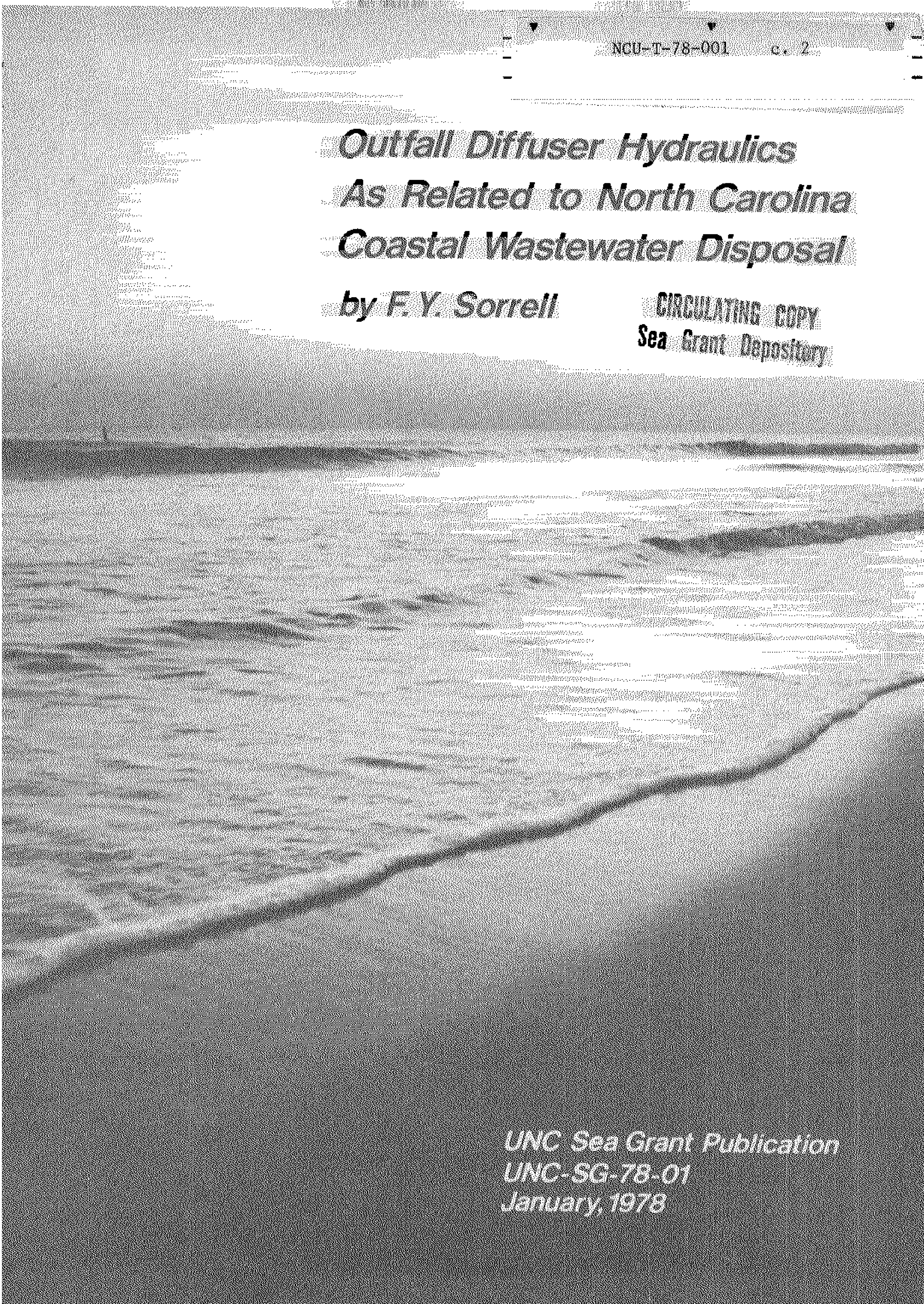

Outfall Diffuser Hydraulics As Related to North Carolina Coastal Wastewater Disposal

by F. Y. Sorrell

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TABLE OF CONTENTS

List of Figures & Tables

Abstract

Results from a study of the requirements and desired functions of the diffuser at the end of an ocean outfall are presented. The study concentrated on outfalls used for wastewater disposal and the most functional geometry for this particular application is discussed. A procedure to calculate the internal flow and discharge parameters was developed for this type diffuser. The most likely locations of outfalls on the North Carolina coast were considered and the wastewater flows at these locations were estimated. These flows and typical discharge parameters, as established by the calculation procedure, were utilized to compute the probable diffuser length and diameter at each location. Preliminary data on diffuser performance or mixing, based on the predicted discharge parameters and expected nearshore conditions, is also provided. The report thus gives a calculation procedure which is applicable for any diffuser and applies this procedure at specific locations to develop preliminary estimates of diffuser size and performance. The results establish the initial conditions of effluent dilution and extent which would be required for any subsquent study of how the effluent will be further mixed by ocean turbulence and transported by ocean currents. In addition, it also provides an estimate of the extent of the diffuser mixing zone and the probable effluent concentrations within the mixing zone.

OUTFALL DIFFUSER HYDRAULICS

I. Introduction

In order to provide minimum oxygen demand and to reduce other environmental effects, it is usually desirable to mix the sewage effluent with background seawater as rapidly and as much as possible. This is accomplished by the geometric arrangement at the discharge end of the outfall pipe, which is referred to as the diffuser. For most ocean outfalls, the diffuser consists of a multiple discharge port manifold at the ocean end of the outfall. If the wastewater were discharged by a single port, the dispersion and dilution would be slower than if discharged over a large area, through a number of ports. In fact, without the use of multiple-outlet diffusers, much longer, and hence more costly, outfalls into deeper water would be necessary to provide the same dilution and consequent shore protection.

In addition to providing maximum dispersion of the effluent, there are several additional hydraulic considerations, which will be discussed in detail in the next section. Moreover, there are the additional constraints of a structurally sound geometry, that can be cleaned with reasonable ease and which is not prohibitively expensive to construct. The combination of hydraulic considerations and structural constraints has resulted in a fairly standard diffuser geometry, but with widely varying dimensions. This is a diffuser which distributes the outflow through many ports over a large area and is often referred to as the submerged multi-port diffuser.

The multi-port diffuser is basically a long manifold and usually undergoes a reduction in pipe diameter toward the far end. The discharge is through many ports that are relatively small compared to pipe area and which usually have simple bell-mouthed holes. For buried pipes and on some steel pipes, the ports are made of short nozzles attached to the pipe. The following report deals with the hydraulic analysis of a diffuser which consists of one long pipe, or several branching pipes, with discharge ports at intervals along the pipes. The report is concerned only with analysis of the internal flow of the diffuser and does not treat structural requirements or the protection necessary for outfall pipes and diffusers. The report is intended to determine the discharge out of each port, and the velocity, pressure and total head at any point in the diffuser as well as the viscous head losses and the total head required at the diffuser entrance. In addition, the procedure is applied to expected diffuser configurations in order to develop the usual or expected values for these parameters.

II. Basic Considerations

A discussion of the basic hydraulic requirements for the diffuser reveal the reason that the multi-port geometry is chosen. Those hydraulic considerations are as follows:

A. Flow Distribution The flow rate out of the individual ports should be fairly uniform along the entire length of the diffuser. This is to provide even mixing and dispersion along the length of the diffuser and to avoid any local build-up of effluent. If the diffuser is not level, i.e. it is laid on a sloping sea bottom, it will be impossible to provide uniform flow distribution among ports for all flow rates (Rawn et.al. 1961). In such cases, the usual procedure is to make the flow distribution fairly uniform at low or medium flow, and to let the deeper ports discharge more than the average port discharge during periods of high rates of flow. One reason for doing this is that substantially less than average discharge from the deeper ports may result in clogging of these ports. Fortunately most of the Eastern U.S. coast, and in particular the N.C. coast, has a relatively shallow slope and therefore most diffusers in these waters can be designed to provide uniform flow for a wide range of flow rates.

B. Velocity in the Diffuser The flow velocity in all sections of the diffuser should be high enough to prevent disposition of any residual particles remaining after treatment. For primary treatment, velocities of 2 feet per second to 3 Ft/s at peak flow are usually adequate, because these will tend to scour any material settled during low flow rates. For sewage that has received secondary or advanced treatment, lower velocities are possible. In this case, the permissible velocities are sufficiently low that it is advisable to have a precise definition of settleable solids before making a decision on minimum flow velocity.

If deposition takes place in any part of the diffuser over an extended period of time, the cross section of the pipe or outlet may become so constricted that local velocity is reduced and a cycle initiated that accelerates the deposition process. This can result in complete clogging of the end ports, and thus failure of the diffuser to supply its predicted mixing or dilution.

