NEEDS FOR PLUME ANALYSIS FOR THERMAL AND TOXIC POINT SOURCE DISCHARGES*

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ABSTRACT

In order to satisfy a variety of regulatory needs related to monitoring, enforcement and setting effluent standards for point source thermal and toxic discharges, EPA has compiled a series of comprehensive nomograms describing the physical behavior of thermal plumes that are particularly suitable for the nonspecialist user involved in these activities. The present paper discusses these needs and summarizes the two workbook volumes containing these nomograms.

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NEEDS FOR PLUME ANALYSIS FOR THERMAL AND TOXIC POINT SOURCE DISCHARGES

INTRODUCTION[1]

In the United States the Environmental Protection Agency (EPA) is responsible for conducting research, for establishing and enforcing standards, and for monitoring pollution in the environment. An important responsibility of EPA is to assist the states and local governments in their own efforts to control pollution.

EPA's functional and program responsibilities lie in the areas of air, water, pesticides, solid waste and radiation. In the specific program area of water, the legal tools necessary to attack the problems of pollution control are provided in the 1972 Amendments to the Federal Water Pollution Control Act.

The objective of the Act is to restore and maintain the chemical, physical and biological integrity of the Nation's waters. The 1972 Amendments changed the thrust of enforcement from water quality standards, regulating the amount of pollutants in a given body of water, to effluent limitations, regulating the amount of pollutant being discharged from a particular point source. Ambient water quality requirements can still dictate the amount of pollutants permitted for each discharge.

EPA is directed to establish guidelines for effluent limitations, identifying the best practicable control technology available for various discharge categories. These requirements must be met by appropriate dischargers by 1977. In addition, EPA must identify the best

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[1] Regulatory and policy related matters are obtained directly from Reference 1.

available technology for preventing and reducing pollution. These requirements must be met by all dischargers by 1983. The goal (not necessarily the requirement) of the act is to eliminate all discharges by 1985.

It is recognized that application of the best practicable or best available waste treatment technology may not always provide an effluent of receiving water quality. In order to accommodate the discharge of water which, at the end of the pipe, will violate receiving water quality standards, an area of mixing is specified. The size of this "mixing zone" is limited to an area which will not cause unacceptable biological stress. Thus, a "mixing zone" is an area where receiving water quality standards do not apply and its size is limited by biological considerations. "Mixing zones" apply to all pollutants including waste heat.

With respect to thermal discharges, the 1972 Amendments state that if the thermal discharger can demonstrate that an EPA limitation is more stringent than that necessary to protect the propagation of fish, shell fish and wildlife, then EPA may permit less stringent control, on a case by case basis.

Therefore, in all levels of federal and regional EPA activities related to establishing and enforcing laws, issuing permits or monitoring point source related discharges, the need for comprehensive understanding of jet and plume behavior exists in order to determine if "mixing zone" limitations are being met. Furthermore, the need for such understanding exists within the state and local government regulatory agencies as well as by participating private citizens.

The majority of those having the need for understanding the physical behavior of plumes lack sufficient mathematical and thermodynamic backgrounds required for direct use of plume models. This necessitates that the material be presented to them in a non-technical language

and yet in a concise manner so that the applicability as well as the limitations of the solutions are clearly understood by such users. Fortunately this task is facilitated in part by the fact that the needs do not require exact plume calculations. The ultimate goal is the protection of water quality based on available biological criteria with an adequate margin of safety. Results based on current methods of analysis for predicting the physical behavior of the plume can well satisfy the accuracy achievable in the biological prediction of possible effects in the environment.

PLUME EXAMPLES

Only a few problems of general interest can be readily analyzed and presented in a comprehensive manner so that a non-specialist user can feel at ease with. The problem of a deeply submerged bouyant jet is one such example that is relatively well understood and provides an excellent opportunity for demonstrating certain general features of a real plume, including the interaction of jet bouyancy and inertial forces with the ambient water.

Reference 2, prepared by EPA, presents a comprehensive treatment of the subject. It is titled "Workbook of Thermal Plume Prediction Volume I, Submerged Discharges." The workbook contains numerous nomograms showing plume characteristics such as trajectory, temperature and width. Data and analyses from numerous sources are presented in a unified format that is sufficiently simple for a non-specialist user. Basic assumptions are carefully stated, and the user is reasonably well guided against misapplication of the information.

Table 1 shows the type of problems addressed in the workbook for various flow conditions and diffusers. All computed trajectories and

plume widths(W) are presented in dimensionless forms using the jet diameter (D) as a reference. The jet and ambient temperatures are used to calculate the local centerline excess temperature ratios.

Corresponding to each entry in Table 1 there are given a group of nomograms describing the jet behavior for several Froude numbers (F), angles of discharge (Θ), stratification numbers (S_t), and velocity ratios. Figure numbers for the nomograms in each group are cross referenced with the jet characteristics and tabulated for easy use. For example, Table 2 lists the figure numbers for 35 nomograms for a discharge into stagnant water at various angles of discharge with the horizontal and for several specific diffuser configurations. The nomograms are presented in pairs. For example, Figures 1 and 2 corresponding to Figures A-1 and A-2 are presented as one pair in the workbook. The first Figure contains temperature-trajectory information and the second, width-trajectory information. The pages containing these figures are placed facing each other in the workbook for convenience.

The user is given a physical explanation of the solutions given by the nomograms. For example, with regards to plume dilution as a function of Froude number, Figure 1 shows that as Froude number decreases the plume dilution increases rapidly as indicated by the converging temperature lines near the vertical axis. This is explained by the fact that for two identical jet velocities and diameters, the jet with a low Froude number has a greater total momentum due to bouyancy, thus causing greater mixing.

Presenting the nomograms for the discharge into a stratified body of water in a general form was particularly difficult because of

dependence on the inital discharge level as well as other parameters. The workbook assumes discharges to take place at various depths Z_S below the thermocline as shown in Figure 3. An example of the nomograms is given in Figure 4. It is explained in the workbook that for a very large stratification number approaching infinity the plume rises indefinitely. In an environment with a finite stratification the plume initially entrains cool water and carries it into warmer layers of water above it. The plume temperature continues to drop while the temperature of the surrounding water continues to increase with elevation. Meanwhile, the plume decelerates due to the loss of bouyancy but continues rising because of its excess momentum even when its centerline temperature at a point along its trajectory equals the local ambient temperature. This excess momentum carries the plume from this point to its terminal height.

