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A PHOTOGRAPHIC METHOD FOR DETERMINING VELOCITY DISTRIBUTIONS WITHIN THERMAL PLUMES

by

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D. M. Nelson, W. Prepejchal,
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Radiological Physics Division

February 1971

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ABSTRACT

Surface-water velocity data were collected at the Waukegan Power Station on August 24, 1970. The measurements were performed by photographing the movement of drift bottles released near the mouth of the outfall. This report discusses measurement technique, data reduction and display, and plume analysis.

INTRODUCTION

Past investigations of the physical structure of thermal plumes have concentrated mainly upon measurements of temperature and material distributions in the plume. Momentum characteristics have been largely ignored.

This situation derives from two factors:

1. Temperature is usually the variable of greatest direct interest--particularly with respect to assessing potential biological stresses.

2. Field measurements of temperature distributions are more easily performed than measurements of velocity distributions.

Recent work at Argonne, however, indicates that the development and evaluation of analytic plume models could be considerably assisted by field measurements of plume-momentum distributions. Velocity data would be particularly useful in the near field or jet region where the Froude number $Fr \gtrsim 10$.

A number of techniques have been used to measure current and eddy structures in the Great Lakes. Csanady and co-workers,[1] for example, have successfully combined dye, drift-object, vane, and speed-sensor techniques in their investigations off Baie du Doré in Lake Huron.

So far as we are aware, however, the work of Hoopes, Zeller, and Rohlich[2] on the Lake Monona plume is the only comprehensive field measurement of the velocity distribution within a thermal plume reported to date. Using transits to track the motion of drogues, Hoopes et al., were able to map the spatial distribution of velocities within the plume. The investigators stated, however, that the drogue tracking technique put certain limitations on the data that could be collected.

The purpose of the present report is to show that photography represents an alternative drogue-tracking technique, having certain advantages over other methods. A demonstration experiment was performed at the Waukegan Power Station outfall. The Waukegan outfall was selected because of its proximity and because of the considerable field data already collected there.

The technique was to photograph the movement of drift bottles released in or near the plant outfall. A clock, which was included in the camera field of view, was used to record the elapsed time between photographs. The technique constituted a direct measurement of the velocity field in the plume surface waters.

The measurements were performed from 2:00 until 5:00 p.m. on August 24, 1970.

EXPERIMENTAL ARRANGEMENT

The Waukegan Power Station is a steam electric, coal-fired fossil plant, located on Lake Michigan just north of Waukegan, Illinois. Figure 1 shows the Waukegan outfall and identifies most of the features pertinent to the experiment. As seen in the figure, a breakwater, beginning at the southern tip of the outfall, extends approximately 600 ft into the lake, making an angle of 45° with the shoreline. The shoreline, breakwater, and channel-outfall surface geometry were surveyed with transits prior to the measurements.

The camera, a 35-mm Nikon F fitted with a 35-mm 60° lens, was mounted atop the tower at the end of the breakwater. Camera elevation above water level was 35 ft. The camera was locked into place on a tripod and was always pointed in one or the other of the two directions shown in the figure. A clock with sweep-second hand was included in the camera views. The clock was mounted about 5 ft from the camera on the tower platform guard rail.

Marker buoys were anchored in the camera field of view prior to the measurements. After placement, the locations of the buoys were determined by triangulation from the two transit positions indicated on the breakwater. Buoy locations were determined to ±5 ft. The marker buoys served as benchmarks against which film plane distances were later calibrated.

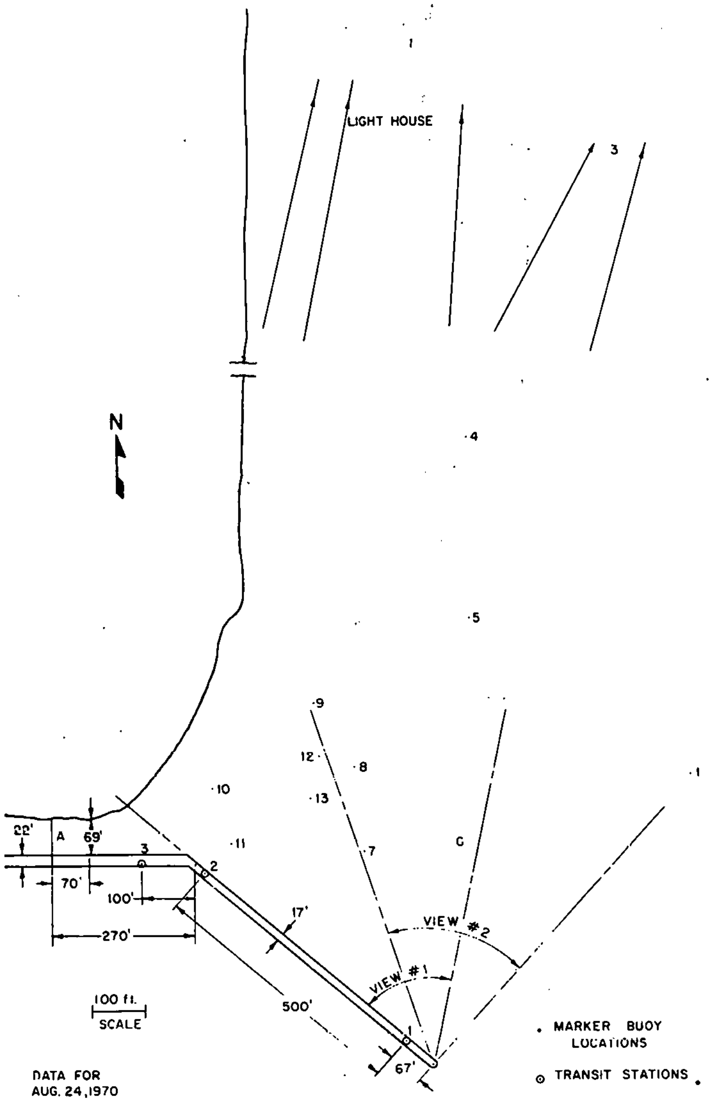

Fig. 1. Plan View of Waukegan Outfall

Standard one-gallon polyethylene bottles served as drift bottles. A unistrut bottom weight and a wire mast carrying a cloth flag were fastened to the bottles. Orange phosphorescent paint was applied to the flags in order to enhance their visibility. When filled to the two-thirds level the bottles were approximately neutrally buoyant.