C. Total Head Loss Some pumping of the effluent is usually necessary, and thus the total head loss, which is supplied by the pump energy, should be kept reasonably small. As a rule, additional head losses of several feet are usually acceptable. In addition to a geometric consideration, this requirement usually provides an upper limit on permissible discharge velocities.

D. Prevention of Seawater Intermission Flow through all of the ports in the diffuser should be maximum to prevent intermission of seawater into the diffuser pipe. If seawater does enter the pipe it will become stagnant and will tend to trap any settleable matter. Such deposits reduce the mixing capacity of the diffuser as described in A and B.

E. Ease in Cleaning Even carefully designed diffusers will require occasional cleaning to remove any accumulated sediments (grease, slime and grit) at intervals of two to seven years. Provision of sufficient access to provide cleaning should be an integral part of the diffuser design.

F. Port Design The outlet ports may quite satisfactorily consist of circular holes in the side of the pipe without nozzles or tubes or other projecting fittings. If the diffuser pipe is buried, then the usual procedure is to provide short nozzles that extend above the sea bottom. Care should be taken to provide overall simplicity; thus any unnecessary nozzles, gadgets or high maintenance devices should be avoided. The nozzles should also be constructed so that replacement is fairly straightforward in case of damage. For maximum mixing, the jets should discharge horizontally with no initial upward or vertical component of discharge velocity. The inside of the port should be bell-mouthed to minimize clogging and to provide a discharge coefficient which remains constant over an extended period (c.f. section 3 for the possible variation in discharge coefficient). If the discharge ports are placed on either side of the diffuser pipe, their location is usually alternated from side to side to prevent any possible flow instability or flow oscillation between ports.

These requirements apply to all diffusers, whether used for disposal and dispersion of wastewater, chemical effluents or condenser cooling water from power plants. Thus most diffusers have fairly typical geometric arrangements, but with rather widely varying dimensions. A summary of the resulting features is as follows:

1. The diffuser pipe diameters are reduced in steps toward the far end in order to provide even flow distribution.

2. Some form of flap or gate is provided at the end of the diffuser which can be opened for flushing and/or cleaning.

3. The port diameters are relatively small compared to the diffuser pipe diameter. The total port area downstream of any section is less than the pipe area at the section.

4. Whenever possible the ports are simple, bell-mouthed holes in the wall of concrete pipe, or simple, short nozzles on steel pipe.

5. The diffuser pipe is reinforced concrete or structural steel.

III. Analysis of the Internal Flow

The hydraulic analysis of the flow internal to the diffuser has as its boundary condition the flow rate supplied at the entrance of the diffuser. Thus the problem is to determine the resulting flow out of each of the diffuser ports. In practice, the problem is solved in the opposite manner. That is, the flow out of the first (most distant from the entrance) port is estimated and the flow out of the subsequent ports, and the corresponding total head and head loss calculated as the computation proceeds toward the entrance of the diffuser. If the resulting total flow rate is not the one specified, then the estimated flow for the first port is modified and the procedure repeated. This method has been found to converge rather rapidly and can provide almost any desired degree of accuracy.

In order to avoid the iteration procedure described above, French (1972) developed a method to yield a system of differential equations. The equations were put in dimensionless form and integrated numerically for the usual or expected range of dimensionless parameters. The major advantage of this is that it provides an increased understanding of how the various flow parameters interact. The results, however, are limited to constant pipe diameter, except in the case of zero pipe friction. Moreover, all of the results are also restricted to the case where the difference in density between the wastewater in the pipe and the ambient seawater outside the pipe has a negligible effect. While this work does provide insight into diffuser operation, the restrictions make it difficult to apply to a general diffuser. Moreover, the previously described method utilizing an iteration procedure can be easily and quickly carried out on a computer: because the overall objective of this work is to be able to evaluate or predict the performance of any proposed diffuser, a complete numerical calculation was adopted. The technique is basically that first utilized by Rawn, et.al. (1961) and subsquently considered in detail by Brooks (1970). Before describing the computation procedure and the computer program, however, a description of the basic phenomena and principles are discussed.

For all calculations, each port is assumed to be at full flow. Based on the work of Rouse (1946), a circular orifice in a large tank will flow full for Froude numbers greater than 0.59. Here, the Froude number $=F=V/gD$ where V= port velocity, g=the acceleration of gravity and D= the port diameter. For a rounded port the criteria for flowing full is usually taken as $F>1$, Brooks (1970). This translates into a flow velocity of greater than 3 Ft/s for most common diffuser conditions. With every port flowing full, there is no way in which the seawater can enter the pipe, once initially expelled. Thus the diffuser will prevent any seawater intrusion.

In making these calculations, the pertinent pressure at any point is the pressure differential between the fluid inside the diffuser and the seawater outside at the level of the port. The pressure in the seawater is assumed to be hydrostatic. Because the seawater is more dense than the wastewater, it will decrease faster with increasing elevation. Thus when working in reverse order from the deepest or farthest point of a diffuser, any decrease in depth tends to increase the pressure differential. The change (increase) in pressure differential due to an increase in elevation ΔZ is $\Delta\rho\Delta Z$ where $\Delta\rho$ is the difference in density between the seawater and wastewater.

The basic premise of the hydraulic analysis is that the ports are far enough apart that the flow in the vicinity of any one port is independent of the rest of the diffuser flow. This does not mean that the discharge jets never interact, but only that their interaction occurs sufficiently far from the diffuser that it does not alter the discharge from the port. This assumption is nearly always very accurate. As a result the discharge from each port can be computed separately, and the total flow in the diffuser pipe obtained by addition of the flows from the individual ports. Between consecutive ports the effective pressure head is increased by the amount of the friction loss plus the density head ($\frac{\Delta\rho}{\rho}\ \Delta F$). Therefore the rate of discharge from a single orifice or port is the basic hydraulic phenomena in the calculation.

The rate of discharge, Q, from an orifice or port in the side of a pipe whose geometric configuration is shown in Fig. 1 can be expressed by:

$$Q(n) = C_D\ ARPT\ (2gE(n))^{\frac{1}{2}} \qquad (1)$$

where

$Q(n)$ = discharge out of n^{th} port

CD = discharge coefficient

ARPT = area of the port

g = acceleration of gravity

$E(n)$ = Total head = $\frac{V2}{2g} + \frac{\Delta P}{\gamma f}$ at the port location

ΔP = pressure difference between inside and outside of pipe at the port location

$\gamma f = \rho g$ = weight of fluid in jet

V = mean velocity inside the pipe

This equation is a semi-empirical expression developed from the application of the Bernoulli equation to the port discharge. This discharge coefficient C_D, is to account for various losses, contraction of the discharge jet and nonuniformities in the discharge. The expression also assumes that there is no energy loss from the main flow down the diffuser pipe as it passes each port. In other words, the decrease in pipe velocity due to port discharge is compensated by complete pressure recovery (the decreased velocity head is replaced by increased pressure head). This is usually a good assumption partially because the velocity decrease at any port is small. This assumption has been considered by McNown (1954) in the analysis of manifold flows.

In general, the correct value for C_D must be found experimentally and depends not only on the geometrical characteristics of the pipe and port, but also on the ratio of the velocity head in the diffuser to the total head (E). Brooks (1970) has investigated the correct representation of the discharge coefficient for ports cast directly into the wall of the diffuser. He developed the following expressions for discharge coefficients at high Reynolds Numbers (RN$\geq$ 20,000):

1) Sharp edged ports, flowing full:

$$C_D = 0.63 - 0.58\frac{V^2/2g}{E} \tag{2}$$

2) For smooth bellmouth ports, flowing full:

$$C_D = 0.975\left(1 - \frac{V^2/2g}{E}\right) \tag{3}$$

These values apply only to small ports or where the port diameter is less than one tenth of the diffuser pipe diameter; they also have been verified in concrete or steel pipes. Vigander, et.al. (1970) has considered the use of corrugated structural steel pipes as the diffuser pipe for the condenser cooling water discharged from a nuclear power plant. For this type of pipe the discharge coefficient is altered because the diffuser ports are placed in the pipe corrugations. In addition, the pipe friction, or head loss between ports, is increased by a corrugated pipe. In some applications the discharge ports consist of riser-nozzle assemblies. The risers are usually used when the main diffuser pipe is completely buried under the ocean bottom. In that event, the discharge coefficient is dependent on the entire geometrical characteristic of the riser nozzle assembly. Some data exists on special configurations that have been used. See e.g. Koh and Brooks (1975).