Other nomograms for conditions of discharge into an ambient current and for shallow discharges are also provided in the workbook. Practical example problems are worked out, not only to show the mechanics of using the nomograms, but also to direct the attention of the user to possible pitfalls of misusing the nomograms for problems they are not intended for.

The second volume of the workbook is devoted to surface discharges (3). In the preface, the reader is introduced to the subject in this manner. "The nomograms provide qualitative results describing the surface plume trajectory, width, temperature, depth, surface area and time of travel along the plume centerline. The nomograms are not intended to be used as exclusive design tools for the surface discharge problem nor for use in a precise prediction of specific plume conditions."

The nomograms are referenced the same way as in the first volume by providing tables, with figure numbers corresponding to specific discharge conditions. Tables 3 and 4 show this information as well as the range of values for which working nomograms are presented.

In addition to what is referred to as "working nomograms" a set of supplementary nomograms are also provided in the workbook. The working nomograms are distinguished from the supplementary nomograms in that the user is not required to specify the program coefficients, such as the turbulent exchange coefficient, drag coefficient, shear and entrainment coefficients. The workbook has made this decision for the user by fitting the program to the mean of a reasonably wide range of data. The supplementary nomograms are intended for special applications where the stated coefficients are known to deviate substantially from those recommended in the workbook.

Figure 5 is an example of a typical temperature, trajectory, width and depth nomogram showing the effects of ambient current on all plume characteristics. The plots are presented for constant jet densimetric Froude number F, channel total width to depth aspect ratio A, dimensionless heat exchange coefficient K, and angle of discharge TH. The dashed lines along the trajectories are made proportional to the local plume depth.

As in the first volume, considerable effort is devoted to familiarize the user with the physics of the problem so that the user gains an intuitive understanding of the nomograms. For example, temperature, trajectory, width and depth plots similar to Figure 5 for variable ambient current are presented to show the effects of variable jet Froude number (see Figure 6), jet aspect ratio (see Figure 7) and initial discharge angle (see Figure 8) on the plume characteristics.

These figures show that plume penetration across an ambient current is enhanced by (1) small ambient current, (2) small densimetric Froude number F, (3) large jet aspect ratio A, and (4) a large angle of discharge. Furthermore, generally hot and wide plumes are found under the same four discharge conditions. Neither the ambient current nor the discharge angle seem to influence the plume depth greatly. A small discharge Froude number causes a thin plume due to its tendency to stratification.

The workbook contains nomograms for the surface plume areas influenced by given isotherms. An example of this type is given in Figure 9. Additional plume information directly useful for ecological studies is the time of travel along the plume centerline. An example of this type of information is given in Figure 10.

CLOSURE

The foregoing examples of plume analysis demonstrate the way EPA has attempted to present a very complex technical problem to benefit those within government agencies in their decision making processes as well as to invite a wider participation of non-government groups to understand and to mount an integrated attack on pollution. It is an attempt to narrow the gap between "what the scientist knows and what the citizen understands." A gap which must be narrowed to enable the "citizen...to make intelligent, effective decisions about the patterns and problems of growth..."[4]

REFERENCES

1. Ruckelshaus, William D. "The Challenge of the Environment: A Primer on EPA's Statutory Authority" U.S. Environmental Protection Agency, Dec. 1972.

2. Shirazi, M. A. and Davis, L. R. "Workbook of Thermal Plume Prediction, Volume I Submerged Discharges." Environmental Protection Technology Series EPA-R2-005a, August 1972.

3. Shirazi, M. A. and Davis, L. R. "Workbook of Thermal Plume Prediction Volume II, Surface Discharges" Environmental Protection Agency, March 1974.

4. Russell E. Train, From an address to the American Association for the Advancement of Science in San Francisco, Feb. 25, 1974.

TABLE 1**

Summary of Subjects for Submerged Heated Jet Discharge Presented in Reference (2)

Diffuser Configuration	Condition of Ambient Water			
	Non-Stratified		Stratified	
	No Current	Moving	No Current	Moving
Single Round Port	RNN	RCN	RNS	RCS
A Row of Multiple Round Ports	MNN	MCN*	MNS	MCS*

*Nomograms not presented for these cases.

**A three-letter code is used for convenient reference. First letter designates type of diffuser; second letter, the type of current; third letter, the degree of stratification.

TABLE 2

Figure Numbers Corresponding to Plume Behavior From Submerged Diffusers Discharging into Stagnant, Non-Stratified Water from Reference (2)

Diffuser		Discharge Angle 0°	30°	60°	90°
RNN Single Jet		A-1,2	A-3,4	A-5,6	A-7
MNN Multiple Jet Diffuser	L/D = 1.5	A-8,9	A-10,11	A-12,13	A-14
	L/D = 10	A-15,16	A-17,18	A-19,20	A-21
	L/D = 20	A-22,23	A-24,25	A-26,27	A-28
	L/D = 30	A-29,30	A-31,32	A-33,34	A-35