PROCEDURE

The Argonne 18-ft fiber-glass boat served as the platform from which the drift bottles were released into the plume. The bottles were dropped by hand as the boat made a right-angle pass across the plume axis. An attempt (not always successful) was made to space the bottles evenly along the lateral dimension of the plume.

Comparison of the wake raised by the boat with the turbulent wave motion indicated that the region of interference caused by the boat extended at most 40 ft "downstream" of the drop. As a precaution, no velocities were constructed from data collected within this region.

Photographs were taken at roughly 10-sec intervals as the drift bottles moved through the first field of view. For those runs that continued through the second field of view, the camera was rotated and the pictures taken at 30-sec intervals.

Fifteen to 30 frames were shot per run. At the end of each run, the bottles were retrieved and a new run begun. The release point along the plume centerline was changed from run to run. This ensured obtaining data across the full width of the plume at several distances from the outfall. In all, five runs were photographed.

Ectachrome X (ASA 64) film was used. The camera focus was set at infinity; the aperture, at f/11; and the shutter speed, at 1/120 sec. Subsequent development indicated nearly perfect exposure. Resolution and color contrast were such that the 20 x 20-in. yellow flag on marker buoy No. 3--2100 ft from camera--was easily discernible.

OUTFALL AND AMBIENT LAKE CONDITIONS

The Waukegan Station was operating at 450 MWe--roughly half capacity--during the period of observation, 2:00 to 5:00 p.m. on August 24. From 9:00 a.m. until 9:00 p.m., the condenser flow rate remained constant at 350,000 gpm = 750 cfs.

The channel discharge velocity was measured at 3:00 p.m. at the point A shown in Fig. 1. The measurement, made from the boat at a depth of 4 ft using an Ekman Merz Model 113 current meter, indicated a velocity of 2.60 ft/sec. A previous set of measurements performed on August 7 had shown the velocity to be uniform over the channel cross section. The discharge velocity on August 7 was 4.3 ft/sec.

As part of another study being conducted on August 24, ambient lake velocities were measured at several points over a 1-square-mile region adjacent to the outfall. The velocity measured at buoy No. 1 at 11:30 a.m. at a depth of 6 ft was $2\frac{1}{2}°$ west of north at 0.61 ft/sec. At 1:30 p.m., 600 ft southeast of the lighthouse at a depth of 6 ft, the velocity was measured as 0.42 ft/sec, 18° west of north.

DATA REDUCTION

The technique used in reducing the film data is summarized below.

Successive frames were projected onto a large white sheet of paper taped to a wall at right angles to the projector axis. The projected image was approximately 10 x 10 ft. From the first frame of a given run, the locations of various stationary features, including the horizon, the lighthouse, and the marker buoys, were drawn on the paper. Finally, the positions of the drift bottles were marked. Succeeding frames were aligned against the stationary features, and then the new locations of the drift bottles were marked.

Real-space coordinates were readily constructed from the projected film coordinates. The optics is such that real-space angular displacements, θ, from the camera axis are linearly related to horizontal film plane displacements, X_F; that is, $\theta = aX_F$, where a is a constant. Real-space distances r from the camera are quadratically related to vertical film plane displacements Y_F, $r = b + cY_F^2$, b and c constant. Using the marker buoys as benchmarks, we easily scaled a template which was used to transform the rectangular film coordinates X_F, Y_F into real-space polar coordinates θ, r.

Figures 2-6 show the streamlines plotted for the five runs. Constant time lines have been included in the Run 2 plot shown in Fig. 3.