The present study is confined to smooth (un-corrugated) pipe with horizontal discharge ports consisting simply of holes in the pipe. This is used because the design is the expected configuration for diffusers that will be used along the Southeastern Coast. If other methods of port construction are utilized, and experimental data on the discharge coefficient is available, it is straightforward to incorporate the new methods into the calculation procedure.

In order to provide a uniform flow distribution, the discharge, Q, is usually small relative to that in the diffuser pipe. Therefore, the difference in upstream and down velocities (V(n) and V (n-1) in Fig. 1) is usually sufficiently small that either V (n) or V (n-1) can be used in Eq. (2) or (3) to compute the discharge coefficient. As will be seen, it is usually more convenient to use V (n-1), the downstream velocity.

IV. Calculation Procedure

As previously mentioned, during the calculation procedure a computer calculates the flow out of each individual port, beginning with the port most distant from the diffuser entrance. The procedure is described in steps below, but several introductory comments are made first. The notation employed in this section is similar to that used in the computer program in order to

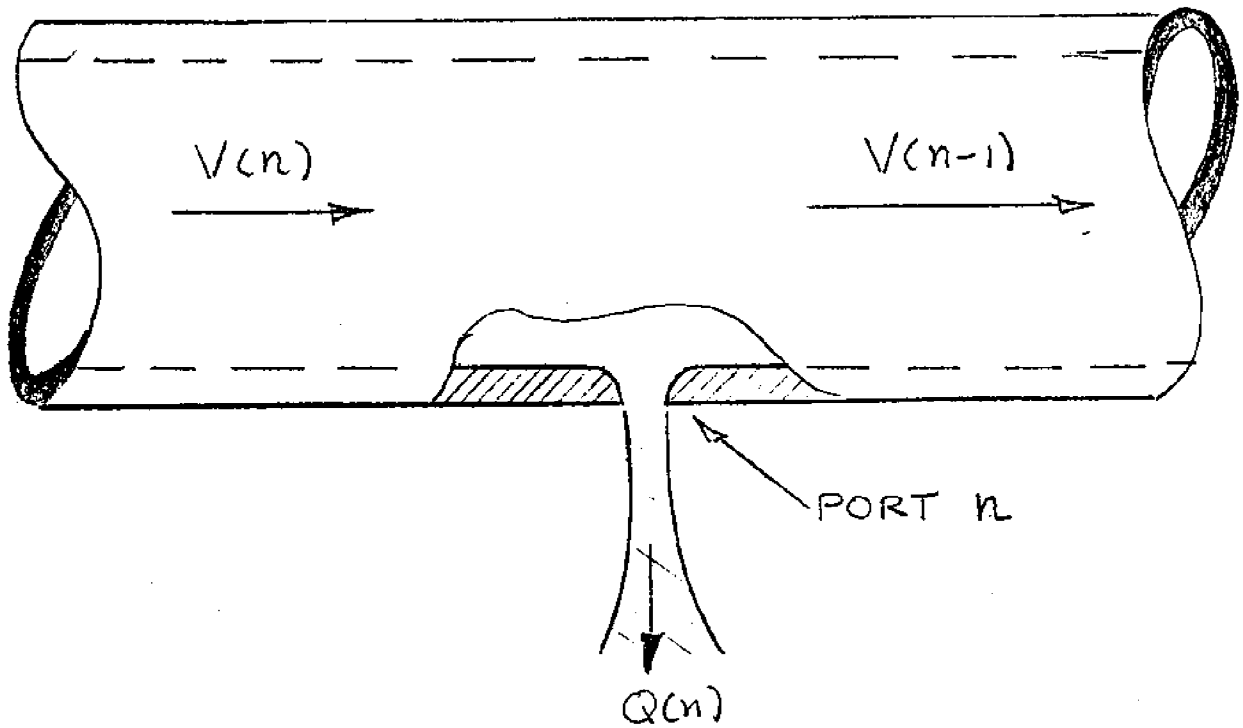

Fig. 1.
DISCHARGE FROM A TYPICAL PORT

facilitate understanding of the program. The program itself is reproduced in Appendix A. The English system of units is utilized. However, most port and pipe diameters are usually given in inches rather than feet. Hence the program is arranged so that these diameters can be input in inches. The rest of the program input is written using the English system in consistent units.

The ports are numbered 1 to n, with port number 1 being the port most distant from the entrance to the diffuser. The first step is to estimate the flow rate of discharge (Ft^3/s) out of port No. 1. The original procedure employed by Rawn et.al. (1961) began estimating the total head at the last port, and then computing the discharge. Here the port velocity is used as the first estimate, primarily because most port velocities will range between 3 and 8 ft/s. Thus step one is to estimate VP (1), the velocity out of port 1. This velocity is then used to calculate the discharge out of port 1, Q (1). Using this discharge, the velocity in the diffuser pipe between port 1 and port 2 can be calculated by:

$$V(1) = Q(1)/ARPP \qquad (4)$$

where V (1) is the pipe velocity between port 1 and port 2 (c.f. fig. 1) and ARPP is the cross-section area of the diffuser pipe. Having the flow velocity in the pipe, the velocity head is calculated via:

$$VH(1) = \frac{V^2(1)}{2g} \qquad (5)$$

where VH(1) is the velocity head between port 1 and port 2. The head loss can then be calculated by:

$$HF = F \times \frac{SEP}{DIAP} \times VH(1) \qquad (6)$$

where HF is the head loss, F is the Darcy friction factor, SEP is the separation between ports, and DIAP is the diameter of the diffuser pipe. The designer usually has the option of changing port size and diffuser pipe size. Port spacing or SEP, however, usually can not be easily changed because an integral number of ports per pipe section is required. As a result, the port spacing is considered fixed in the present calculation procedure. Modification into variable port spacing can be easily made, however, if it is ever needed.

After calculation of the head loss between ports, the increase in pressure head, DENHD, is calculated by:

$$\text{DENHD} = \frac{\Delta\rho}{\rho}\,\Delta Z \tag{7}$$

where $\Delta\rho$ is the density difference between the discharged fluid and the seawater outside the diffuser, ρ is the discharge fluid density and ΔZ is the difference in elevation between the two ports. The total head at port 2 is then the sum of the head at port 1 plus the head loss and pressure head between the ports, i.e.

$$E(2) = E(1) + \text{DEHD} + \text{HF} \tag{8}$$

where E(1) is the total head at port 1 and consists of only the velocity head, i.e. E(1) = VH(1). Having computed the total head, one can then use VH(1) to determine the ratio of velocity head to total head. This ratio is then used in Eq. (2) or (3), as appropriate, to yield the discharge coefficient for the second port. After computing discharge coefficient, the discharge out of the second port is computed from equation (1). i.e.

$$Q(2) = \text{CD ARPT} \ (2gE(2))^{\frac{1}{2}} \tag{9}$$

where the terms are defined after equation (1). The flow from ports (1) and (2) are then combined and used to compute the flow rate in the diffuser pipe between ports (2) and (3):

$$\text{QT} = \text{QT} + Q(2) \tag{10}$$

where QT is the total flow rate in the diffuser at the n^{th} port; in this case QT on the right of eq. (10) is simply Q(1). The combined flow rate is then used to compute the velocity in the diffuser pipe via:

$$V(2) = QT/ARPP \qquad (11)$$

where V(2) is the pipe velocity upstream of the 2nd port (c.f. fig. 1) This pipe velocity is then used to compute the velocity head and the procedure beginning with equation 5 repeated to yield the discharge from port (3). The general expressions used to obtain the discharge from the n^{th} port are as follows:

$$VH\ (n) = V^2\ (n)/2g \qquad (5a)$$

$$HF = F \times \frac{SEP}{DIAP} \times VH(n) \qquad (6a)$$

$$DENHD = \frac{\Delta\rho}{\rho}\ \Delta Z \qquad (7a)$$

$$E(n) = E(n-1) + HF + DENHD \qquad (8a)$$

$$Q\ (n) = CD\ APRT\ \ (2g\ E(n)\ )^{\frac{1}{2}} \qquad (9a)$$

$$AT = QT + Q(n) \qquad (10a)$$

$$V(n) = QT/ARPP \qquad (11a)$$

The use of these equations is repeated (by use of a do loop in the computer) until the flow out of the last or n^{th} port is calculated. By summing the discharge from the individual ports, the total flow discharge by the diffuser can be computed. In addition, the total head and head loss that must be supplied at the diffuser entrance can also be calculated by summing the head loss between ports. In most cases, this flow rate is not the desired flow rate that is to be discharged by the diffuser, simply because the initial estimate for the discharge from port 1 was not correct. Therefore the estimated discharge for port (1) is altered and the calculation procedure repeated. The present calculation procedure uses the difference between the computed and desired flow rates as an estimate of the correction that should be made to the estimate for the discharge of port (1). The actual procedure computes the difference between the two flow rates, ΔQ, by

$$\Delta Q = QACT - QT \quad (12)$$

where QACT is the desired diffuser flow rate and QT the computed diffuser flow (eq. 10a). The correction on the estimated value of Q(1) is then

$$\Delta Q(1) = 0.85\ \Delta Q/QACT \quad (13)$$

The factor of 85% is used to assure rapid convergence of the solution, but without oscillation about the desired discharge. This number has been chosen primarily on the basis of experience in making the calculation. The correction is repeated until the computed flow rate QT is within any desired accuracy of the actual flow rate. After this accuracy has been reached, the program then prints the velocity in the pipe V(n), the area of each port APRT(N), the discharge of the port Q(N), the approximate port discharge velocity VP(N), and the distance from the end of the diffuser for each port. In addition, the final flow rate and head loss are also printed in the output.