TABLE 3

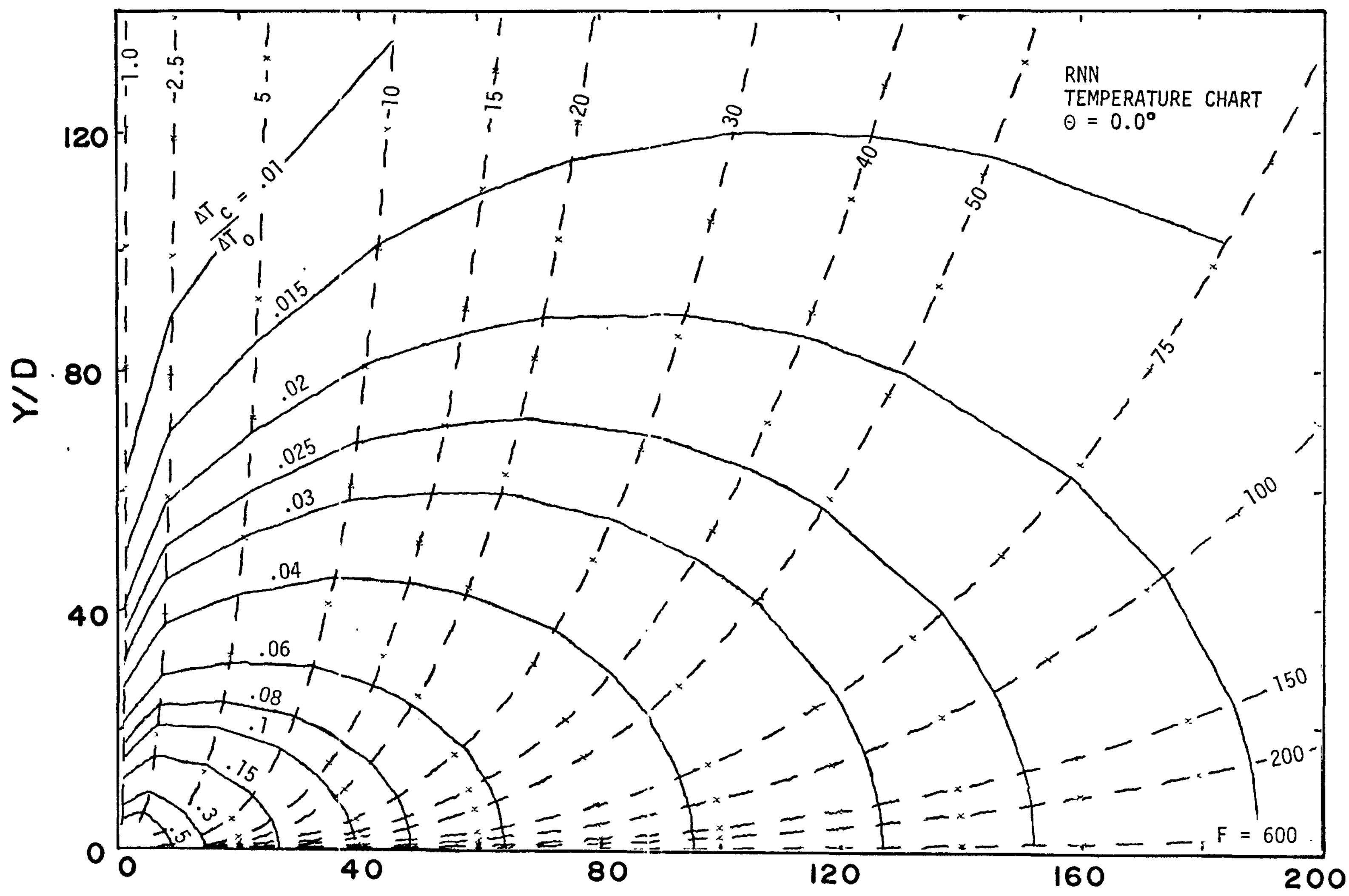
Figure Numbers for (TTWD) Working Nomograms for Θ_o = 90° and K = 10^{-5} from Reference (3)

F→ ↓A	2	4	6	10
1	A1	A2	A3	A4
5	A5	A6	A7	A8
10	A9	A10	A11	A12
15	A13	A14	A15	A16

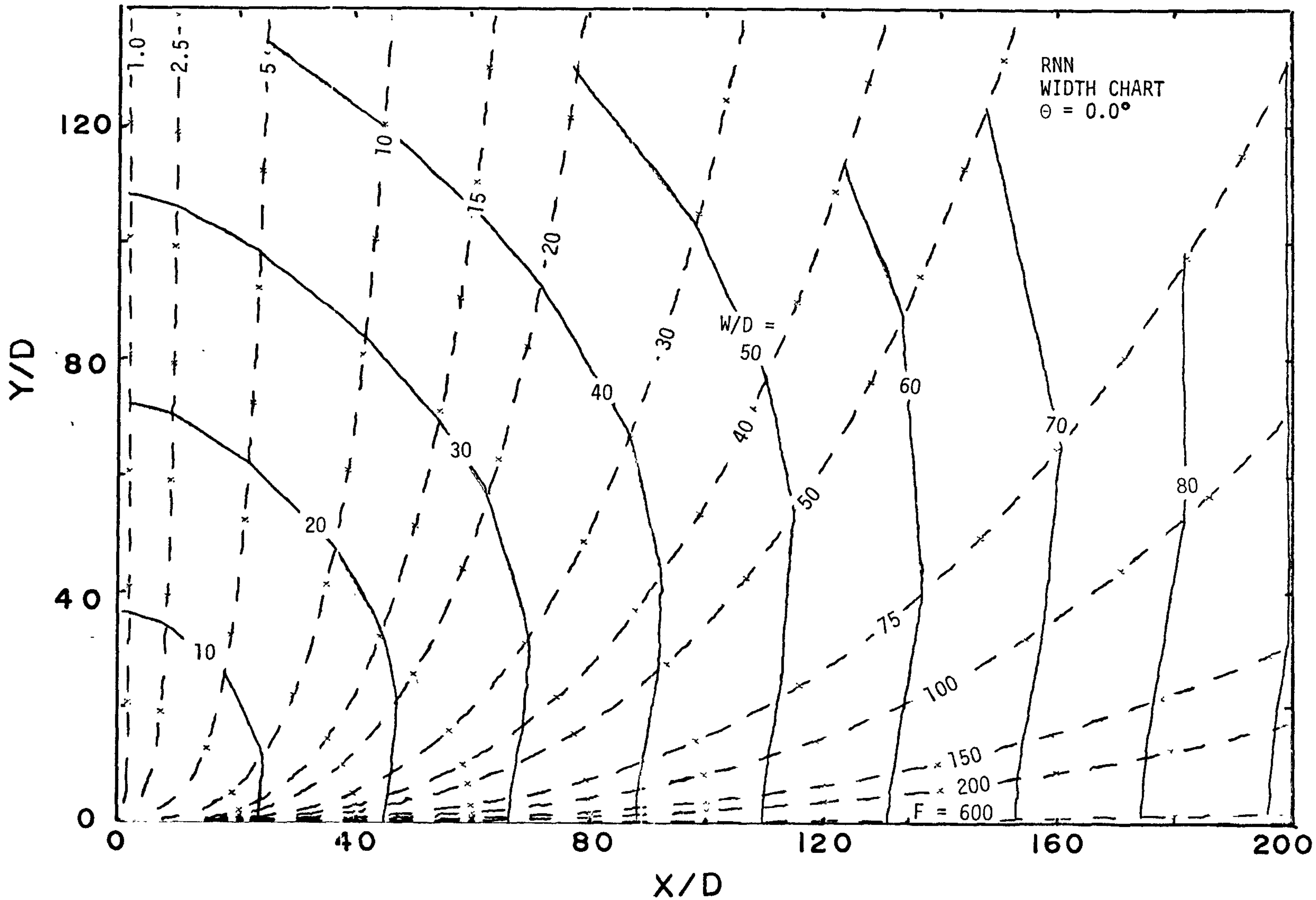
TABLE 4

Summary of Figure Numbers for (TTWD) Working Nomograms from Reference (3)