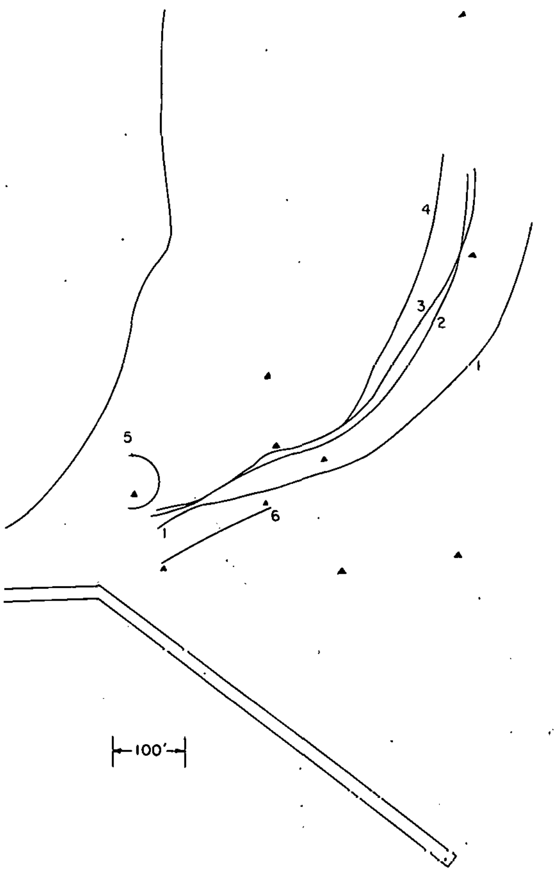

Fig. 2. Drift-bottle Streamlines for Run 1

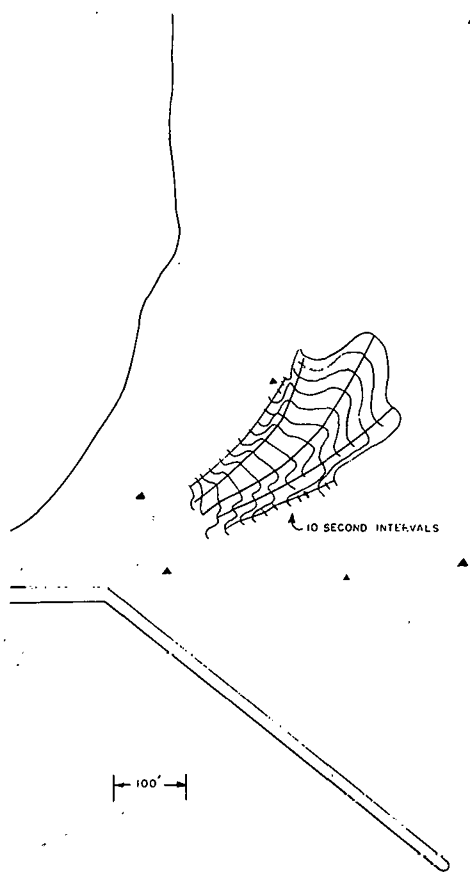

Fig. 3. Streamlines and Time Lines for Run 2

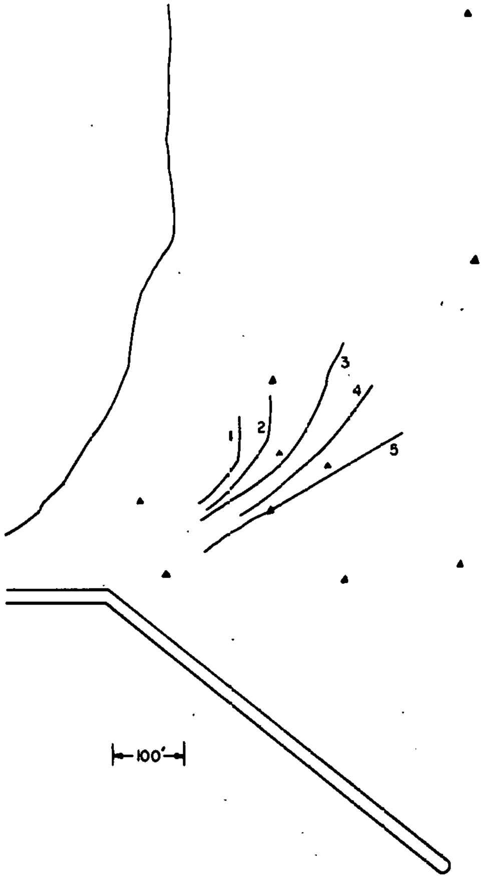

Fig. 4. Drift-bottle Streamlines for Run 3

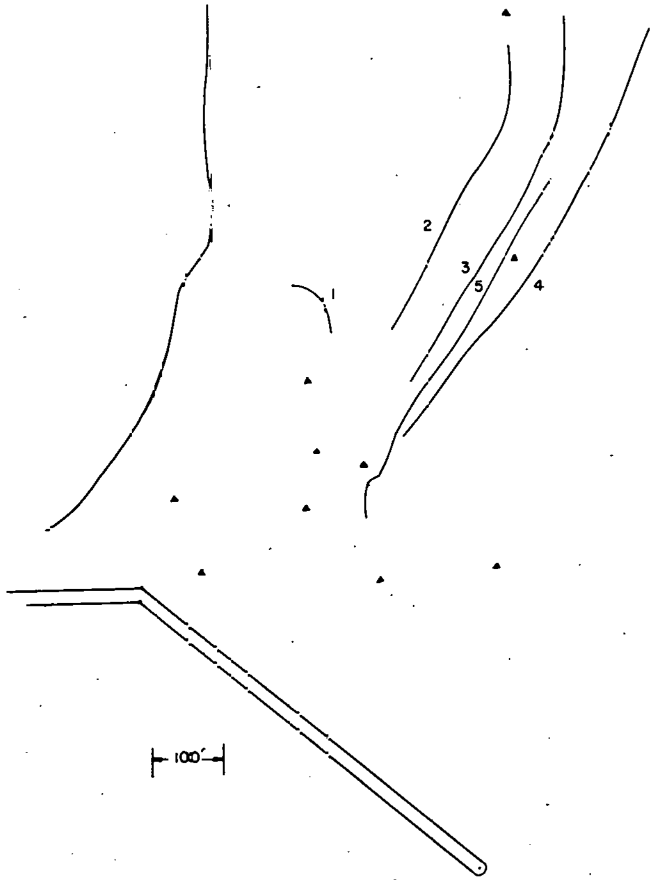

Fig. 5. Drift-bottle Streamlines for Run 4

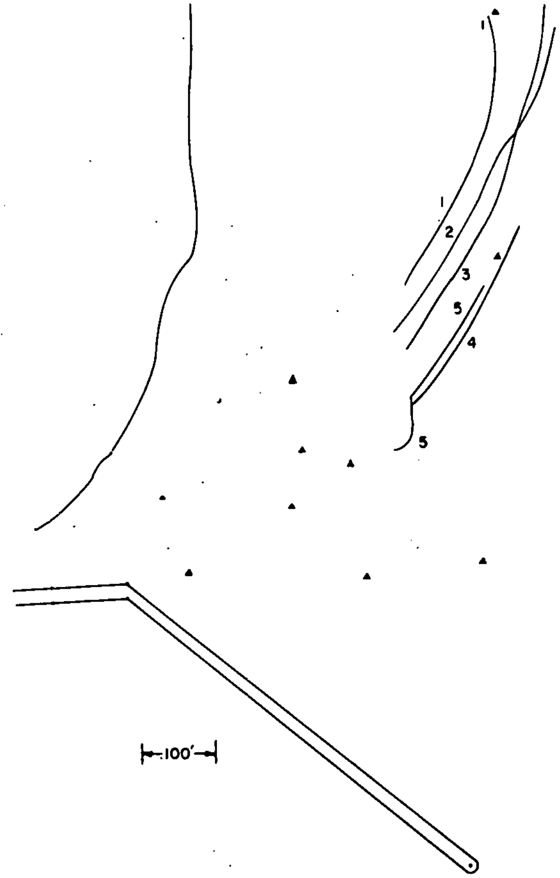

Fig. 6. Drift-bottle Streamlines for Run 5

Velocities were determined by measuring with a compass the streamline pathlength between time lines and by then dividing by the corresponding time interval. The velocity was then recorded in tabular form along with the x,y real-space coordinates of the midpoint of the segment of streamline under consideration. In this manner, more than 300 plume velocities and associated spatial coordinates were constructed for the five runs.