In some situations, when the variation of parameters over the length of the diffuser are being studied, it may be more convenient to have the output in non-dimension form. Therefore the program also computes the ratio of velocity head to total head, defined as B(n), the non-dimension discharge per unit length, given the symbol R(n), and the non-dimensional length of the diffuser itself, denoted by X(n). The form of these parameters are those suggested by the work of French (1972), and the reader is referred to this paper for a discussion of the rationale employed in the non-dimensional procedure. When investigating the relative uniformity of the discharge, the non-dimensional form of output is often more convenient. Therefore, the non-dimensional parameters are also calculated and printed in the output.

V. Application & Results

As an example, the diffuser program (provided in Appendix A) was used to compute the performance of the proposed Hampton Roads outfall and diffuser.

This outfall is designed to serve the Virginia Beach area, an area with conditions somewhat typical of those in a large Southeastern urban area. While North Carolina nearshore conditions are nearly identical, the State's coastal urban areas are considerably smaller in population and area; hence they will have lower wastewater flows. Table 1 (pg.21) provides the estimated wastewater flows for North Carolina urban areas. These figures are based on population estimates in each area.

The Hampton Roads advanced wastewater treatment facility is designed to operate with an initial discharge of 35 million gallons per day. This figure is predicted to increase to 65 MGD by the year 2010. The outfall and initial portion of the diffuser consist of a 66-inch diameter pipe. The diffuser itself is 2400 feet long. Starting at the seaward end, the diffuser consists of 109 three and one-fourth-inch diameter ports, alternating on eight feet spacing in a 42-inch pipe. The spacing is maintained at 8 feet, alternating on either side of the pipe over the entire 2400-foot length. The ports are of the simple bell-mouthed type, cast in the pipe wall. The next section consists of 52 three-inch diameter ports in a 54-inch pipe. The last section has 32 two and seven-eights-inch diameter ports followed by 66 two and three-fourths-inch diameter ports, with the final size being two and five eights inches and consisting of 42 ports. The ports in the last section are all in 66-inch pipe. Thus the diffuser consists of three different stepped pipe sizes and five different port sizes, with a total of 300 ports. The present proposal is to lay the diffuser on the ocean floor along a contour line with the entire diffuser at the same elevation. Thus the flow distribution among ports should be the same for all flow rates. This is fairly typical for the southeastern coast, where the nearshore bottom has a very small slope. Therefore it is usually possible to provide a constant depth for the entire length of the diffuser.

The results of the computation for 65 MGD are given in Appendix B. The results provide the total energy head E(n), the velocity in the diffuser pipe V(n), the computed discharge out of each port, Q(n), and the approximate velocity, VP(n), out of the port as a function of distance from the seaward end of the diffuser. The port number is also included. In addition to these dimensional values, the non-dimensional distance, X(n), and discharge per unit length, R(n), are also provided in the output.

The results in Appendix B are in numerical form and are useful for detailed analysis of the diffuser. However, when the diffuser has a large number of ports it is easier to visualize the flow dynamics graphically. An example is given by figure 2, which is a plot of the discharge per port verses distance along the diffuser. The figure provides an easy check of uniformity in the discharge over the length of the diffuser. Two features are noteworthy. First, there is a discontinuous change in discharge with each change in port diameter. The ports are systematically reduced in size to produce approximately the same discharge per unit length. This is typical of all proper diffuser designs. Second, the relative discharge among ports remains the same at different flow rates. As mentioned previously, this is because the diffuser is level.

The distribution of velocity in the diffuser pipe is shown in figure 3. Again there is a discontinuous change in velocity where the pipe undergoes a diameter change. The purpose of the decrease in pipe diameter as one proceeds toward the end of the diffuser is to keep the pipe velocity from becoming too low, as is clearly shown.

When analyzing the performance, or dilution, provided by a particular

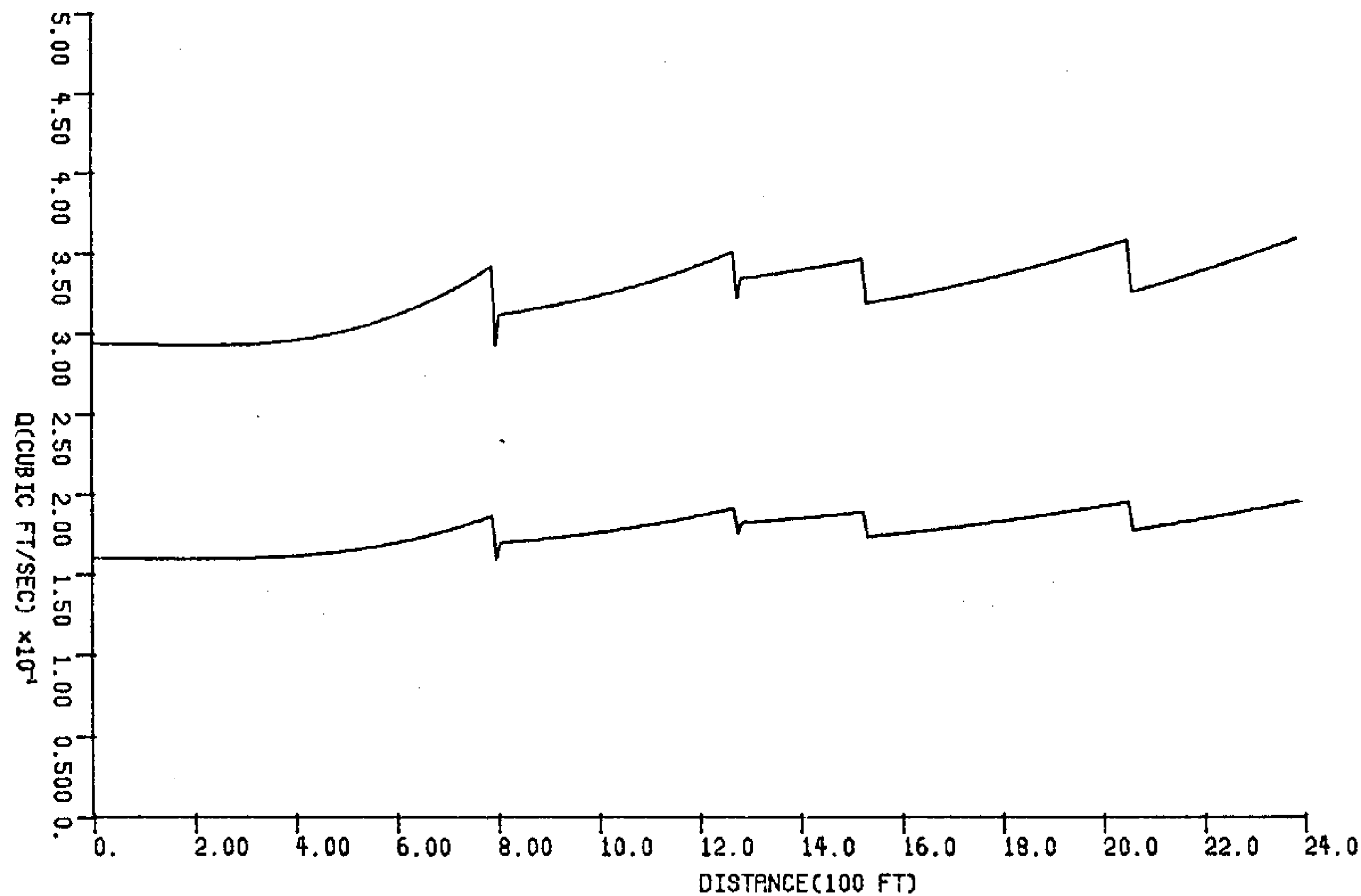

Fig. 2.