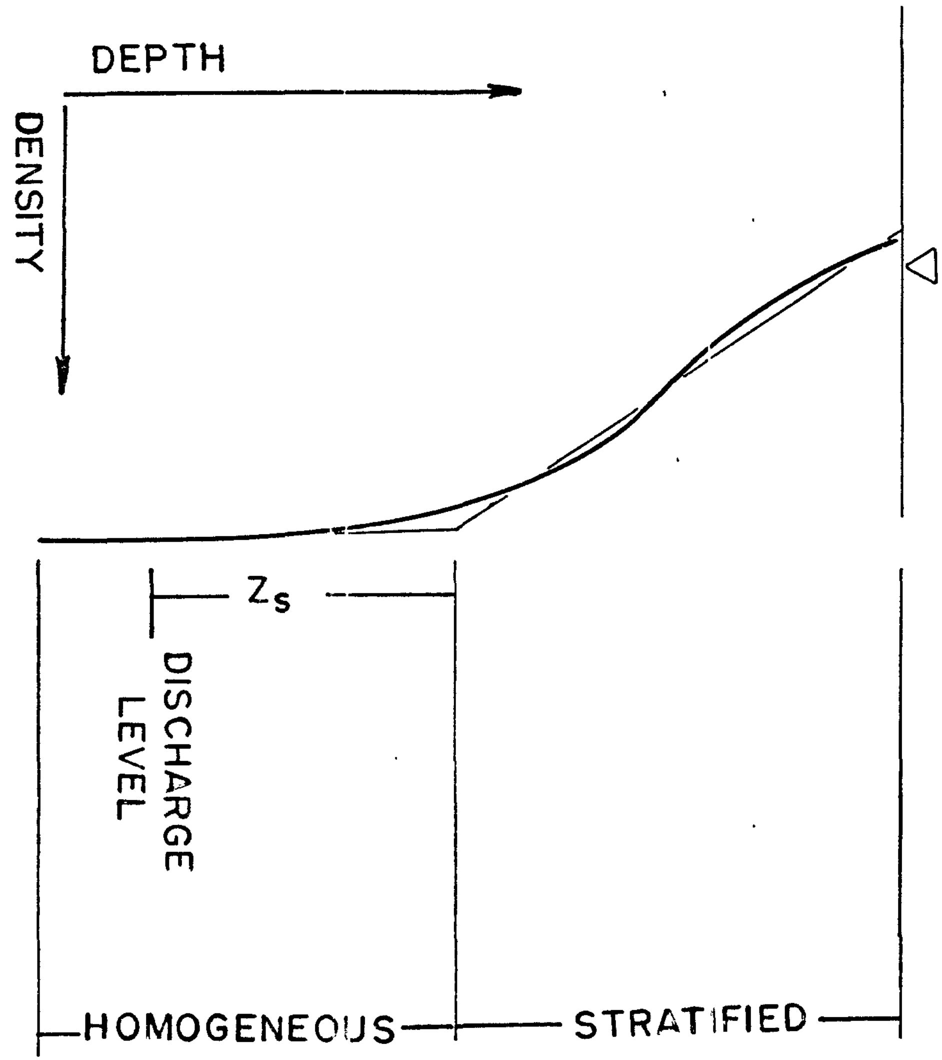
Θ_o→ ↓K	90°	60°	120°
10^{-5}	A1-A16	A17-A32	A33-A48
10^{-4}	A49-A64	A65-A80	A81-A96
10^{-6}	A97-A112	A113-A128	A128-A144



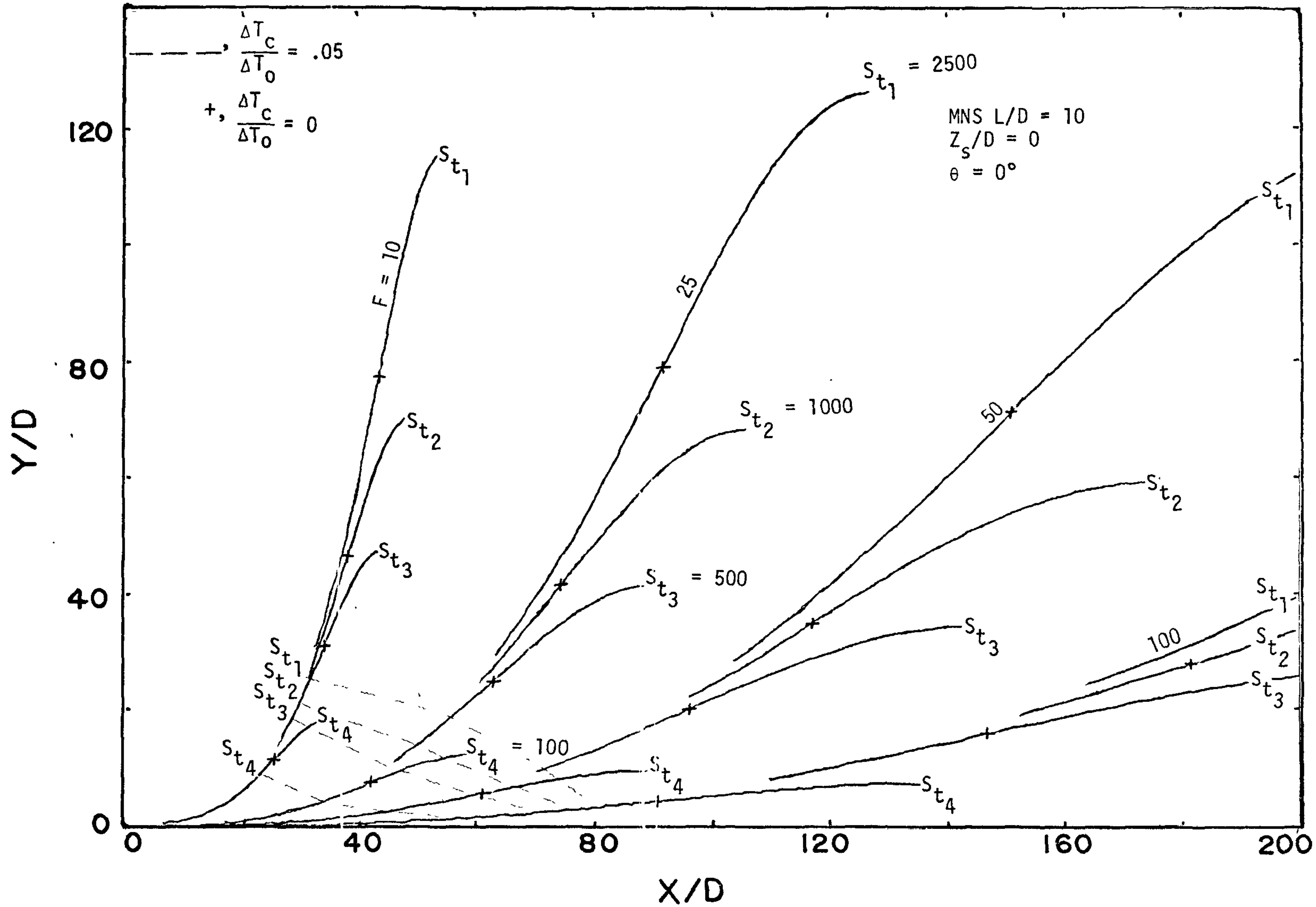
FIG(1) TEMPERATURE-TRAJECTORY PLOT FOR A SINGLE SUBMERGED JET (REF 2, FIG A-1)



