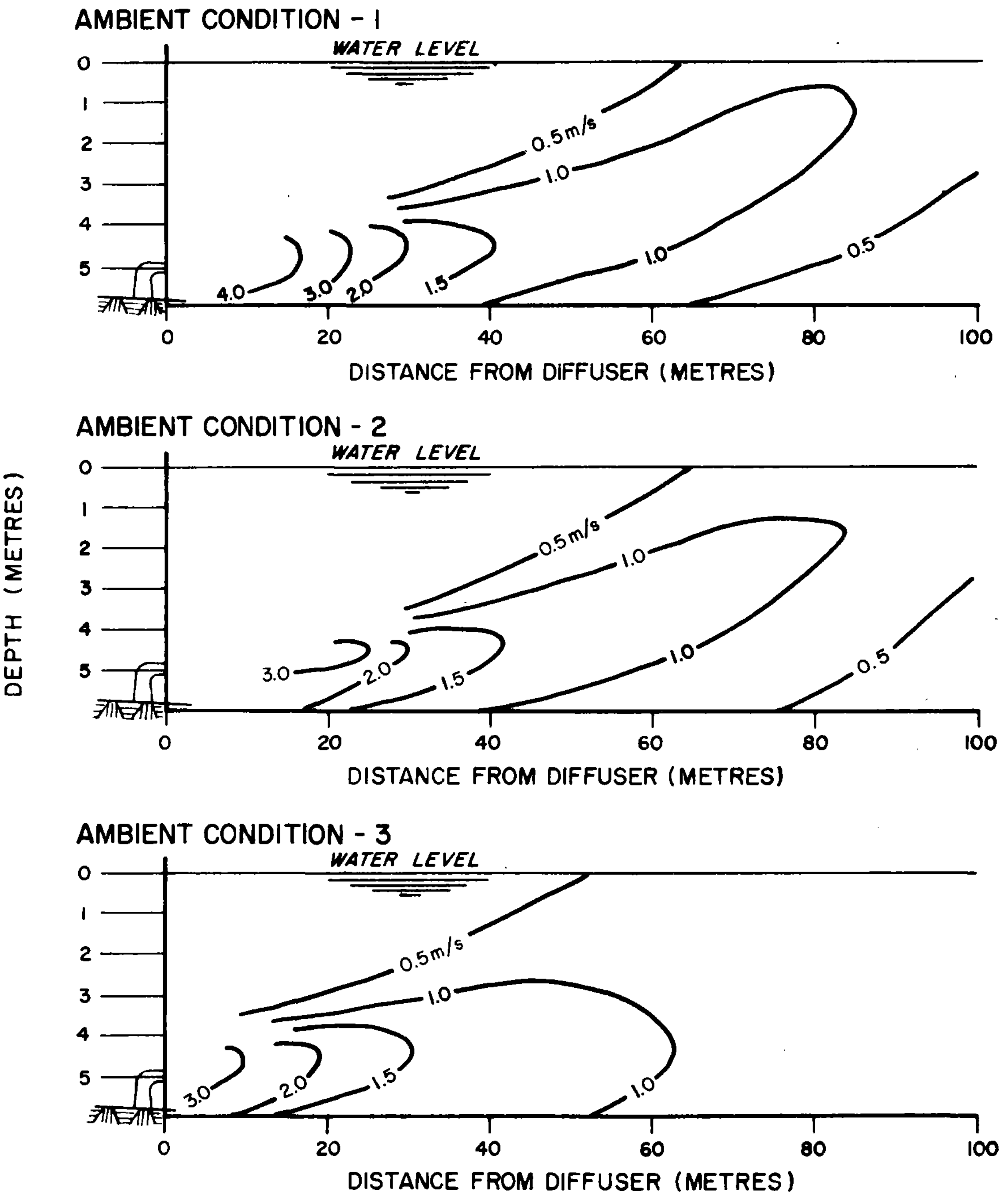

FIGURE 9

TYPICAL SUBSURFACE ISOVELS

NOTE

AMBIENT CONDITION 1 - STILLWATER UNIFORM TEMPERATURE AND WARM WATER (18.6°C)

AMBIENT CONDITION 2 - STILLWATER, LINEARLY STRATIFIED TEMPERATURE (0.182 C°/m) AND WARM WATER (18.6°C AT DIFFUSER LEVEL)

AMBIENT CONDITION 3 - STILLWATER, UNIFORM TEMPERATURE AND COLD WATER (1.9°C)

THE ISOTHERMS ARE BASED ON A NUCLEAR PLANT OF 3000 MW

- unstratified at 18.6 degrees Centigrade
- stratification of 0.182 Centigrade degrees per metre at 18.6 degrees Centigrade surface temperature.
- unstratified at 1.9 degrees Centigrade.

The notable features of the illustrations are:

- the rapid rates of initial temperature and velocity reduction along the plume trajectory e.g., 11.1 degrees Centigrade to less than 4.0 degrees Centigrade within 7.62 metres (25 feet) of the point of discharge
- the limited extent of contact between the plume and the lake bed
- the greater buoyancy of the plume in the unstratified warm ambient lake condition
- the least persistence of the 1.0-Centigrade degree isotherm for the stratified, warm lake condition as compared to the least persistence of the 1.0 m/s (3.28 fps) isovel for the unstratified, cold lake condition.

The total surface areas and plume volumes calculated for thirty generating stations on the Canadian shoreline are presented as a function of plume temperature excess and diffuser design criterion* in Figures 10 and 11, respectively. The data are for a still-water, warm ambient, unstratified lake condition.

The notable features of the illustrations are:

- the sensitivity of area to decreasing isotherm values, e.g., 150 square kilometres per Centigrade degree for the

---

*The three sets of diffuser designs prepared for the study provide for maximum point temperature excesses of 1.1 degrees Centigrade (2 degrees Fahrenheit), 1.7 degrees Centigrade (3 degrees Fahrenheit), and 3.3 degrees Centigrade (6 degrees Fahrenheit) at the lake surface under a critical combination of lake temperature, current direction and velocity, and level.

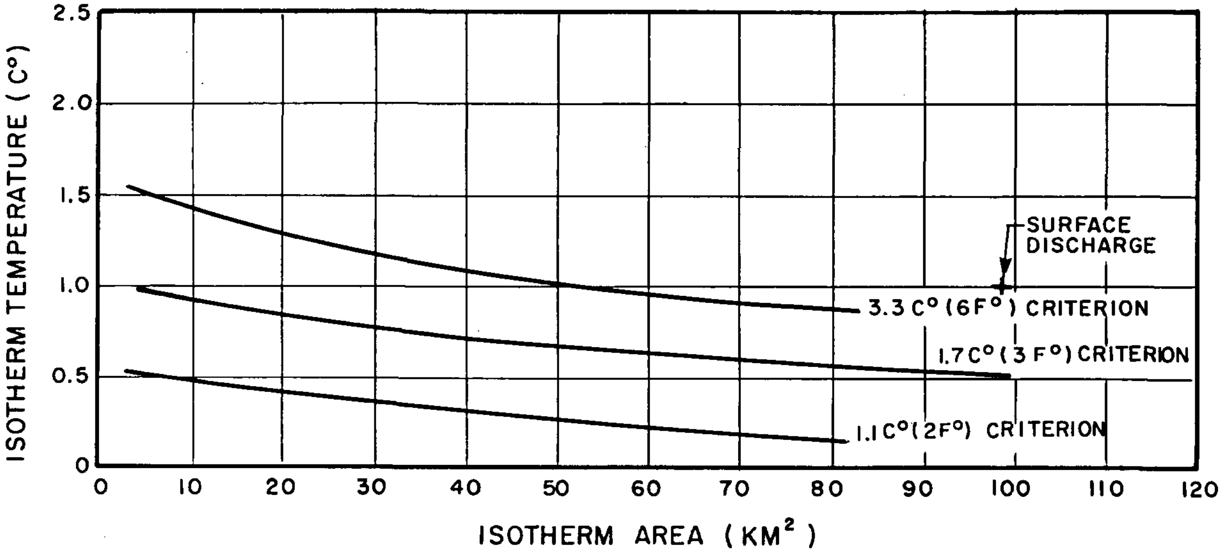

FIGURE 10

ISOTHERM TEMPERATURE VERSUS
TOTAL ISOTHERM AREA FOR ALL LAKES (STILLWATER)