DISCHARGE PER PORT VERSES DIFFUSER LENGTH
UPPER CURVE 65 MGD, LOWER 35 MGD.

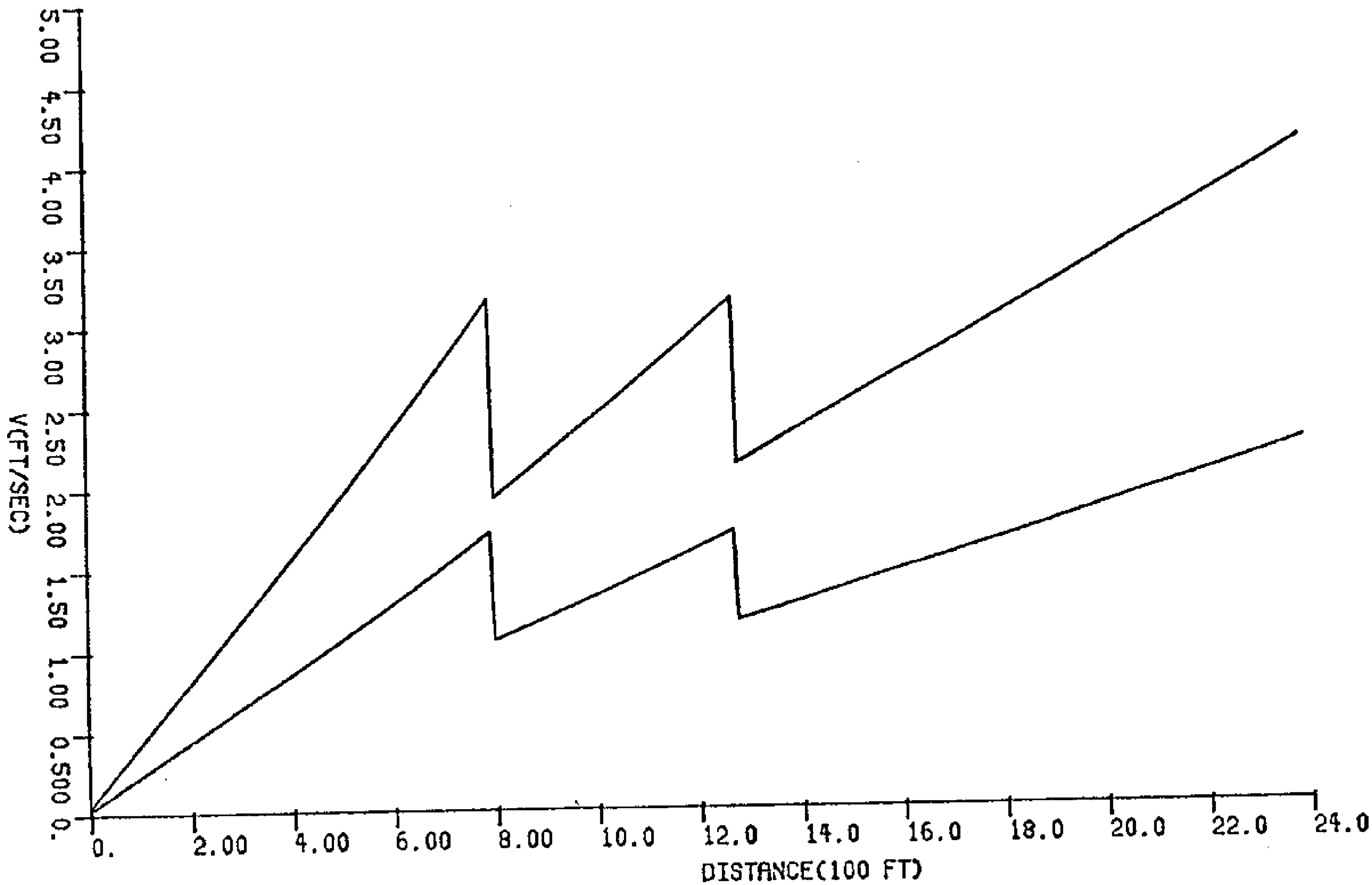

Fig. 3.

DIFFUSER PIPE VELOCITY VERSES DIFFUSER LENGTH
UPPER CURVE 65 MGD, LOWER 35 MGD

diffuser, the numerical results given in Appendix B are more useful. However, probably a better idea of the overall operation is given in figure 2 and 3. From these figures and those generated from other configurations, the following conclusions can be drawn.

During the design process, the engineer can vary the pipe diameter, the port diameter and possibly the port spacing. In order to keep the pipe velocity high enough, it is often necessary to reduce the size of the pipe in one or more steps from the entrance to the seaward end. The size of the discharge ports is usually varied in such a way as to provide approximately uniform discharge over the length of the diffuser. As previously mentioned, the spacing between ports is difficult to change because practical considerations dictate that the spacing remain equivalent to a length of pipe or some multiple thereof.

For a diffuser which is laid at zero slope (level), the relative distribution of flow will be the same at all flow rates. This was previously discussed and is illustrated in figure 2. The reason is because all the head terms are proportional to the square of the velocity and that there are no pressure head changes due to change in elevation. In this case one calculation will be sufficient for all rates of flow. For example, to double the rate of flow, one would simply quadruple all the heads and double all the velocities and discharges. In practice, the computation is usually only made in order to confirm the result. However the concept is useful in understanding diffuser operation.

The sum of all port areas must be less than the cross-sectional area of the pipe at any location along the diffuser. It is impossible to have all ports flow full if the aggregate port area is larger than the pipe cross-section, otherwise the average velocity of discharge would have to be less than the velocity of flow in the pipe. Brooks (1970) has indicated that the best area ratio (Σ port area: pipe area) is usually about one half to one third. These values are small enough to get good flow distribution and full flow among ports without producing velocities so high that the total head and head losses become unduly large.

VI. Parameters Range for Potential North Carolina Diffusers.

From a comparison of diffuser pipe length at various outfalls, it is possible to compute the ratio of length in feet to the design value of the average daily discharge in MGD. This is referred to as the diffuser loading, and provides some idea of the length and subsequent mixing provided by the diffuser.

Diffuser loading for West coast outfalls usually range from 15 to 20 ft/MGD. This is a relatively low value (high loading) and is possible because the outfalls are in deep (150-200 ft.) water. In shallow water, higher values of loading become necessary. For example, the Hampton Roads diffuser, which is at a depth of approximately 32 feet, has a diffuser loading of 37 ft/MGD. Assuming that 35 to 45 ft/MGD is a typical value for Southeastern coastal waters, the expected diffuser lengths for the wastewater flows given in Table 1 have been computed. These are included in Table 1 under the column titled "probable diffuser length". Moreover, the pipe diameter can also be estimated by using these flow rates and the expected values of the entrance velocity. With an assumed pipe velocity of 4 ft/sec, the pipe diameter has been calculated. The computed values are also given in Table 1 under the column, "probable pipe diameter". Experience indicates that port diameter for these diffusers will probably be on the order of 1 to 2 inches; the lower bound being set by the smallest practical bell-mouthed hole that can be consistently manufactured. The discharge velocity from these ports should range from 4 to 10 ft/sec.

TABLE 1

ESTIMATED WASTEWATER FLOWS AND
DIFFUSER PARAMETERS

LOCATION	YR 2000 WASTEWATER FLOW MGD	PROBABLE LENGTH -FT-	DIFFUSER DIAMETER INCHES
DARE BEACHES	4.0	200	16
BOGUE ISLAND & MOREHEAD CITY	9.0	500	24
WRIGHTSVILLE BEACH	1.4	80	10
WRIGHTSVILLE BEACH & WILMINGTON	14	600	32
SURF CITY REGION	1.0	50	8

As previously mentioned, the amount of mixing or dilution provided by the diffuser is a major concern. In order to compute the dilution of the wastewater discharge from a particular diffuser, one must have the discharge parameters, (computed as described in this report), the actual diffuser geometry, the depth of discharge, and the nearshore ocean conditions. However it is possible to make a reasonably valid estimate of all of these quantities, and thus one can make an order of magnitude calculation of the probable dilution that will occur. Because the approximate amount of dilution or mixing possible is of considerable concern, the estimate was made as follows.

The likely range of discharge parameters and port sizes have already been discussed. The data provided in Table 1 gives an estimate of diffuser size and the volume of discharge. The actual diffuser geometry is assumed to be that for a conventional, properly designed diffuser using standard or typical design values. The nearshore ocean conditions that were used were based on an average of historical data. The depth of discharge was estimated by a study of bottom topography off the North Carolina coast. With the exception of the Northeastern section (Dare Beaches), the depth of the ocean floor off of North Carolina is extremely shallow. Even in the Dare Beach area, the slope is much less than in many other areas of the United States. For this reason, North Carolina outfall diffusers will probably be located in relatively shallow water. For this study, diffuser depths were estimated at between 20 and 40 feet. This corresponds to an offshore distance in North Carolina of from 1 to 5 miles.