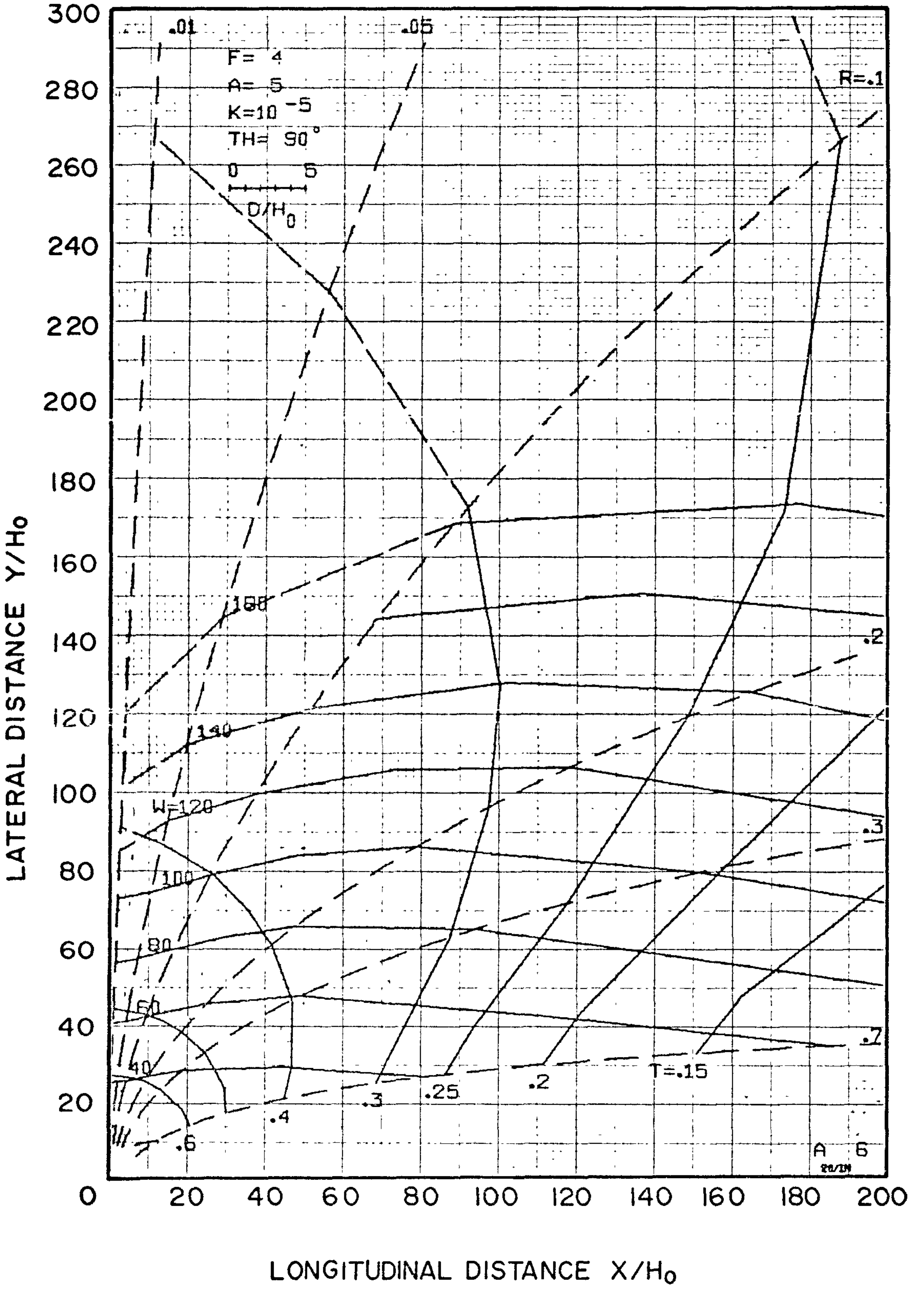
FIG(2) WIDTH-TRAJECTORY PLOT FOR A SINGLE SUBMERGED JET (REF 2, FIG A-2)