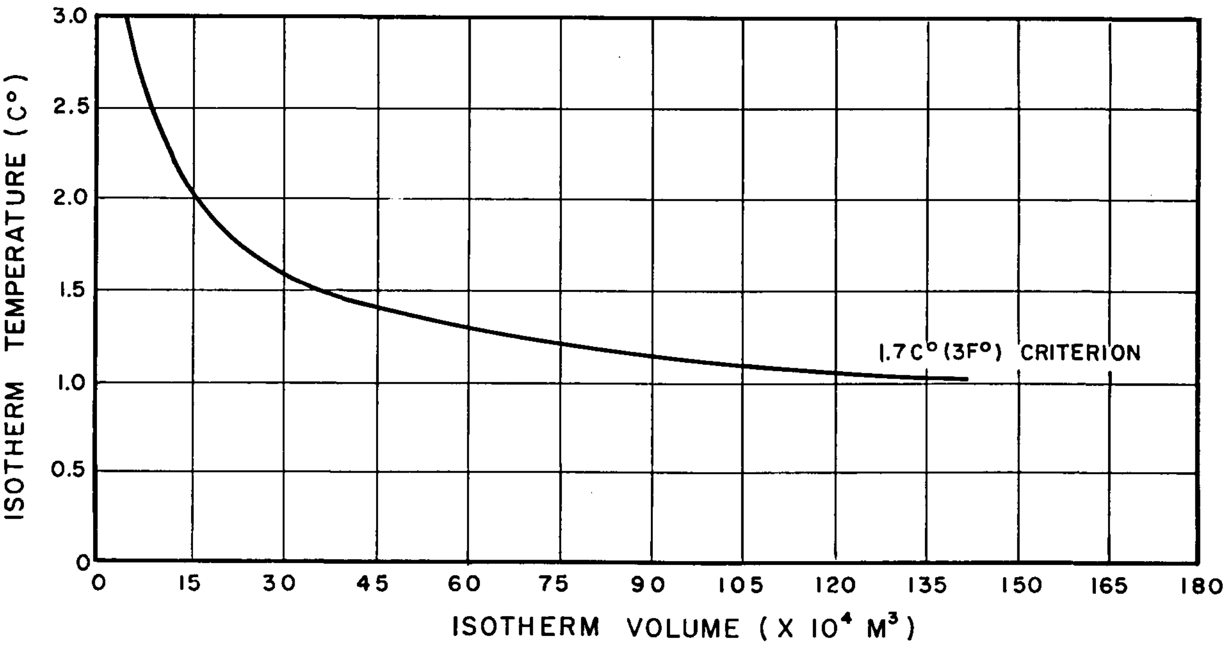

FIGURE 11

ISOTHERM TEMPERATURE VERSUS
TOTAL ISOTHERM VOLUME FOR ALL LAKES (STILLWATER)

ACRES

3.3-Centigrade degree criterion (6-Fahrenheit degree criterion) at the 1-Centigrade degree isotherm of temperature excess

- the sensitivity of area to decreasing severity of diffuser design criterion; e.g., for the 1-Centigrade degree isotherm, about 27 square kilometres per Centigrade degree (15 square kilometres per Fahrenheit degree specified in the criterion).
- the marked decrease in sensitivity of isotherm volume to temperature excess with increasing values of temperature excess; e.g., $12 \times 10^3$ cubic metres per Centigrade degree at 2.5-Centigrade degree excess compared with $960 \times 10^3$ cubic metres per Centigrade degree at 1.0-Centigrade degree excess for the 1.7-Centigrade degree (3-Fahrenheit degree design criteria.

A corresponding 1-Centigrade degree temperature excess area of 98 square kilometres, estimated from Kenny's[1] work, for surface discharges is also plotted in Figure 10 for comparison. A multiport diffuser designed for a temperature criterion of about 5.0 Centigrade degrees (9 Fahrenheit degrees) would yield the equivalent 1-Centigrade degree area. The average and maximum point temperatures within that area would, however, be lower for the multiport diffuser.

*Drift current* effects on isotherm areas are illustrated in Figures 12 and 13 for 1.7-Centigrade degree (3-Fahrenheit degree) diffuser designs in still, unstratified, warm ambient lake conditions. The area contained by the 1-Centigrade degree surface isotherm is used as the basis of illustration in Figure 13.

The most notable feature of the curves in Figures 12 and 13 is the marked increase in the area contained by a given isotherm of temperature excess with increasing drift current velocities.