By utilizing these assumptions, curves of expected dilution were calculated for typical diffusers in North Carolina coastal waters. These curves are given in figures 4 and 5. Figure 4 is for widely-spaced port separations and 5 is for closely spaced ports. For this study, closely spaced ports are defined as those which are closer than one-fifth of the water depth.

It is emphasized that these figures are based on a number of assumptions. Thus the intent here is to provide preliminary estimates of the dilution that can be expected in the mixing zone of the diffuser. Obviously the performance of a specific diffuser should be analyzed before making any conclusions on that particular diffuser. The spatial extent of the mixing zone can be crudely estimated as a triangular zone extending the length of the diffuser to the ocean surface, assuming a 90^{0} vertex at the diffuser.

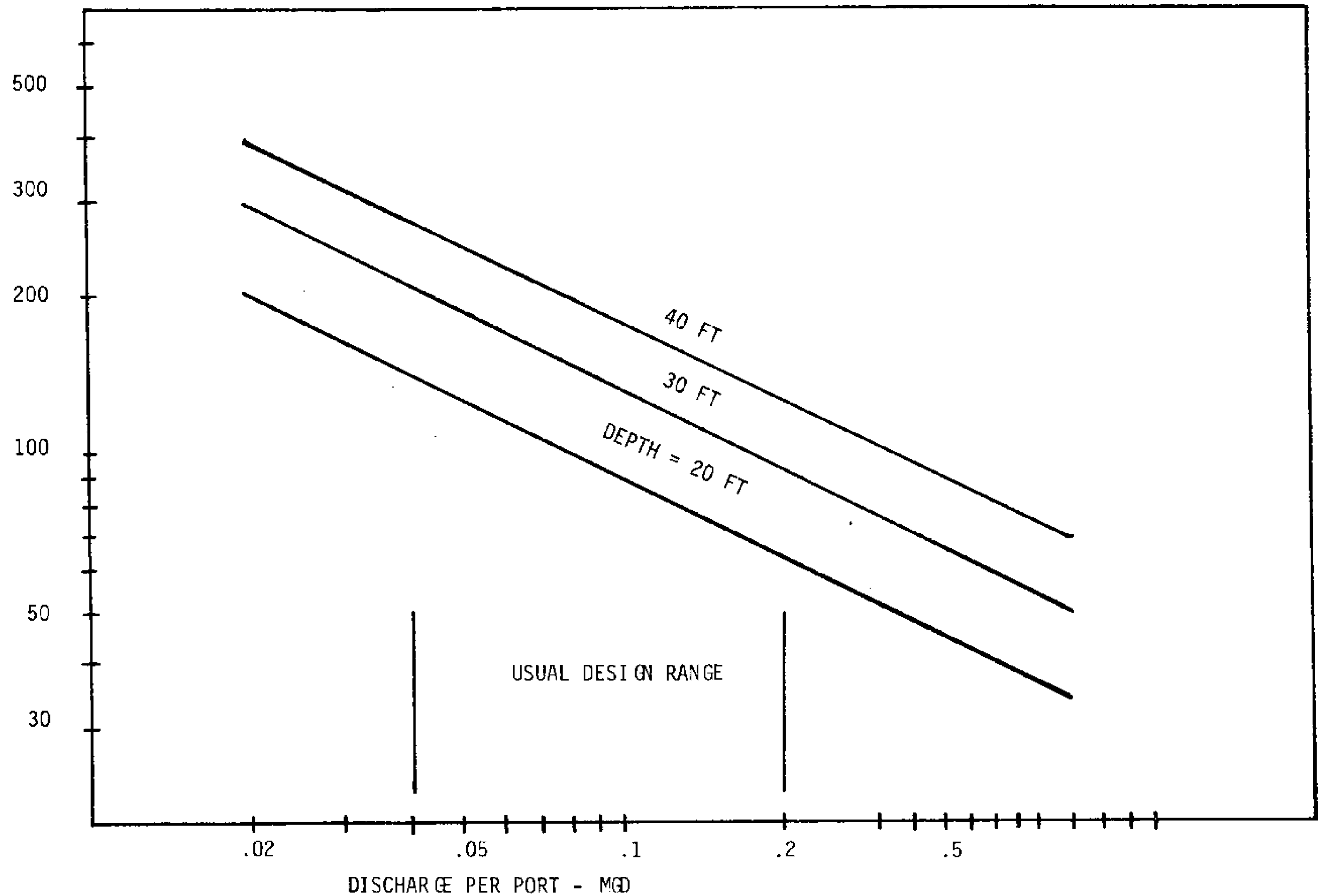

Fig. 4.