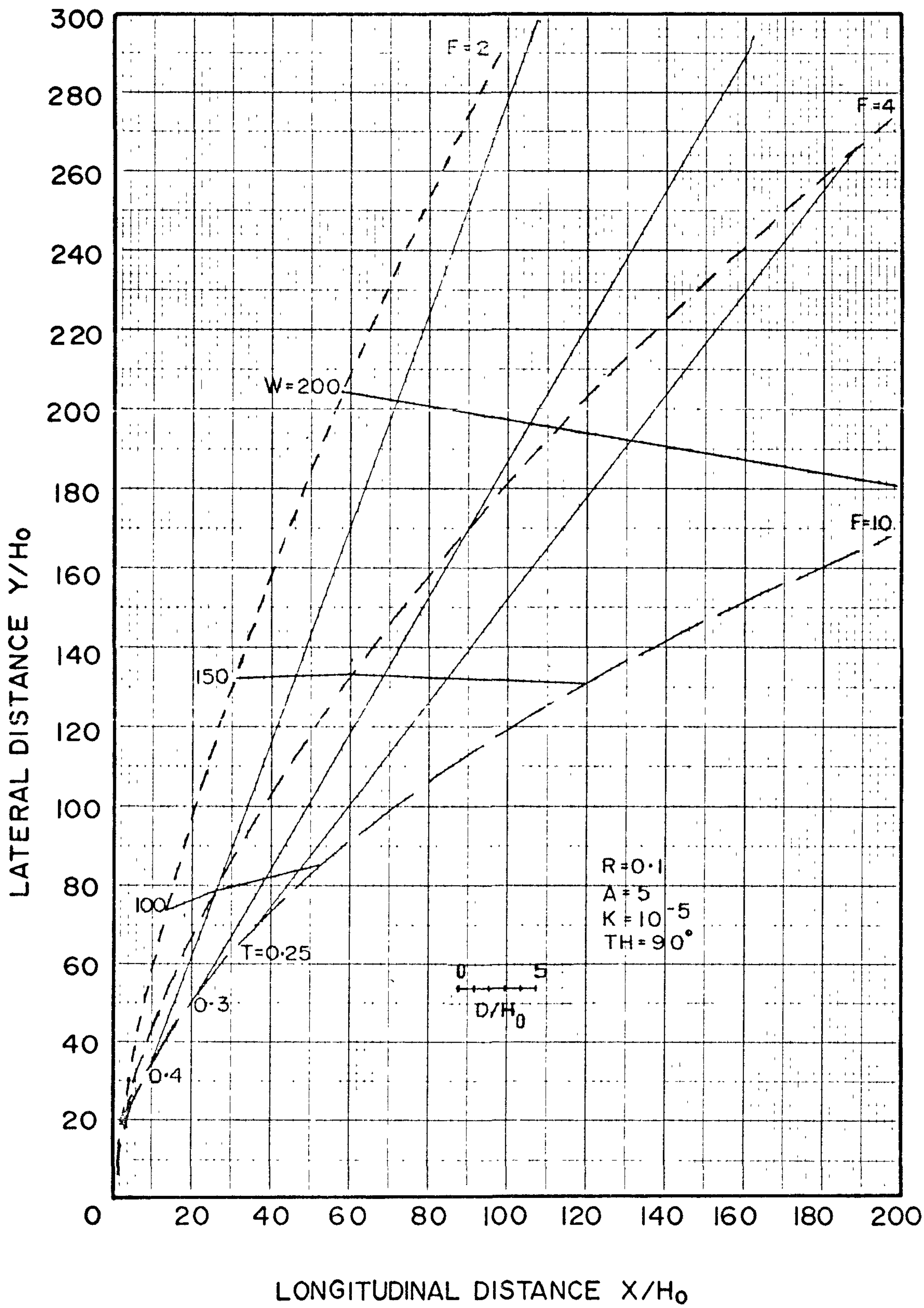
FIG(3) LINEARIZATION OF A NATURAL DENSITY STRATIFICATION AND DEFINITION OF Z_s



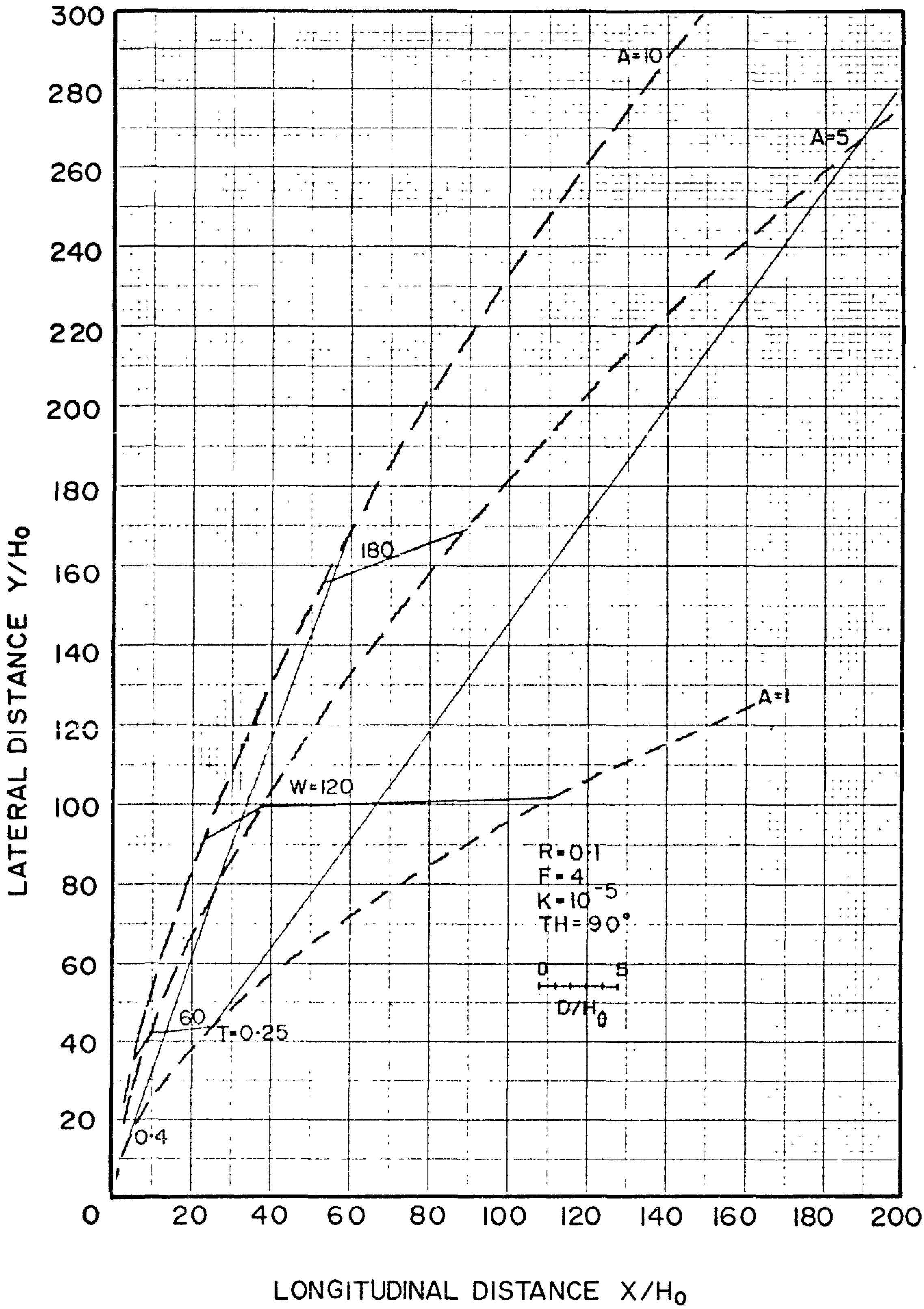
FIG(4) TEMPERATURE-TRAJECTORY PLOT FOR MULTIPLE SUBMERGED JETS IN STRATIFIED WATER (REF 2, FIG B-13)