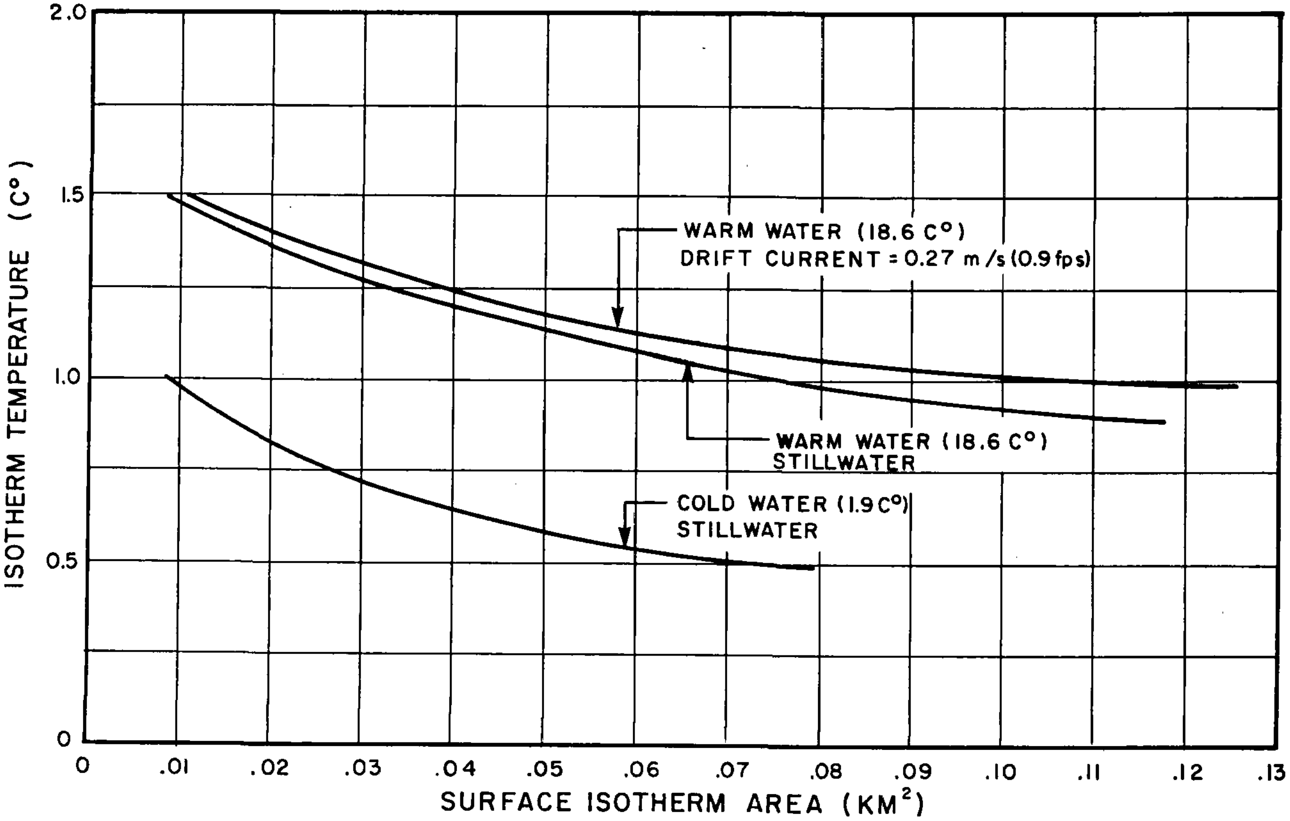

FIGURE 12

EFFECTS OF DRIFT CURRENT AND COLD WATER ON SURFACE ISOTHERM AREA

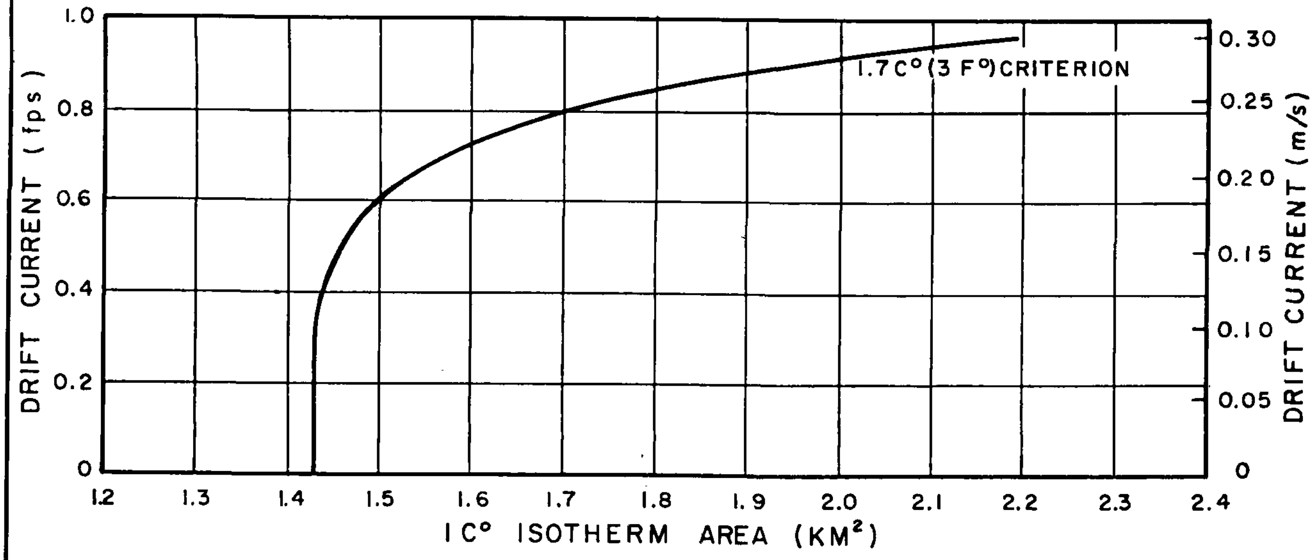

FIGURE 13

DRIFT CURRENT VERSUS TOTAL 1C° ISOTHERM AREA FOR ALL LAKES

ACRES

The increasing areas are attributable to:

- reduced mixing by boundary shear in the jet region with decreasing relative velocity between the discharge and the ambient current
- the bending of successive individual plumes from the row of jets each toward the next plume in the line where it is entrained, as a significant proportion of the dilution flow for the next plume, before it has itself been sufficiently diluted.

The latter effect is so significant that decreases in isotherm areas of individual surface plumes normally associated with increase in ambient current and, therefore, in diffusivity are not generally evident in physical model tests of multi-port diffusers of this type. However, limited physical model experience for one specific diffuser with crosscurrent velocities much greater than normal for the Great Lakes,i.e. greater than 0.61 m/s, (2.0 fps) indicates there exists, for each site arrangement, a critical value for the relative velocity above which the surface isotherm areas will begin to decrease with increasing ambient velocity.

The effects of ambient temperature on lake surface isotherm areas and plume volumes are illustrated in Figure 12 and in the upper graph in Figure 14.

Whereas decreasing the ambient temperature decreases the surface isotherm areas appreciably (Figure 12), it does not appear to alter the isotherm volumes appreciably (Figure 14). In the cold ambient condition, the plume does not rise to the lake surface and spread laterally as much as it does in the warm ambient, because of the lower density differentials. In the warm ambient condition, densimetric spread on the lake surface contributes appreciably to the plume dispersion.