In retrospect, the above procedure for reducing the photographic data appears exceedingly cumbersome and tedious. The entire process could be considerably facilitated by using semiautomatic film-coordinate digitizers, such as the SCAMP or HERMES machines. Particle physicists have been using these machines for some time as a means of digitizing and outputting on paper tape the spark coordinates of optical spark-chamber events. The software requirement for the coordinate transformations and the velocity calculations of the present study would be minimal.

DATA DISPLAY

For display and analysis, the velocity data were first computer-processed. Figure 7 is a velocity map developed from the raw data by the two-dimensional interpolation routine SYMAP.[3]

The data from all five runs are represented in Fig. 7. After interpolation, the velocity determined at each cell of the grid was binned into one of the five velocity intervals: 0.0-0.7, 0.7-1.4, ..., 2.8-∞ ft/sec. In Fig. 8, the smoothed data have been divided among three bin levels.

With the exception of the measurement at point A in Fig. 1, velocities were not measured in or very near the mouth of the outfall, that is, to the left of the dashed line in Figs. 7 and 8. To provide an initial boundary field near the outfall, we entered "artificial" velocities of 2.6 ft/sec in certain cells to the left of the dashed line. Similarly, since the ambient lake currents were not measured over the entire map area, we found it convenient to assume a uniform lake background velocity of 0.5 ft/sec. This velocity is roughly consistent with the several ambient velocities measured. Comparison of velocity maps developed with and without these artificial boundary data indicated that the velocity distribution within the plume proper was negligibly affected by their inclusion.

PLUME CHARACTERISTICS

Plume characteristics, such as the rate of spreading and bending, are most easily discussed in terms of a plume model. For the brief description that follows, we shall use a simplified version of the Gaussian model developed by Hoopes, Zeller, and Rohlich.