AVERAGE SURFACE DILUTION FOR
WIDELY SPACED DISCHARGE PORTS

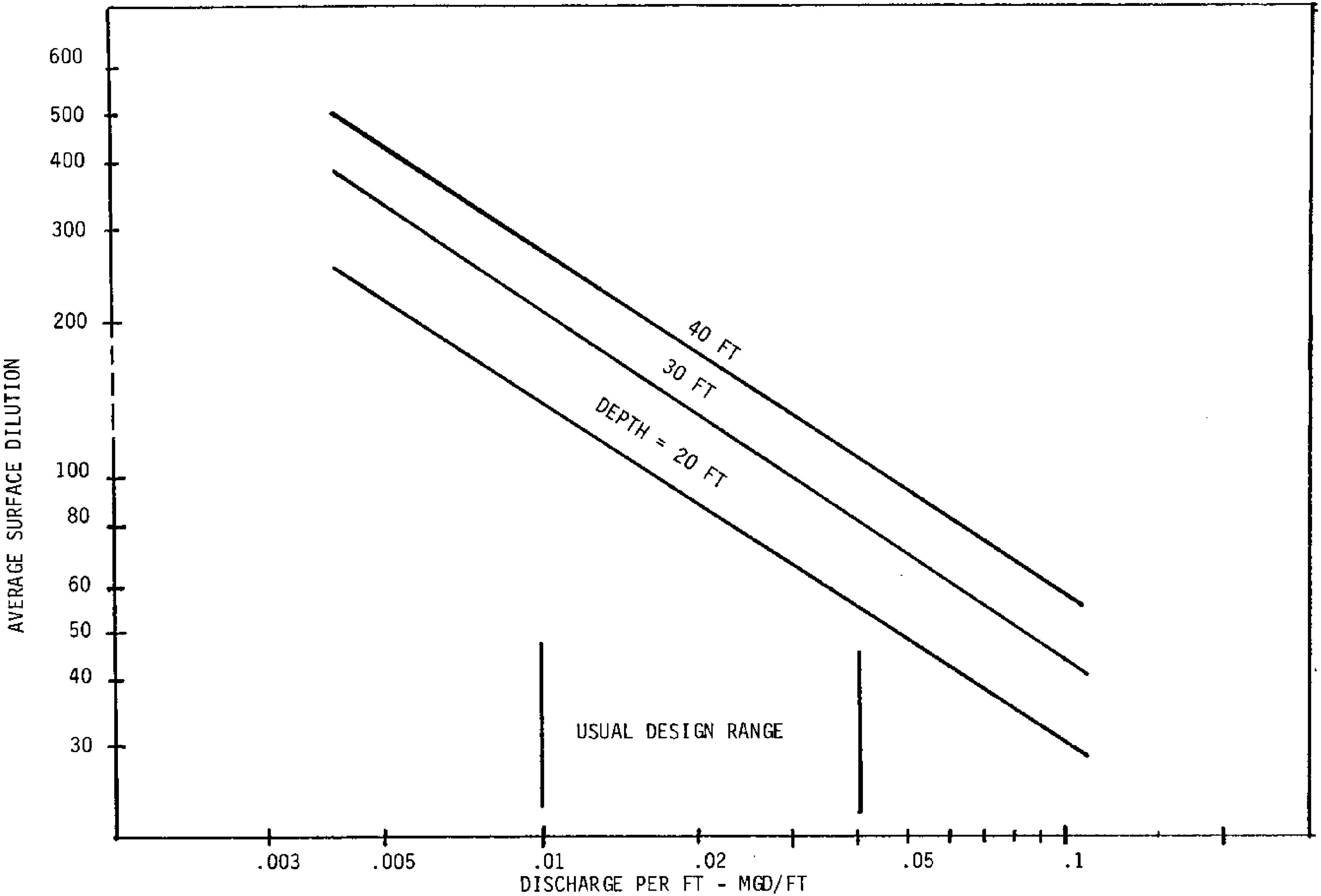

Fig. 5
AVERAGE SURFACE DILUTION FOR
CLOSELY SPACED DISCHARGE PORTS

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APPENDIX A

COMPUTER PROGRAM TO CALCULATE INTERNAL FLOW

```
C
C      M= NUMBER OF PORTS
C      QACT=ACTUAL FLOW RATE  CUBIC FT/SEC
C      DIA(N)= DIAMETER OF PORTS
C      ARPT= AREA OF THE PORT
C      DPIP= DIAMETER OF PIPE
C      ARPP= AREA OF PIPE
C
C      DIS= DISTANCE FROM SEA END OF THE PIPE
C      C1,C2.... DISTANCE FORM SEAWARD END OF DIFFUSER WHERE THERE
C      IS A CHANGE IN PORT DIA., PIPE DIA., OR PIPE SLOPE
C      SEP= PORT SEPARATION
C
C      VEL= VELOCITY OF SEWAGE OUT OF PORT
C      Q(M)= DISCHARGE OF NTH PORT
C      CD= DISCHARGE COEFFICIENT FOR THE PORT
C      V(M)= MEAN PIPE VELOCITY BETWEEN NTH PORT AND N+1 PORT
C      VH(M)= VELOCITY HEAD AT NTH PORT
C      HF(M)= HEAD LOSS DUE TO FRICTION BETWEEN N+1 AND NTH PORT
C      F= DARCY FRICTION FACTOR
C      E(M)= TOTAL HEAD AT THE NTH PORT
C
C      L= OPERATOR FOR PORT CONFIGURATION. L=1. BELL MOUTH PORT  L=2 SHARP
C      EDGE PORTS
C
C      RHO= DENSITY OF SEWAGE
C      SRHO= DENSITY OF SEAWATER
C      THET= ANGLE OF INCLINATION OF PIPE
C
C      X(N)= NORMALIZED LENGTH
C      DM= PORT PARAMETER
C      R(N)= NORMALIZED PORT DISCHARGE PER UNIT LENGTH
C      B(N)= VELOCITY HEAD/ TOTAL HEAD
C
       DIMENSION DIA(5),V(300),Q(300),VH(300),HF(300),CD(300),ARPT(300)
       DIMENSION E(300),THET(1),DIS(300),DPIP(5)
       DIMENSION X(300),R(300),B(300),VP(300)
       DIMENSION RQA(2)
       DATA RQA/54.,100./
       READ(1,100)GRAV,F,RHO,SRHO
   100 FORMAT(4F10.5)
       READ(1,110) DIA(1),DIA(2),DIA(3),DIA(4),DIA(5)
   110 FORMAT(5F10.2)
       READ(1,120) DPIP(1),DPIP(2),DPIP(3)
   120 FORMAT(3F10.2)
       READ(1,200)C1,C2,C3,C4
   200 FORMAT(4F10.2)
       READ(1,220)THET(1),QACT,VEL
   220 FORMAT(3F10.2)
       READ(1,300)L,M,SEP
   300 FORMAT(2I10,F10.2)
       DO 22 NN=1,5
       DIA(NN)=DIA(NN)/12
    22 CONTINUE
       DO 24 MM=1,3
       DPIP(MM)=DPIP(MM)/12
```

```
   24 CONTINUE
      ARPT(1)=3.142/4*DIA(1)**2
      Q(1)=VEL*ARPT(1)
      DO 1002 NT=1,2
      QACT=RQA(NT)
      GO TO 5
   91 Q(1)=(1.0-CRE)*Q(1)
      GO TO 5
   92 Q(1)=(1.0+CRE)*Q(1)
    5 ARPP=3.142/4*DPIP(1)**2
      V(1)=Q(1)/ARPP
      VH(1)=V(1)**2/(2*GRAV)
      VP(1)=Q(1)/ARPT(1)
      IF(L.EQ.1) GO TO 10
      CD(1)=0.63
      GO TO 20
   10 CD(1)=0.975
   20 DM= CD(1)*(DIA(1)**2)/SEP
      QT=Q(1)
      E(1)=(Q(1)/(CD(1)*ARPT(1)))**2/(2*GRAV)
      X(1)=0.
      B(1)=V(1)**2/(2*GRAV*E(1))
      R(1)=1.0
      DIS(1)=0.0
      HFT=00.0
      K=M-1
      DO 600 I=1,K
      N=I+1
      DIS(N)=SEP*I
      IF(DIS(N).GE.C4) GO TO 55
      IF(DIS(N).GE.C3) GO TO 50
      IF(DIS(N).GE.C2) GO TO 40
      IF(DIS(N).GE.C1) GO TO 30
      DIAM=DIA(1)
      DIAP=DPIP(1)
      THETD=THET(1)
      GO TO 60
   30 DIAP=DPIP(2)
      DIAM=DIA(2)
      GO TO 60
   40 DIAP=DPIP(3)
      DIAM=DIA(3)
      GO TO 60
   50 DIAM=DIA(4)
      GO TO 60
   55 DIAM=DIA(5)
   60 ARPT(N)= 3.142/4.*DIAM**2
      ARPP=3.142/4*DIAP**2
      VH(I)=V(I)**2/(2*GRAV)
      HF(I)=F*SEP*VH(I)/DIAP
      HFT=HFT+HF(I)
      THETR=THETD*3.14159/180
      DELZ=SEP*SIN(THETR)
      DENHD=(SRHO-RHO)*DELZ/RHO
      E(N)=E(I)+HF(I)+DENHD
      IF(L .EQ. 1) GO TO 70
```

```
      CD(N)= 0.63 -0.58*(V(I)**2/(2*GRAV*E(N)))
      GO TO 80
   70 CD(N)=0.975*((1-VH(I)/E(N))**0.375)
   80 CONTINUE
      Q(N)= CD(N)*ARPT(N)*SQRT(2*GRAV*E(N))
      QT=QT+Q(N)
      V(N)=QT/ARPP
      VP(N)=Q(N)/ARPT(N)
      B(N)=V(N)**2/(2*GRAV*E(N))
      R(N)=CD(N)/CD(1)*SQRT(E(N)/E(1))
      DM= CD(1)*(DIA(1)**2)/SEP
      X(N)=DM*DIS(N)/(DIAP**2)
  600 CONTINUE
      QRE=(QACT-QT)*100/QACT
      QRE2=QRE**2
      CRE=SQRT(QRE2)/120.00
      WRITE(3,388)CRE,QT,VP(1)
  388 FORMAT(1X,'FLOW RATE CORRECTION',5X,'CRE=',F10.5,5X,'QT=',F10.5
     C,5X,'PORT VEL=',F10.5,//)
      PE=50.0
      IF(QRE2.LE.PE) GO TO 90
      IF(QRE.LT.0.) GO TO 91
      IF(QRE.GT.0.) GO TO 92
   90 CONTINUE
      WRITE(3,400)
  400 FORMAT(5X,'X(N)',5X,'R(N)',7X,'E(N)',7X,'V(N)',
     C7X,'APRT(N)',7X,'Q(N)',7X,'VP(N)',7X,'DIS(N)',7X,'N',//)
      DO 900 J=1,M
      WRITE(3,800) X(J),R(J),E(J),V(J),ARPT(J),Q(J),VP(J),DIS(J),J
  900 CONTINUE
      WRITE(3,1000)QACT,QT,VEL,VP(1)
      WRITE(4,801)(V(J),J=1,M)
      WRITE(4,801)(Q(J),J=1,M)
      WRITE(4,802)(DIS(J),J=1,M)
  801 FORMAT(10F6.4)
  802 FORMAT(10F6.1)
 1002 CONTINUE
  800 FORMAT(1X,4F10.5,3X,F10.5,3X,2F10.5,3X,F10.2,4X,I4)
 1000 FORMAT(///,2X,'DESIGN FLOW RATE=',F10.5,5X,'COMPUTED FLOW RATE=',
     CF10.4,5X,'EST PORT VEL=',F10.7,5X,'ACTUAL PORT VEL=',F10.7)
      STOP
      END
```