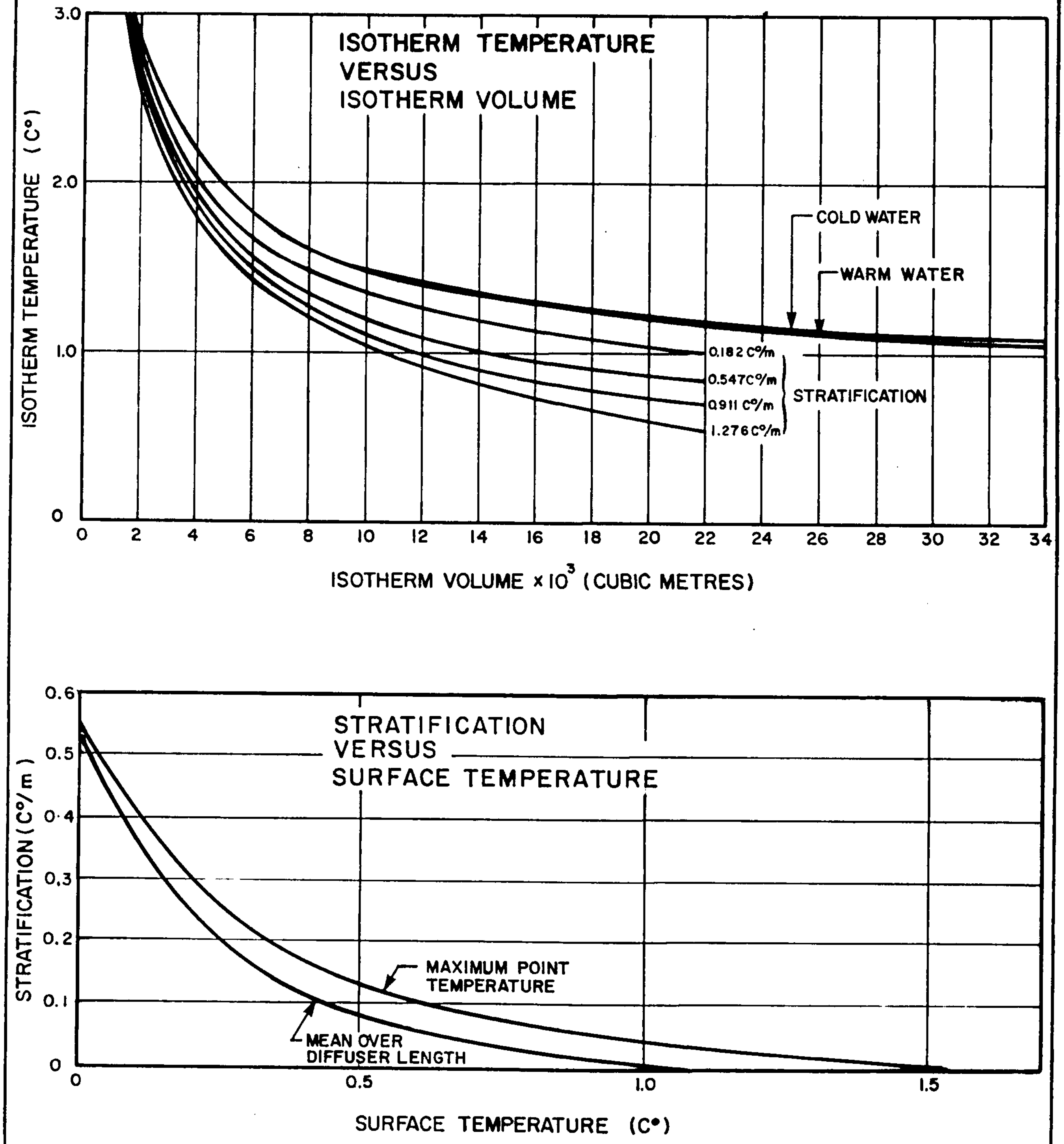

FIGURE 14

EFFECTS OF STRATIFICATION AND COLD WATER ON ISOTHERM VOLUME AND SURFACE TEMPERATURE (STILLWATER)

NOTE

FOR A TYPICAL 3000 MW NUCLEAR PLANT

The effect of ambient lake stratification is illustrated in Figure 14. Greater degrees of stratification evidently result in smaller values for each of surface temperatures, isotherm areas and plume volumes.

The exposure time of living organisms to various levels of temperature excess in passing through a condenser cooling system with an offshore multiport discharge arrangement is illustrated in Figure 15 for a typical 3,000-Mw station. The corresponding exposure data are shown for an alternative shoreline surface discharge.

The most notable features in comparing the temperature exposure for the alternative discharge arrangements are:

- the rapid rate of temperature increase in the condenser common to both discharge arrangements
- the relatively long exposure to the maximum temperature excess in the discharge tunnel for the multiport alternative
- the relatively rapid rate of temperature decrease immediately after discharge for the multiport diffuser
- the lower rate of decay of temperature excess in the surface discharge plume.

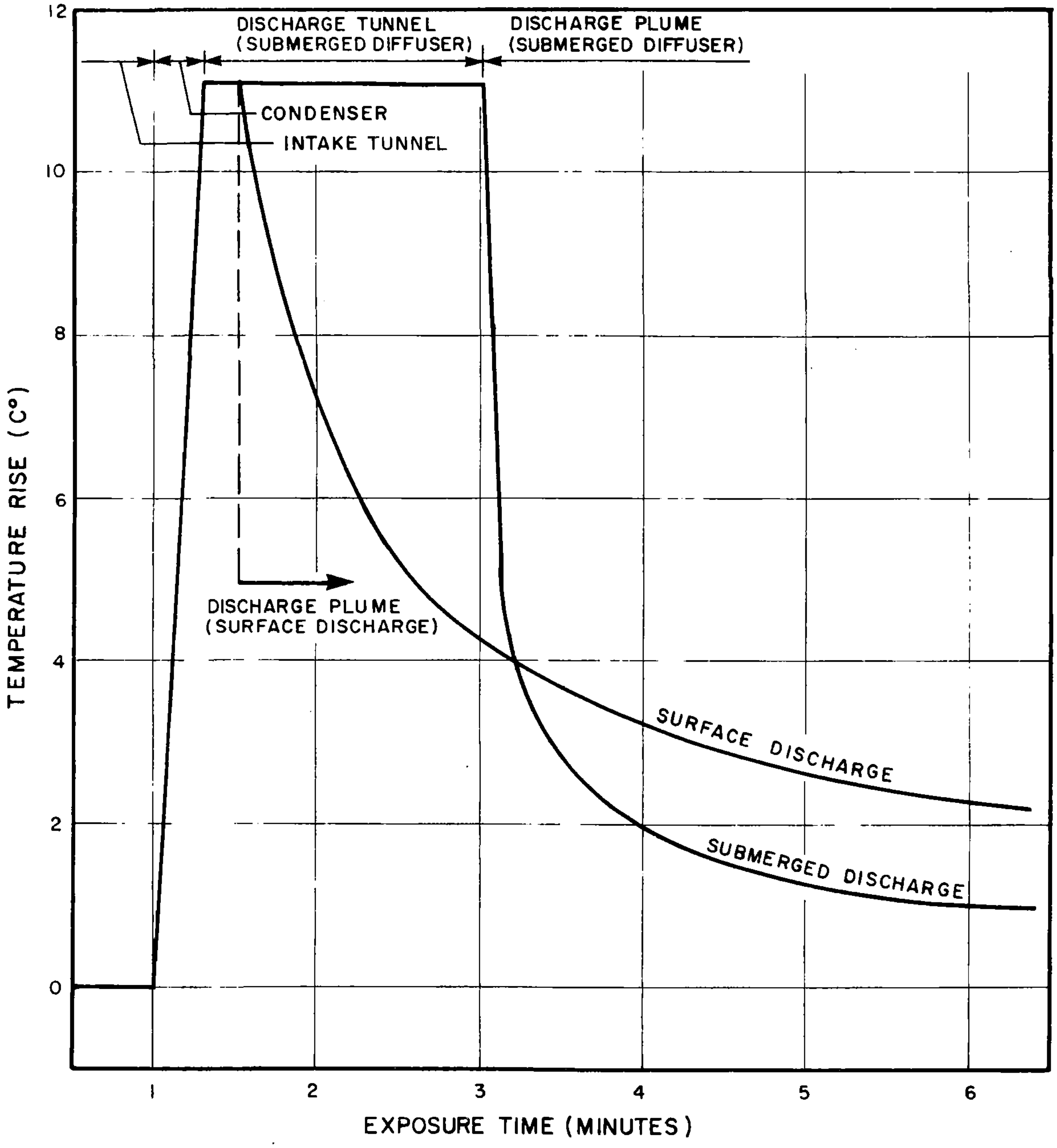

FIGURE 15

EXPOSURE TIME

NOTE

THIS EXPOSURE TIME WAS ESTIMATED FOR A TYPICAL NUCLEAR PLANT WITH THE FOLLOWING CHARACTERISTICS

CAPACITY = 3000 MW
TEMPERATURE RISE ACROSS CONDENSER = 11.1 C°
DIFFUSER DISCHARGE = 152.9 $m^3/s$ (5400 cfs)
INTAKE TUNNEL LENGTH = 520 m (1700 ft)
DISCHARGE TUNNEL LENGTH OF SUBMERGED DIFFUSER = 300 m (984 ft)

ACRES

## 4 - ADDED COST OF MULTIPORT DIFFUSERS

The submerged jet diffuser is a near-field dilution device that is designed to meet a near-field, or local, temperature criterion. The cost of the device is thus directly related to the local diffusion of the thermal discharge and only indirectly to the far-field nature of the plume. The far field is, in fact, some function of the diffusion achieved in the near field. It has thus been necessary in this study to consider local diffusion to obtain cost data to be used in an assessment of the economic and far-field environmental implications of the use of offshore submerged multiport diffusers.