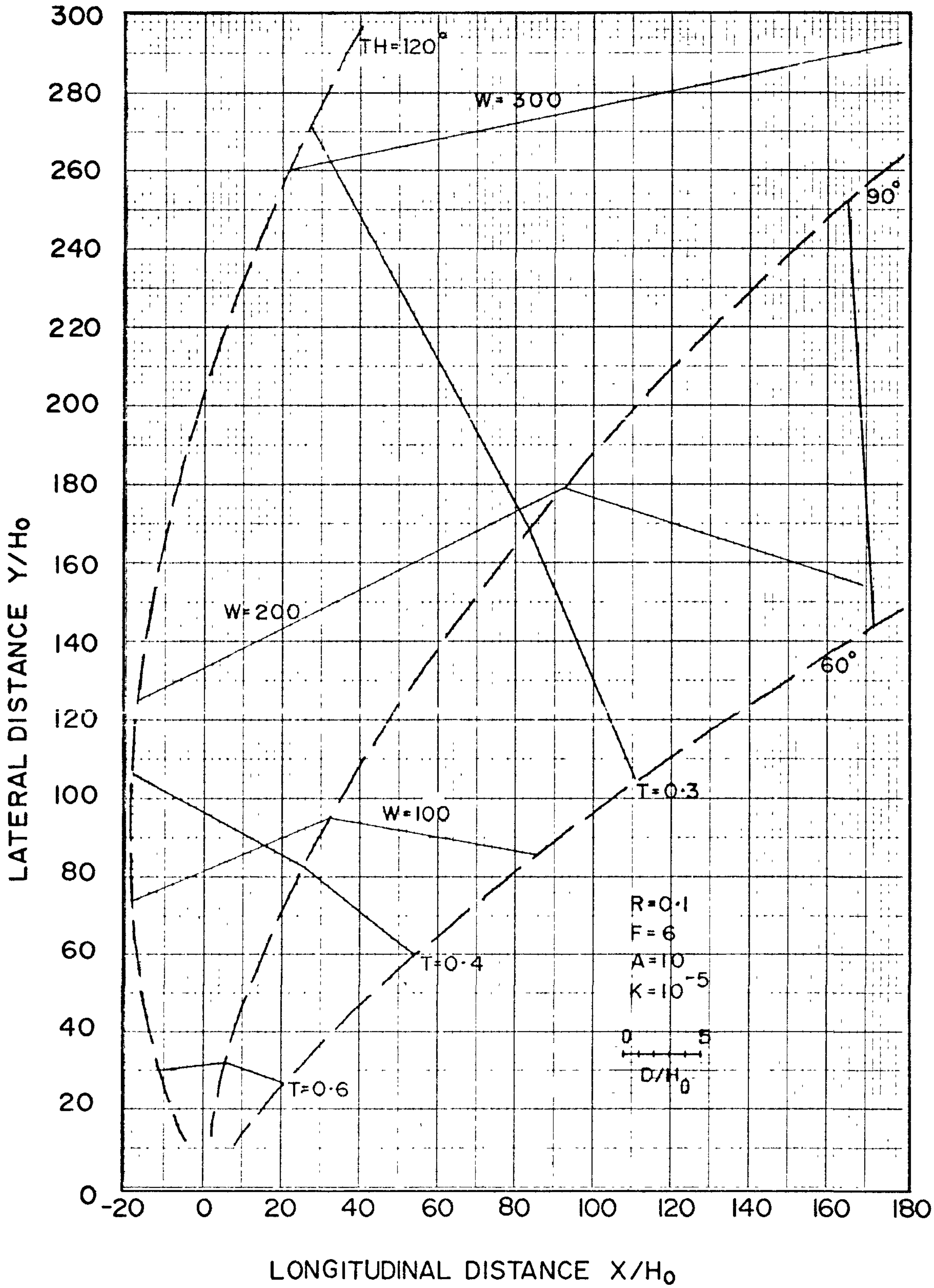
FIG(5) TEMPERATURE, TRAJECTORY, WIDTH, AND DEPTH (TTWD)-PLOTS FOR SURFACE JET DISCHARGE SHOWING EFFECTS OF AMBIENT CURRENT



FIG(6) TEMPERATURE, TRAJECTORY, WIDTH, AND DEPTH (TTWD)-PLOTS FOR SURFACE JET DISCHARGE SHOWING EFFECTS OF DENSIMETRIC FROUDE NUMBER



FIG(7) TEMPERATURE, TRAJECTORY, WIDTH, AND DEPTH (TTWD)-PLOTS FOR SURFACE JET DISCHARGE SHOWING EFFECTS OF JET ASPECT RATIO



FIG(8) TEMPERATURE, TRAJECTORY, WIDTH, AND DEPTH (TTWD)-PLOTS FOR SURFACE JET DISCHARGE SHOWING EFFECTS OF DISCHARGE ANGLE