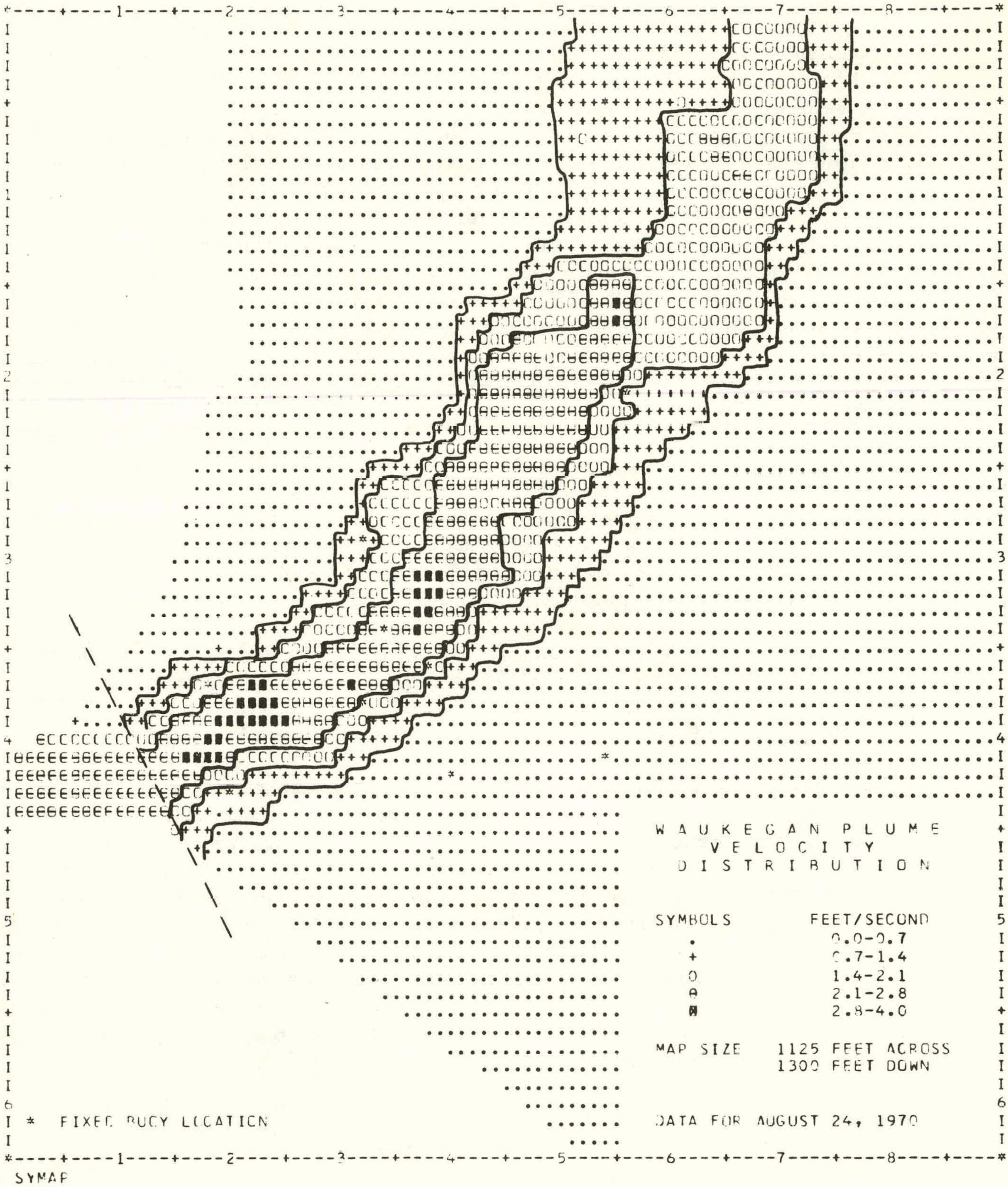

Fig. 7. Velocity Map Developed by SYMAP: Five Levels

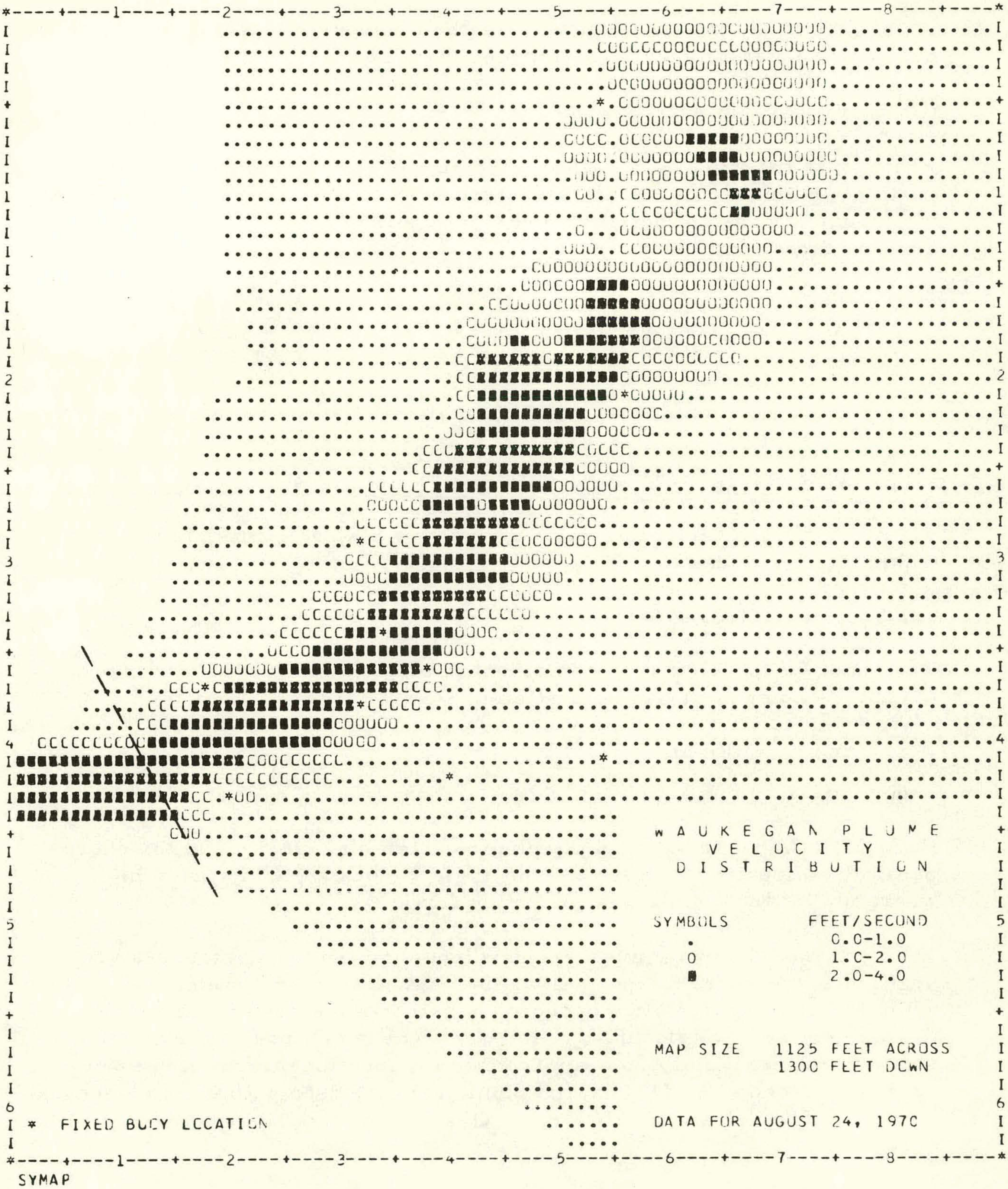

Fig. 8. Velocity Map Developed by SYMAP: Three Levels

We first write the equation for the momentum flux through a plume cross section at a distance s from the outfall:

$$m = \rho \int dz \int dy\, v^2,$$

where v is the velocity parallel to the axis of the plume, and z and b are vertical and horizontal displacements, respectively. Following Hoopes et al.,[2] we assume a constant depth z_0 and a uniform velocity distribution in the vertical direction to obtain

$$m = \rho z_0 \int_{-b}^{b} dy\, v^2(y). \tag{1}$$

If the horizontal velocity distribution is Gaussian, that is,

$$v(y) - v_m e^{-y^2/2\sigma^2},$$

where v_m is the centerline velocity and $b = b(s) = \sqrt{2}\sigma(s)$ is the half width, Eq. 1 reduces to

$$m = 1.20\, \rho z_0 b v_m^2. \tag{2}$$

The shore-perpendicular x-component of momentum flux and the shore-parallel y-component can be written

$$m_x = m \sin \beta;$$

$$m_y = m \cos \beta.$$

Here β is the angle between the plume centerline velocity and the shore-parallel y-direction. At $s = 0$, the angle β equals 90° and $m = m_{x_0}$, where m_{x_0} is the discharge momentum flux.