As the performance of a diffuser is very much a function of the local lake conditions (e.g., depth of water, bed slope, lake currents) and diffuser costs are a direct function of the local diffusion required, it follows that diffuser costs for a given plant vary appreciably from site to site. Further, it has been Acres experience in designing diffusers for stations varying in size from 375 Mw to about 2,400 Mw, that the difficulty of meeting a specified temperature criterion at a given site increases with the size of the installation. Indications are, in fact, that for a specified temperature criterion, there may be an upper limit to the size of plant that can be accommodated at a given site with a given submerged diffuser concept. It is thus not sufficient to use a diffuser cost per unit of installed capacity for a "typical" generating station to obtain global estimates of diffuser costs for the total installed capacity at a number of different sites.

For the foregoing reasons, the global cost estimates in this study have been based on a site-by-site evaluation of diffuser costs, using 30 existing and projected sites,[4, 5] (to the year 2000) on the Canadian shores of the Great Lakes. The total installed capacity of 105,272-Mw considered comprised units from 100-Mw to 8,000-Mw. The estimates were made for designs which would satisfy each of three hypothetical maximum-point temperature criteria: 1.1, 1.7, 3.3 Centigrade degrees (2, 3 and 6 Fahrenheit degrees) above ambient.

## 4.1 - Methodology

Each site of thermal electric generating plant considered in the study was treated as outlined in the four subsections hereunder:

### (a) Site Description

Each generating site was described by:

- lake current directions, magnitudes and frequencies
- surface temperature ranges and means, by season
- temperature stratification
- water surface level, range and mean
- lake-bottom materials and geology
- hydrography.

In the absence of data at a specific site, generalized information for the area was utilized in conjunction with appropriate assumptions or estimations.

The site information was used in selecting critical lake conditions for diffuser design, determining diffuser system general arrangements and location offshore, and ascertaining the appropriateness of diffuser design and construction alternatives at the site.

## (b) Plant Characteristics

Each generating site was described by:
- installed capacity
- load factor
- efficiency
- heat rejection
- cooling water temperature rise.

For projected sites, where detailed descriptions were not available, experience at other similar installations was utilized to obtain likely values for the various factors. Also, at these sites, the cooling water temperature rise in the condenser was treated as a design variable in selecting the economic, preliminary diffuser design arrangement.

## (c) Preliminary Design

For each generating site, alternative diffuser designs for each of the three specified temperature dilution requirements and selected adverse lake conditions were prepared and documented, respectively, by means of:

- a parametric relationship for dilution, jet submergence and jet densimetric Froude number
- the semi-empirical, analytical model described in Section 2.

The design alternatives were selected in consideration of their appropriateness for construction at the specific generating sites.

### (d) Selection of Economic Design

The costs of the various design alternatives at each site were prepared from unit cost estimates for the various cooling system components (e.g., tunnels, manifolds, nozzles, pumps). The total capitalized costs include mobilization costs, construction costs, and annual operating and maintenance expenses. A discount rate of 10 per cent over a period of 20 years was used for the capitalization.

The least cost alternative for each criterion was then selected as being most appropriate to the site and suitable for comparison with costs for an alternative shoreline surface discharge.

## 4.2 - Basis of Multiport Diffuser Costs

The components of the diffuser system were priced in unit quantities to facilitate the costing of the alternative designs for each plant size and location.

The components included diffuser nozzles, manifolds, tunnels, pumps and cost of power for pumping. Excluded, because of being common to both shoreline and offshore multiport discharges, were the intake structure and the intake and discharge wet wells.

The diffuser nozzles were costed separately since special fabrication would be required. Figure 5 shows the various nozzle dimensions used. The curve of cost versus nozzle diameter adopted for the analysis is shown in Figure 17.

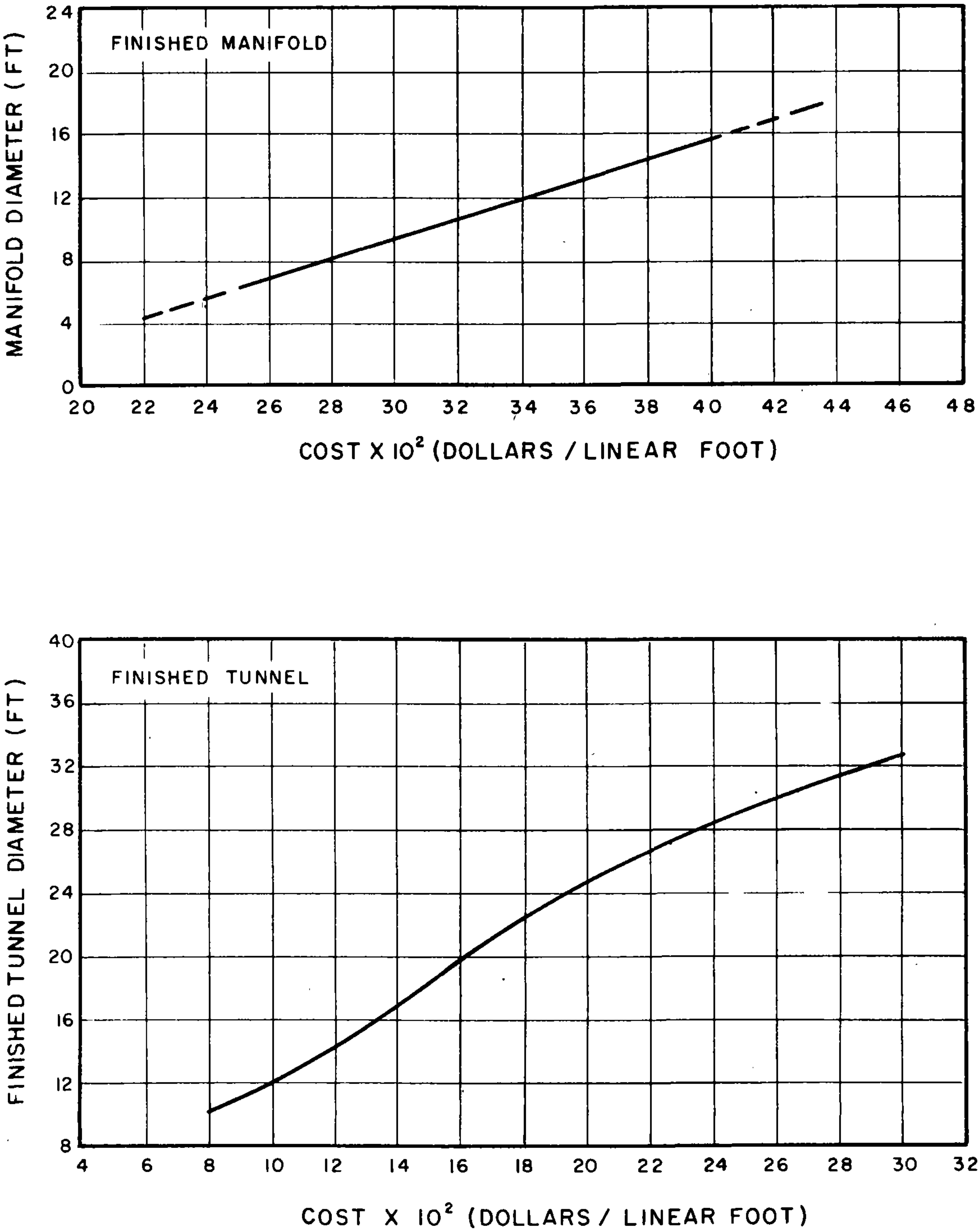

FIGURE 16

COST CURVES I

LEGEND

——— BASED ON CALCULATED COSTS

– – – EXTRAPOLATED

The manifolds were designed to have four to six nozzles per section, with the sections reducing in steps such that a near constant velocity about equal to the main tunnel velocity was maintained. Costing of the manifolds was based on the assumptions that:

(a) Overburden depth is approximately 3.05 metres (10 feet);

(b) Poured concrete may be seated on reasonably competent rock;

(c) An excavation slope of 2:1, run to rise, is possible.