APPENDIX B

SAMPLE COMPUTER PROGRAM OUTPUT

FLOW RATE CORRECTION CRE= 0.34615 QT= 76.43042 PORT VEL= 4.00000

FLOW RATE CORRECTION CRE= 0.06214 QT= 49.97343 PORT VEL= 2.61541

FLOW RATE CORRECTION CRE= 0.01422 QT= 53.07877 PORT VEL= 2.77792

X(N)	R(N)	E(N)	V(N)	APRT(N)	Q(N)	VP(N)	DIS(N)	N
0.0	1.00000	0.12617	0.01663	0.05762	0.16006	2.77792	0.0	1
0.00584	0.99999	0.12617	0.03327	0.05762	0.16005	2.77789	8.00	2
0.01168	0.99995	0.12617	0.04990	0.05762	0.16005	2.77779	16.00	3
0.01751	0.99990	0.12617	0.06653	0.05762	0.16004	2.77763	24.00	4
0.02335	0.99982	0.12617	0.08316	0.05762	0.16003	2.77743	32.00	5
0.02919	0.99973	0.12618	0.09979	0.05762	0.16001	2.77717	40.00	6
0.03503	0.99962	0.12619	0.11642	0.05762	0.16000	2.77687	48.00	7
0.04087	0.99950	0.12620	0.13304	0.05762	0.15998	2.77654	56.00	8
0.04670	0.99937	0.12622	0.14967	0.05762	0.15995	2.77617	64.00	9
0.05254	0.99923	0.12623	0.16629	0.05762	0.15993	2.77578	72.00	10
0.05838	0.99908	0.12626	0.18291	0.05762	0.15991	2.77536	80.00	11
0.06422	0.99892	0.12629	0.19952	0.05762	0.15988	2.77493	88.00	12
0.07006	0.99876	0.12632	0.21614	0.05762	0.15986	2.77449	96.00	13
0.07590	0.99860	0.12636	0.23275	0.05762	0.15983	2.77404	104.00	14
0.08173	0.99844	0.12641	0.24935	0.05762	0.15981	2.77359	112.00	15
0.08757	0.99828	0.12646	0.26596	0.05762	0.15978	2.77314	120.00	16
0.09341	0.99812	0.12652	0.28256	0.05762	0.15975	2.77270	128.00	17
0.09925	0.99797	0.12659	0.29916	0.05762	0.15973	2.77228	136.00	18
0.10509	0.99782	0.12666	0.31576	0.05762	0.15971	2.77188	144.00	19
0.11092	0.99769	0.12675	0.33235	0.05762	0.15969	2.77150	152.00	20
0.11676	0.99756	0.12684	0.34895	0.05762	0.15967	2.77115	160.00	21
0.12260	0.99745	0.12695	0.36554	0.05762	0.15965	2.77083	168.00	22
0.12844	0.99735	0.12706	0.38213	0.05762	0.15963	2.77056	176.00	23
0.13428	0.99727	0.12719	0.39872	0.05762	0.15962	2.77033	184.00	24
0.14011	0.99720	0.12732	0.41530	0.05762	0.15961	2.77015	192.00	25
0.14595	0.99716	0.12747	0.43189	0.05762	0.15960	2.77003	200.00	26
0.15179	0.99714	0.12763	0.44847	0.05762	0.15960	2.76997	208.00	27
0.15763	0.99714	0.12780	0.46506	0.05762	0.15960	2.76997	216.00	28
0.16347	0.99716	0.12798	0.48165	0.05762	0.15960	2.77004	224.00	29
0.16931	0.99722	0.12818	0.49823	0.05762	0.15961	2.77019	232.00	30
0.17514	0.99730	0.12839	0.51482	0.05762	0.15962	2.77042	240.00	31
0.18098	0.99741	0.12862	0.53141	0.05762	0.15964	2.77074	248.00	32
0.18682	0.99756	0.12886	0.54801	0.05762	0.15966	2.77114	256.00	33
0.19266	0.99774	0.12912	0.56460	0.05762	0.15969	2.77164	264.00	34
0.19850	0.99796	0.12939	0.58120	0.05762	0.15973	2.77224	272.00	35
0.20433	0.99821	0.12967	0.59781	0.05762	0.15977	2.77295	280.00	36
0.21017	0.99851	0.12998	0.61442	0.05762	0.15982	2.77377	288.00	37

0.60523	1.69859	0.40633	1.89645	0.04125	0.19465	4.71854	2048.00	257
0.60760	1.70227	0.40829	1.90466	0.04125	0.19507	4.72877	2056.00	258
0.60996	1.70598	0.41025	1.91213	0.03744	0.17745	4.73907	2064.00	259
0.61233	1.70979	0.41224	1.91961	0.03744	0.17785	4.74966	2072.00	260
0.61469	1.71362	0.41424	1.92711	0.03744	0.17825	4.76031	2080.00	261
0.61705	1.71748	0.41625	1.93463	0.03744	0.17865	4.77103	2088.00	262
0.61942	1.72136	0.41828	1.94216	0.03744	0.17905	4.78181	2096.00	263
0.62178	1.72527	0.42033	1.94972	0.03744	0.17946	4.79265	2104.00	264
0.62415	1.72919	0.42239	1.95728	0.03744	0.17987	4.80355	2112.00	265
0.62651	1.73314	0.42447	1.96487	0.03744	0.18028	4.81452	2120.00	266
0.62888	1.73711	0.42656	1.97248	0.03744	0.18069	4.82556	2128.00	267
0.63124	1.74111	0.42868	1.98010	0.03744	0.18111	4.83665	2136.00	268
0.63360	1.74512	0.43080	1.98774	0.03744	0.18152	4.84781	2144.00	269
0.63597	1.74916	0.43295	1.99539	0.03744	0.18194	4.85904	2152.00	270
0.63833	1.75323	0.43511	2.00307	0.03744	0.18237	4.87032	2160.00	271
0.64070	1.75731	0.43728	2.01076	0.03744	0.18279	4.88167	2168.00	272
0.64306	1.76142	0.43948	2.01847	0.03744	0.18322	4.89309	2176.00	273
0.64542	1.76555	0.44169	2.02620	0.03744	0.18365	4.90457	2184.00	274
0.64779	1.76971	0.44392	2.03395	0.03744	0.18408	4.91611	2192.00	275
0.65015	1.77389	0.44616	2.04171	0.03744	0.18452	4.92772	2200.00	276
0.65252	1.77809	0.44842	2.04949	0.03744	0.18495	4.93940	2208.00	277
0.65488	1.78232	0.45070	2.05730	0.03744	0.18539	4.95113	2216.00	278
0.65725	1.78657	0.45300	2.06512	0.03744	0.18583	4.96294	2224.00	279
0.65961	1.79084	0.45531	2.07296	0.03744	0.18628	4.97480	2232.00	280
0.66197	1.79513	0.45764	2.08081	0.03744	0.18673	4.98674	2240.00	281
0.66434	1.79945	0.45999	2.08869	0.03744	0.18717	4.99873	2248.00	282
0.66670	1.80379	0.46236	2.09659	0.03744	0.18763	5.01080	2256.00	283
0.66907	1.80816	0.46474	2.10450	0.03744	0.18808	5.02293	2264.00	284
0.67143	1.81255	0.46715	2.11244	0.03744	0.18854	5.03512	2272.00	285
0.67379	1.81696	0.46957	2.12039	0.03744	0.18900	5.04738	2280.00	286
0.67616	1.82140	0.47201	2.12836	0.03744	0.18946	5.05970	2288.00	287
0.67852	1.82586	0.47447	2.13635	0.03744	0.18992	5.07209	2296.00	288
0.68089	1.83034	0.47694	2.14437	0.03744	0.19039	5.08455	2304.00	289
0.68325	1.83485	0.47944	2.15240	0.03744	0.19086	5.09707	2312.00	290
0.68562	1.83938	0.48195	2.16045	0.03744	0.19133	5.10966	2320.00	291
0.68798	1.84394	0.48448	2.16852	0.03744	0.19180	5.12232	2328.00	292
0.69034	1.84852	0.48703	2.17661	0.03744	0.19228	5.13504	2336.00	293
0.69271	1.85312	0.48960	2.18473	0.03744	0.19276	5.14782	2344.00	294
0.69507	1.85775	0.49219	2.19286	0.03744	0.19324	5.16068	2352.00	295
0.69744	1.86240	0.49480	2.20101	0.03744	0.19372	5.17360	2360.00	296
0.69980	1.86707	0.49743	2.20918	0.03744	0.19421	5.18659	2368.00	297
0.70217	1.87177	0.50008	2.21738	0.03744	0.19470	5.19964	2376.00	298
0.70453	1.87650	0.50275	2.22559	0.03744	0.19519	5.21276	2384.00	299
0.70689	1.88124	0.50543	2.23383	0.03744	0.19568	5.22595	2392.00	300

DESIGN FLOW RATE= 54.00000 COMPUTED FLOW RATE= 53.0788 EST PORT VEL= 4.0000000
FLOW RATE CORRECTION CRE= 0.39101 QT= 53.07877 PORT VEL= 2.77792