If the horizontal pressure gradients and the shear stresses are negligible, the shore-perpendicular momentum flux, m_x, remains constant; while the shore-parallel component, m_y, increases due to entrainment of the ambient lake water. If v_L represents the magnitude of the ambient shore-parallel velocity, m_y approaches the functional form $1.20\, \rho z_0 b v_L^2$ as β approaches 0°. That is, the plume velocity decays to the ambient lake velocity. The volumetric flow rate, $Q = 1.49\, \rho z_0 b v_L$, increases due to the spreading.

The above description of jet behavior closely follows the preliminary stages of the analysis by Hoopes et al. Without going into the further details of their analysis, we can make a simple test of their model by comparing the observed versus predicted rates of plume bending and velocity decay.

Rewriting their equations for v_m and $\tan\beta$ a given distance s from the outfall (page 29 of their report), we have

$$v_m = 1.244 \frac{m}{m_y + 1.49\,\rho z_0 b_0 v_0 v_L} v_L \tag{3}$$

and

$$\tan\beta = \frac{m_x}{m_y}. \tag{4}$$

At $\tan\beta = 1$, $\beta = 45°$, these equations can be solved for the centerline velocity. For $\beta = 45°$, from Eq. 4 and from the conservation of the x-component of the momentum flux, $m_y = m_x = m_{x_0}$. Substitution in Eq. 3 and cancellation of common factors gives

$$v_m = \frac{1.75\,v_0}{1.244 + \frac{v_0}{v_L}}. \tag{5}$$

For $v_0 = 2.6$ and $v_L = 0.5$ ft/sec, $v_m = 0.7$ ft/sec. Figure 6 shows a centerline velocity at $\beta = 45°$ of about 2.5 ft/sec, which is considerably greater than the predicted value. It should also be noted that the presence of the breakwater makes it likely that the value of v_L substituted into Eq. 5 is an overestimate, producing a corresponding overestimate in the predicted v_m. The effects of wind shear are not included in the analysis leading to Eq. 3. Hoopes et al., considered effects arising from wind stress, but concluded that they were probably negligible for the wind speeds (0-15 mph) encountered during the Lake Monona measurements. Wind speeds during the Waukegan measurements were 10-15 mph.

We can also compare the velocity data with the results obtained by Wiegel, Mobarek, and Jen from laboratory studies of warm water jet discharges over sloping bottoms.[4] Wiegel et al., investigated the mixing properties of jets from rectangular nozzles approximating open channels. Figure 9 shows their straightline fits to their temperature data on log-log paper. The centerline excess temperatures have been plotted as a function of centerline path length from the outfall. For the rectangular nozzles, the path length is expressed in multiples of $4R_H$, where $R_H = z_0 b_0/(2z_0 + 2b_0)$ is the hydraulic radius; the fit to the deep-water circular-nozzle data is plotted against s/D_0, where D_0 is the nozzle diameter.

We have plotted our observed x-component of centerline velocity on the same plot. The x-component of centerline velocity rather than the centerline velocity itself has been plotted in order to eliminate first-order effects arising from uncertainty regarding the distribution of the shore-parallel ambient lake velocity. Comparing velocity data with temperature data is justified by previously observed similarities between momentum and temperature fields. It can, in fact, be shown from conservation of momentum and energy that centerline temperature and velocity must decay proportionally if the lateral distribution of temperature and momentum are both Gaussian.

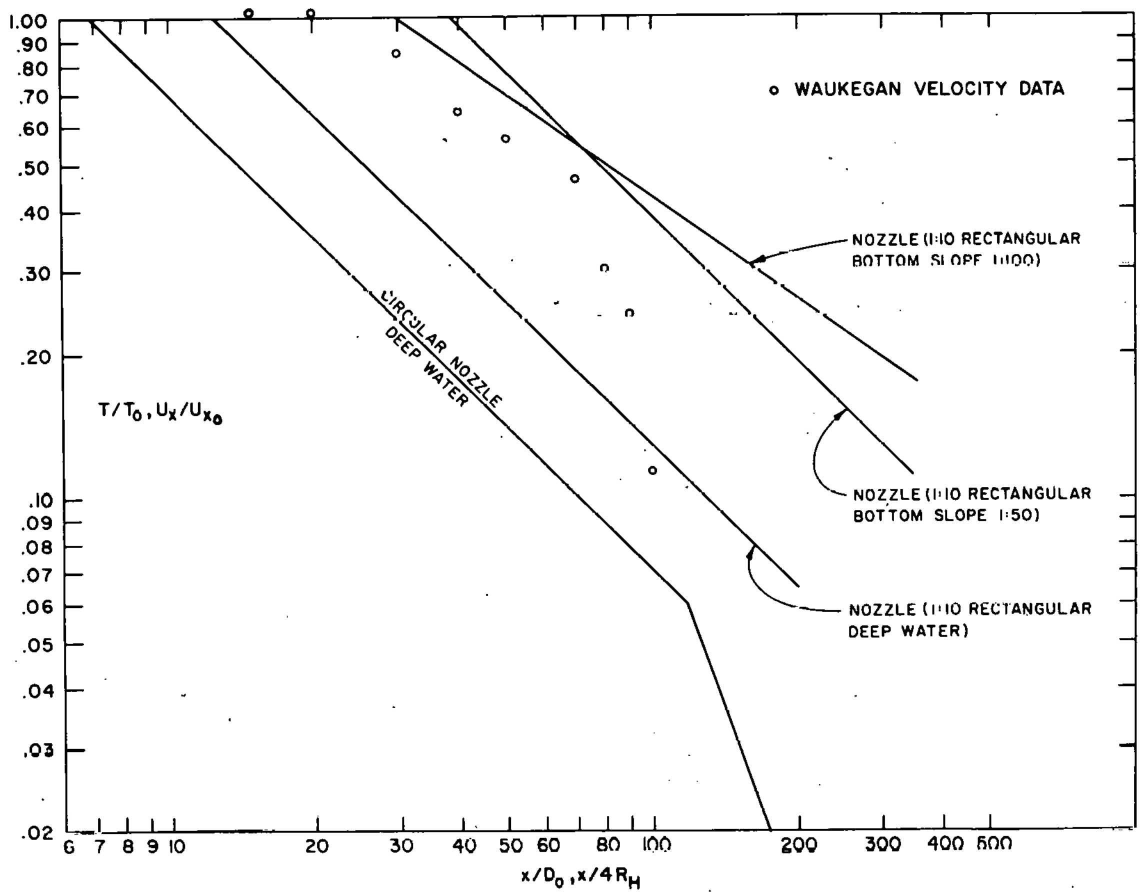

Fig. 9. Comparison of Waukegan Velocity Data with the Fits of Ref. 4 to Surface-temperature Concentration along Jet Axis