A typical manifold layout has been presented in Figures 4 and 5. The cost curve on Figure 16 presents the total cost of the manifold per linear foot. These costs include all materials, labor and equipment for underwater installation.

Tunnels were assumed to be concrete lined, with wire mesh and rock bolts supporting the crown. The tunnel diameter selected at each site was based on an economic analysis of head loss. Cost of the tunnels was based on the assumptions that:

(a) The rock is competent and moderately jointed;

(b) Dewatering requirements are moderate;

(c) Nominal rock bolting and mesh are required.

The cost curve in Figure 16 was developed on the basis of Robert's[6] data.

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[6] Robert, S. Mayo and Associates, Tunneling - The State of the Art, U.S. Dept. of Commerce, National Bureau of Standards, No. PB178036, January 1968.

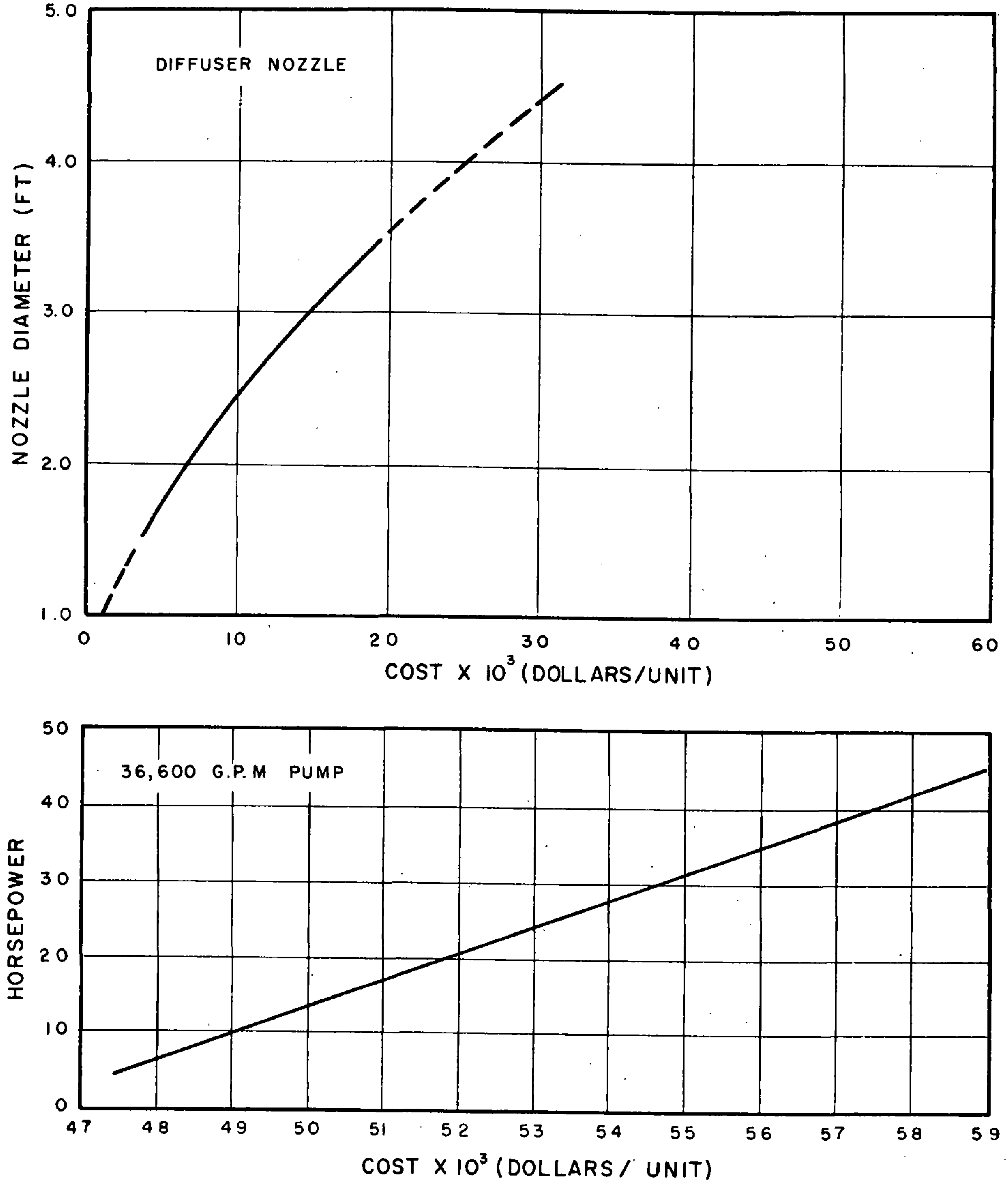


FIGURE 17

COST CURVES II

LEGEND

—— BASED ON CALCULATED COSTS

– – – EXTRAPOLATED

Pumping plant for a particular discharge alternative was selected on the basis of discharge and estimated head losses in the system, plus 20 per cent for stand-by capability. Motor horsepower requirements were then calculated from the discharge and total system head loss. The head loss estimates included:

(a) Exit loss, diffuser to receiving lake;

(b) Bend loss in the diffuser nozzle;

(c) Manifold tee loss from manifold to nozzle;

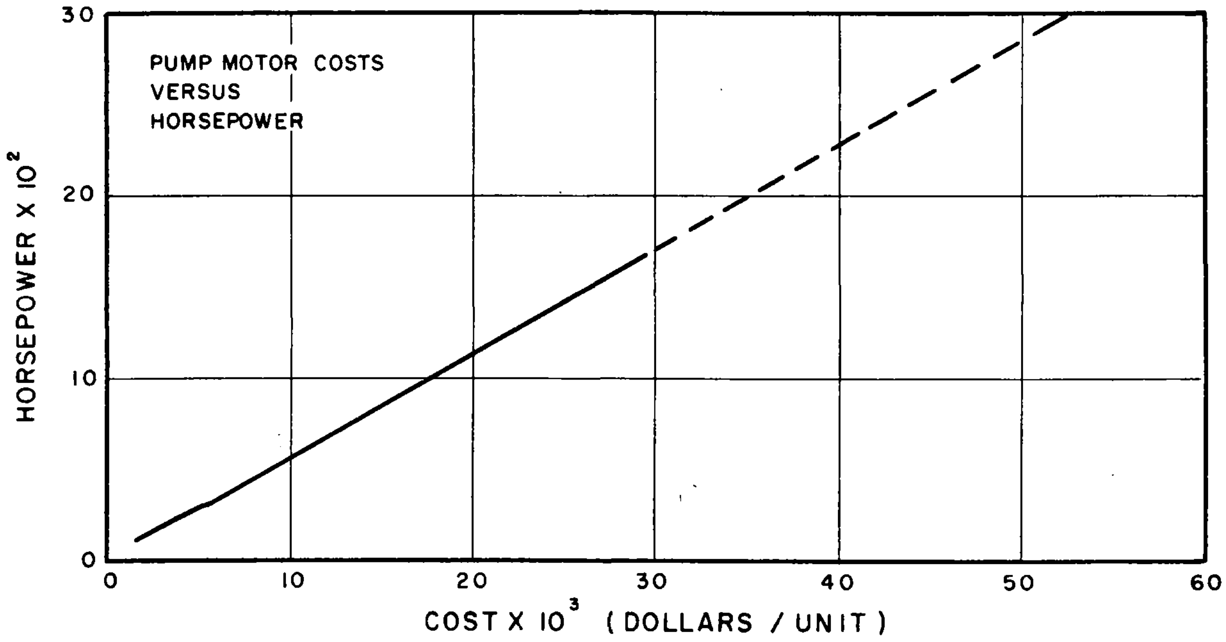
(d) Friction losses in diffuser manifold and the discharge tunnel;