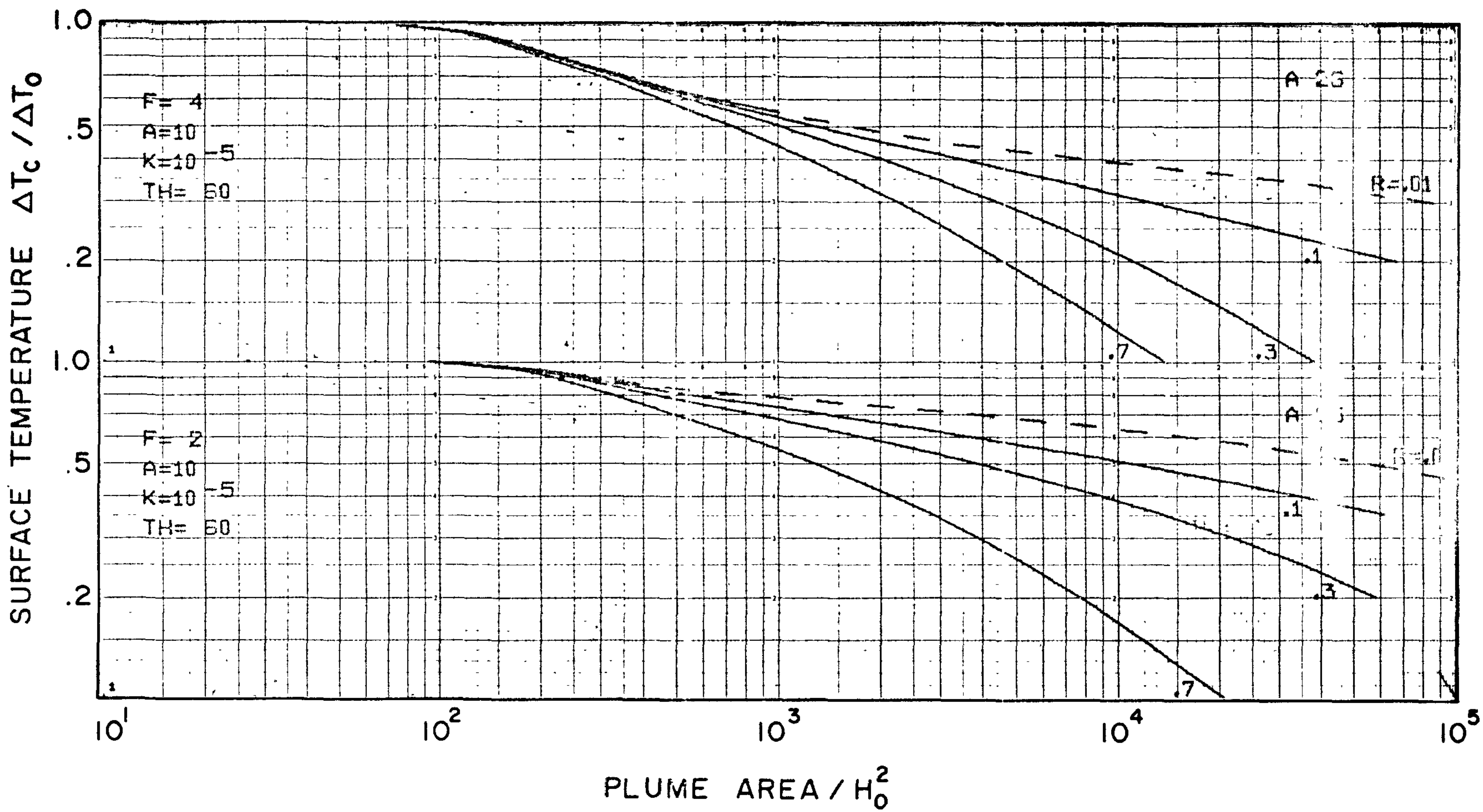


FIG (9) TEMPERATURE, AREA (TA)-PLOTS FOR SURFACE JET DISCHARGE

Due

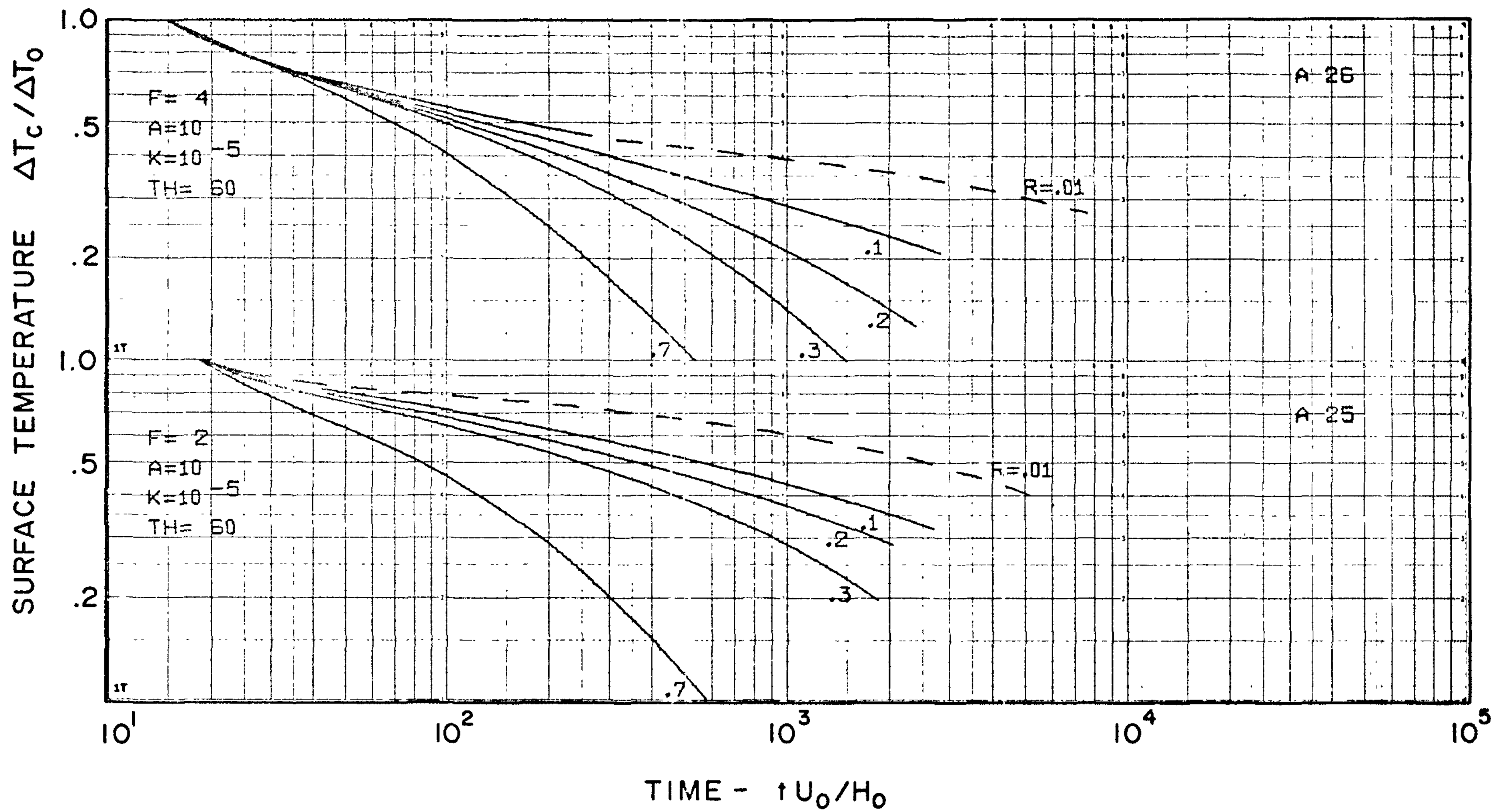


FIG (10) TEMPERATURE, TIME (Tt)-PLOTS FOR SURFACE JET DISCHARGE