While the depth contours near the Waukegan outfall are irregular and not well mapped, the bottom slope is roughly 1:100. Before "breaking" at $x/4R_H \approx 75$, the Waukegan velocity data are in reasonable agreement with the 1:100 rectangular-nozzle data of Wiegel _et_ _al_.

One feature of the Waukegan plume, so far not discussed, is the observed increase in surface velocities at several points along the plume. One of these increases occurs very near the mouth of the outfall, another about 400 ft from the outfall, and yet another about 750 ft from the outfall (see Fig. 7). These velocity increases are probably a function of the bottom topography.

The Waukegan Station Laboratory (WSL) sounded depths in the region immediately adjacent to the outfall and breakwater on August 24, the day of our measurements. Figure 10 is a reproduction of a map that WSL constructed from these measurements. The bar (hatched region in Fig. 10) identified from boat by WSL was also visible from the tower platform at the end of the breakwater. This bar, which, unfortunately, was not well mapped, lies just beneath the second region of velocity increase noted above. Conservation of mass flow in a jet of uniform width restricted by bottom topography would produce an increase in plume velocity.

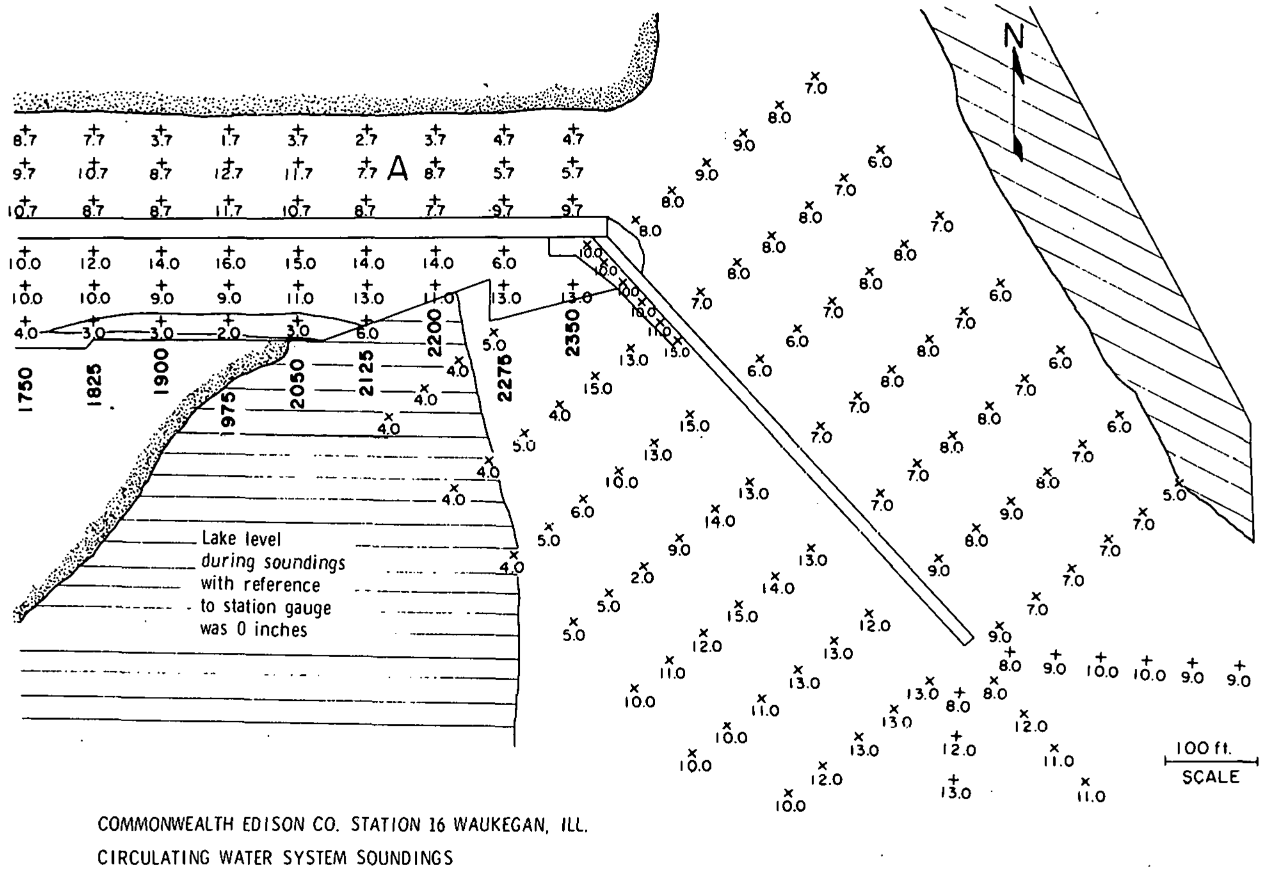

Fig. 10. Depth Soundings (Ref. 5)

The velocity increase near the outfall mouth cannot be unambiguously explained in terms of the depth soundings in Fig. 10. The decreasing depths along the channel centerline toward the mouth of the channel would tend to produce greater velocities just past the mouth of the outfall than those measured at point A; however, this effect is partly offset by the increasing depths along the edges of the channel. The soundings in the channel and near the mouth of the channel are not thought to be as accurate as those over the rest of the map, since it was extremely difficult to hold the small boat for the time required to make these measurements.[5]

Detailed soundings are not available for the region of velocity increase located about 750 ft from the outfall.