(e) The loss from the discharge tunnel to the manifold.

Manufacturers cost estimates for three pump sizes ranging from a 0.91-metre (36-inch), 138.35-$m^3$/min (36,600-Igpm) unit to a 3.05-metre (120-inch), 945.0-$m^3$/min (250,000-Igpm) unit and total dynamic heads ranging from 1.52 metres to 13.72 metres (5 feet to 45 feet) were used as the basis for the pump costs. The curve of Figure 17 for the smallest unit is presented as typical of pump costs.

The motor cost data in Figure 18 were also based on manufacturers' cost estimates.

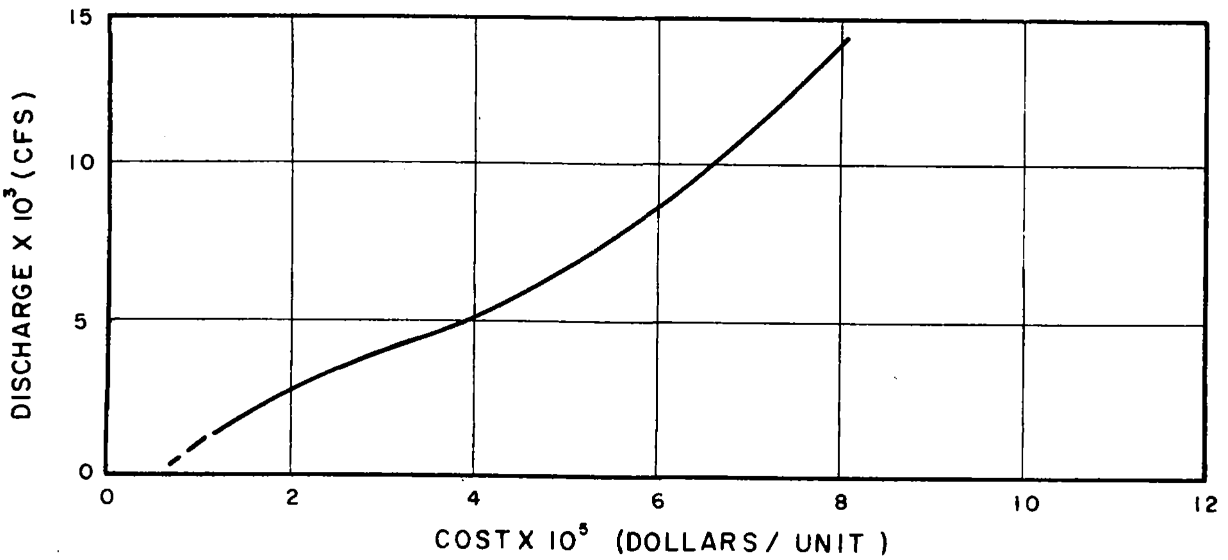
Cost of power for pumping was estimated as the present value of energy costing 7.5 mills per kwh, a 20-year operating period, and a 10 per cent per annum discount rate. The estimated values were then added to construction costs to establish total capital and operating costs.



PUMP MOTOR

**NOTE**

PRICE FOR HORIZONTAL CLASS B INSULATED MOTOR 1800 RPM AT 4160 VOLTS



SHORELINE SURFACE DISCHARGE

FIGURE 18

COST CURVES III

LEGEND

——— BASED ON CALCULATED COSTS

– – – EXTRAPOLATED

### 4.3 - Basis of Surface Discharge Costs

A typical shoreline surface discharge arrangement was designed and costed as a function of cooling water discharge rate to provide the basis for estimating the additional costs of offshore multiport discharges.

The conduit components of the two discharge alternatives were assumed to be identical circular concrete conduits from the generating plant to a point near the lakeshore,which was used as the datum for cost estimating.

Beyond the costing reference point, the shoreline discharge facility comprises three components. These are:

(a) A circular concrete tunnel expanding to a rectangular section at the shoreline. The rectangular section has a width equal to twice its height and provides a densimetric Froude number of 5 at the shoreline.

(b) A dredged channel with concrete bottom and sheet pile sides extending 30.48 metres (100 feet) offshore. The dredged channel has the same dimensions as the rectangular conduit.

(c) A dredged area[7,8] at the end of the outlet channel to permit unhindered dilution of the plume.

The cost of the surface discharge arrangement as a function of cooling water discharge is shown in Figure 18.

---

[7] Tamai, N., Wiegel, R.L. Tornberg, G.F. Horizontal Surface Discharge of Warm Water Jets. ASCE Power Division. October 1969.

[8] Jen, Y., et al. Surface Discharge of Horizontal Warm Water Jets. ASCE Power Division. April 1966.

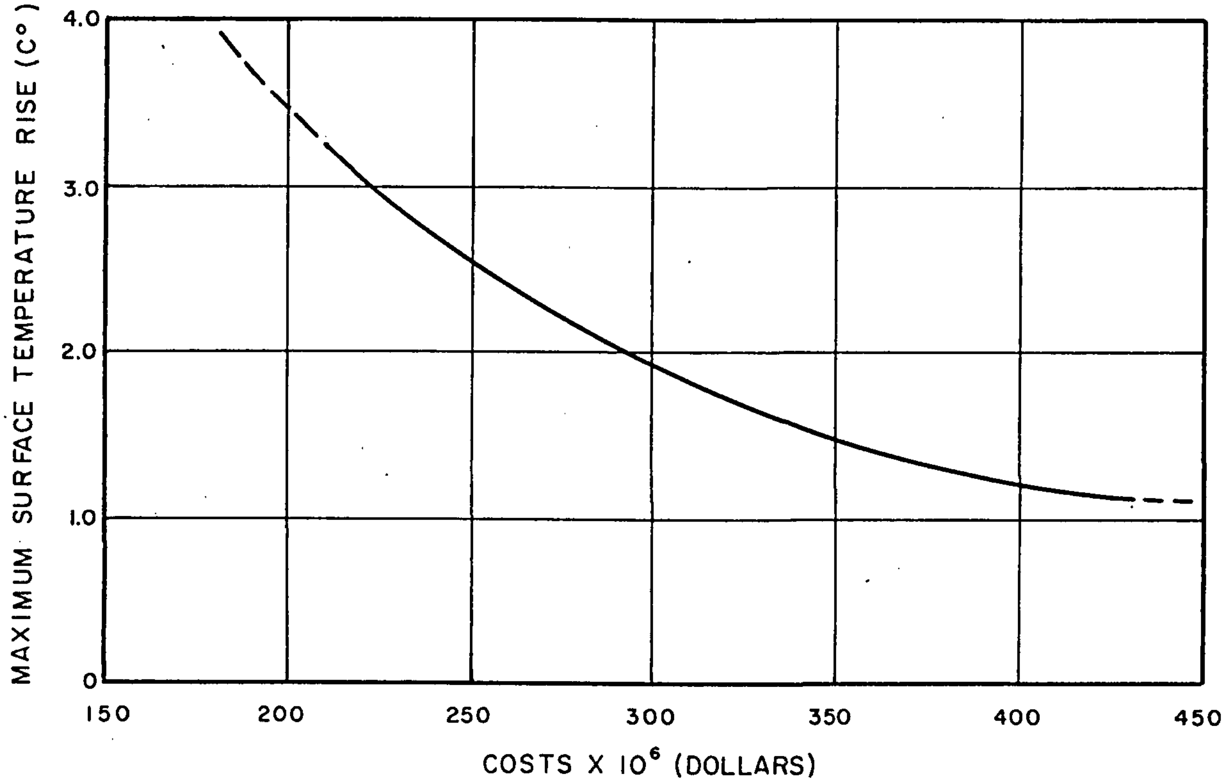


FIGURE 19

TOTAL ADDED COSTS OF SUBMERGED DIFFUSERS

NOTE

- THE COSTS SHOWN ARE THE TOTAL ADDED COSTS OF OPTIMUM SUBMERGED DIFFUSERS OVER THE COSTS OF SURFACE DISCHARGE SYSTEMS
- THE COSTS INCLUDE CAPITAL AND OPERATING COSTS

LEGEND

——— BASED ON CALCULATED COSTS

– – – – EXTRAPOLATED

## 4.4 - Added Cost Versus Design Criterion

The estimated cost differential between using offshore multiport discharges and onshore surface discharges for all existing and projected (to year 2000) thermal electric generating plants on the Canadian shores of the Great Lakes is presented in Figure 19 and Table 1. The cost differentials were estimated for each of three lake surface temperature dilution design criteria.

TABLE 1

Cost Differentials - (Offshore Multiport Discharge Minus Onshore Surface Discharge)

| Design Criteria* | Total Cost $ x $10^6$ | Per Cent Increase in Capital Cost | Increase/ Unit Capacity $/kw | Increase/Unit Energy Mills/ kwh | Per Cent |
|---|---|---|---|---|---|
| 1. $\Delta Tm \leq 2F^{o}$ | 433 | 1.1 | 4.13 | 0.036 | 0.48 |
| 2. $\Delta Tm \leq 3F^{o}$ | 326 | 0.8 | 3.11 | 0.027 | 0.36 |
| 3. $\Delta Tm \leq 6F^{o}$ | 198 | 0.5 | 1.99 | 0.018 | 0.24 |

*$\Delta Tm$ = Maximum surface temperature rise.

The total costs include capital, operating, and maintenance costs for the discharge systems over a 20-year period and for a discount rate of 10 per cent.

The percentage increase in capital cost is based on unit costs for thermal plant construction of $200/kw for fossil fuelled stations and $500/kw for nuclear stations.

An energy cost of 7.5 mills/kwh was assumed for estimating both pump operating costs, and the percentage increase in energy costs for offshore multiport diffusers.

Load factors of 80 per cent and 40 per cent for nuclear and fossil fuel plants, respectively, were used in conjunction with a 20-year operating period to estimate the increase in energy costs.

## 5 - COMPARISON WITH SURFACE DISCHARGES

The quantity of heat received by the Great Lakes from thermal electric generating stations utilizing them as a condenser cooling water source will be essentially the same, regardless of the type of discharge structure used. The five[3] mechanisms of thermal discharge dissipation within the receiving lake will be the same,regardless of the discharge type. However, the relative effectiveness of the various mechanisms is different for the two discharge alternatives. This in combination with the differences in location,relative to the lakeshore and lake surface,results in significantly different distributions of the rejected heat and, consequently, temperature within the lakes.

The mechanisms of heat exchange between the lake and the ultimate "sink" for all the waste heat -- the atmosphere -- are also the same for the two alternatives. In both cases, the majority of this exchange generally can be expected to occur over the large areas of the far field where the plume temperature excesses are relatively low.

It seems apparent then, that the principal feature for comparison in judging which discharge alternative is more appropriate to achieve the environmental objectives at a given site is the plume temperature distribution within the receiving lake. The possible beneficial or detrimental effects of the secondary features of each alternative must, of course, also be weighed in such a judgment.

In terms of the Canadian shorelines of the Great Lakes, the use of offshore multiport diffusers instead of shoreline surface discharges potentially would yield a measure of environmental protection at some cost to the power user by distributing rejected heat differently within the receiving lake. The upper limit of the costs for such protection and the corresponding protection gained, as characterized by the difference between the 1-Centigrade degree isotherm areas for the two discharge alternatives, are summarized in Table 2.

TABLE 2

Additional Costs and
1-Centigrade Degree
Isotherm Area Reductions

| Diffuser Design Criterion* | Total Additional Cost $\$ \times 10^6$ | Per Cent Increase in: Capital Cost | Energy Cost | 1C° Isotherm Area Reduction $Km^2$ | Per Cent |
|---|---|---|---|---|---|
| 1. $\Delta Tm \leq 2F^o$ | 433 | 1.1 | 0.48 | 98.3 | 99.8 |
| 2. $\Delta Tm \leq 3F^o$ | 326 | 0.8 | 0.36 | 97.0 | 98.6 |
| 3. $\Delta Tm \leq 6F^o$ | 198 | 0.5 | 0.24 | 43.5 | 44.3 |

*ΔTm = Maximum surface temperature rise.

No proper evaluation of the relative merits of shoreline surface discharges and offshore multiport diffusers can be made until an environmental objective, either local or comprehensive, has been prepared to provide a basis for comparison. As establishment of environmental objectives and study of effects of the physical characteristics of plumes on organisms are not within the scope of this study, a conditional comparison of the principal difference between the two discharge alternatives is all that is possible.

Thus, the offshore multiport diffuser will be an attractive alternative _if_ the environmental objective requires:

- separation of shore areas from all but infrequent occurrences of temperature excess of low value and short duration
- rapid reduction of temperature excess immediately after discharge to avoid "chaining" of adjacent plumes on shorelines when outfalls are close together
- rapid reduction of temperature excess to avoid excessive temperature rises at nearby features such as water intakes or the mouths of fish spawning creeks,

and _if_ the foregoing requirements outweigh the _potential_ disadvantages of:

- additional exposure of organisms to the maximum cooling water temperature excess in the longer discharge conduit
- the higher energy in the discharge system
- higher cost.

On the other hand, the onshore surface discharge will be an attractive alternative _if_:

- it is established with certainty that the plant site has a low potential for deleterious thermal effects on the shoreline
- the plant heat rejection rate is relatively small
- the discharge is isolated from other thermal discharges or thermally sensitive lake features,

and _if_ there is only minor objection to:

- the discharge and its channel extending into the shallow water area to form both a physical and thermal barrier to longshore movement of bottom materials and mobile organisms

- extensive construction activity in the shallower nearshore area where benthos are generally more prolific
- moderate surface velocities in nearshore areas where very small water craft and swimmers are likely to be active.

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