It is obvious that an accurate description of the Waukegan jet will require the detailed mapping of the bottom topography.

TEMPERATURE DATA

Surface-temperature data were collected immediately after the drift-bottle measurements.

The temperature measurements were completed within 45 min. Considerable detail was sacrificed in order to get temperature data as nearly synoptic with the velocity data as possible. Figure 11 shows the measurement points and the isotherms which were fitted by eyeball to the data. The data were far too sparse to permit processing with the SYMAP routine.

The plume centerline constructed from the temperature data appears to bend over more rapidly than the centerline constructed from the velocity data. This shift may be due to an increase in ambient lake velocity subsequent to the plume-velocity measurements. An alternate explanation is that the shift is due to the difference between the rates of diffusion of the temperature field and of the velocity field. The spread coefficient for the temperature field is typically observed to be ≈ 1.16 times that for the velocity field.[4] The more rapid mixing of the temperature field with the ambient lake waters would cause the temperature-field centerline to bend over more rapidly than the velocity-field centerline.

CONCLUSIONS

The direct field measurement of velocity distributions appears to be a feasible, complementary method for examining the structure of thermal plumes.

The photographic technique described above can provide accurate, nearly synoptic, plume-velocity data. The data-reduction technique used in the present study was primitive; however, the semiautomatic digitizing of drift-bottle coordinates using machines of the SCAMP or HERMES type appears feasible and offers the possibility for fast, accurate data processing.

For those sites where in situ towers for camera mounting are not available, investigators could provide their own. Portable, 60-ft towers are commercially available for less than $800.

The measurements reported here pertain only to surface-water velocity distributions. A more complete plume description will require the measurement of velocity distributions as a function of depth. Such experiments might employ simple drogues of the type used by Hoopes et al., in their measurements of the Lake Monona thermal plume.[2]

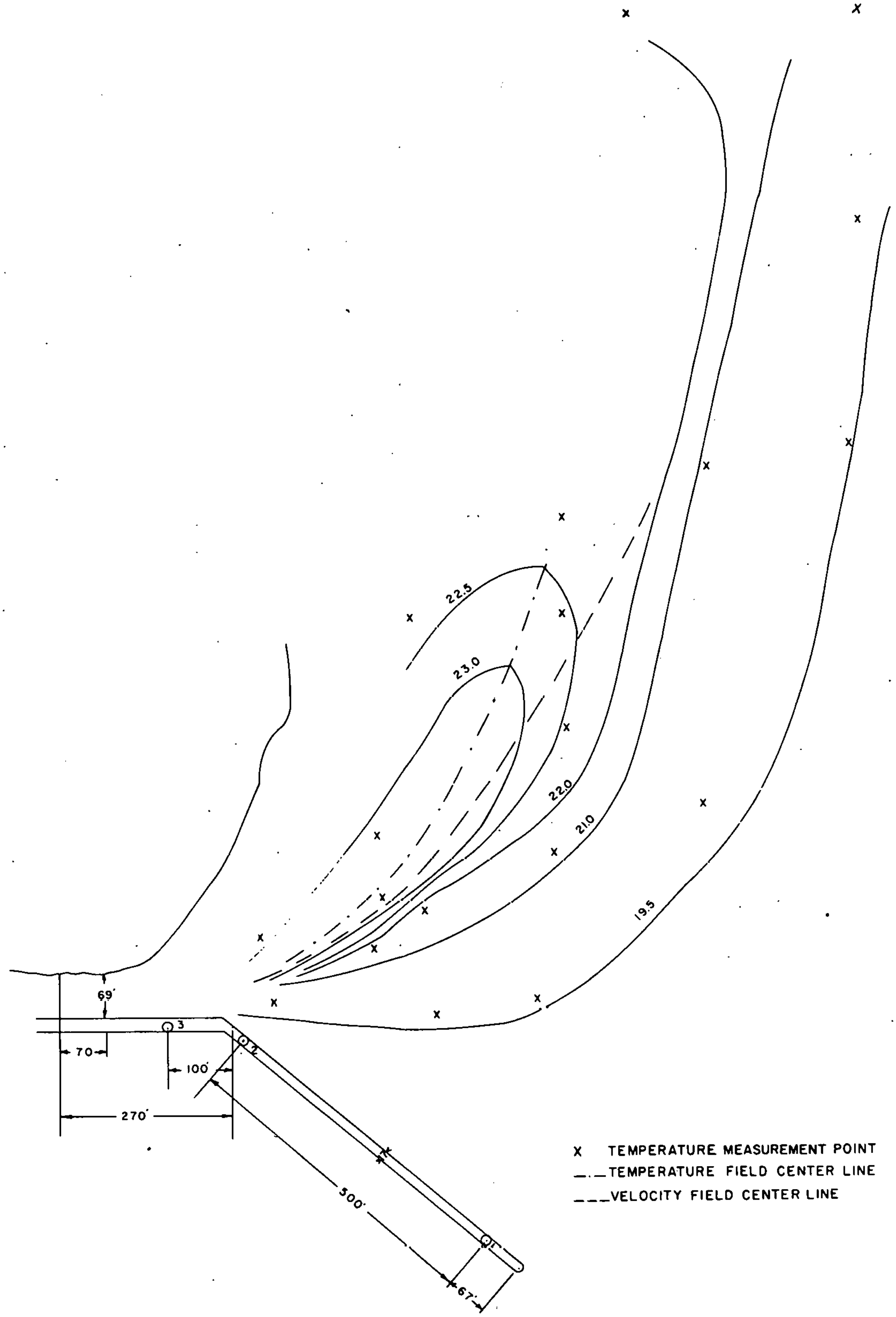

Fig. 11. Temperature Distribution--5:15 p.m., August 24, 1970

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