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WATER RESOURCES RESEARCH PROGRAM

ARGONNE NATIONAL LABORATORY'S
THERMAL PLUME MEASUREMENTS:
INSTRUMENTS AND TECHNIQUES

by

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	1
1 INTRODUCTION	1
2 DESCRIPTION OF A TYPICAL THERMAL PLUME SURVEY	3
2.1 Thermal Plume Mapping	3
2.2 Ambient Receiving-Water Conditions	3
2.3 Measurement of Plant-Discharge Conditions	5
2.4 Instrument Calibration and Data Handling	5
3 SPECIAL SUPPORTING STUDIES FOR THERMAL PLUME SURVEYS	7
3.1 Aerial Infrared Photography	7
3.2 Velocity and Temperature Measurements in the Near-Field Region of Thermal Plumes	7
3.3 Jet-Dynamics Measurements	7
3.4 Eddy-Diffusivity Measurements	8
3.5 Bathymetric Measurements and Location of Submerged Structures	8
3.6 Drogue Studies	8
4 DESCRIPTION OF EQUIPMENT AND INSTRUMENTATION USED FOR THERMAL PLUME SURVEYS	9
4.1 Survey Boat and Related Equipment	9
4.2 Thermistor Bar	9
4.3 Towed Thermistor Chain	15
4.4 Survey-Boat-Position System	20
4.5 Data-Acquisition System	20
4.6 Real-Time Boat-Position-Plotting System	25
4.7 Shipboard Current Meter	27
4.8 In-Situ Current Meter	27
4.9 In-Situ Thermograph	31
4.10 Temperature-Profiling Equipment	31
4.11 Temperature-Calibration Equipment	31
4.12 Meteorological Measurements	37
4.13 Shipboard Ambient Measurements	37
5 EQUIPMENT FOR SPECIAL SUPPORTING STUDIES	41
5.1 Aerial Infrared Photography	41
5.2 Velocity Measurements in the Near-Field Region of Thermal Plumes	41
5.3 Jet-Dynamics Measurements	41
5.4 Eddy-Diffusivity Measurements	41
5.5 Location of Submerged Structures	44
5.6 Drogue Studies	44

TABLE OF CONTENTS (Contd.)

	<u>Page</u>
6 EQUIPMENT AND INSTRUMENT DEVELOPMENT	47
6.1 Survey Boats	47
6.2 Systems for Establishing Survey-Boat Position	47
6.3 Data Acquisition Systems	47
6.3.1 Mark I	47
6.3.2 Mark II	49
6.3.3 Mark III and Mark IV	49
6.4 Current Meters	53
6.4.1 Survey-Boat Measurements	53
6.4.2 In-Situ Current Measurements	55
6.5 Thermographs	55
6.6 Meteorological Instruments	55
7 SUMMARY	61
REFERENCES	62
ACKNOWLEDGMENTS	63
APPENDIX A Instrument Specifications	A1
APPENDIX B Analysis of Towing Properties of the Towed Thermistor Chain	F1
APPENDIX C ANL Publications Related to Thermal Plume Studies	C1

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1	Survey Boat Equipped with A-Frame Hoist and Towed Thermistor Chain	10
2	Thermistor Bar	11
3	Diagram of Survey Boat with Thermistor Bar and Surface-Following Thermistor	12
4	Surface-Following Thermistor	13
5	Thermistor Bar Service Panel	14
6	Section of Towed Thermistor Chain with Molded Breakout, Thermistor Plug, Plug Extraction Tool, External Strain Member, and Fairing	16
7	Diagram of Section of Towed Thermistor Chain	17
8	Diagram of Survey Boat with Towed Thermistor Chain and Surface-Following Thermistor	18
9	Diagram of Thermistor Chain under Tow	19
10	Shore-Based Transponder for Survey Boat-Position System	21
11	Data Acquisition System, Mini-Ranger Console, and Programmable Calculator	22
12	Position Plotter with Typical Survey Plot	23
13	Block Diagram of Data Acquisition, Mini-Ranger, and Position-Plotting Systems	24
14	Typical Isotherm Plot of Thermal Plume	26
15	Shipboard Current Meter, Direction Vane, and Deck Readout	28
16	In-Situ Current Meter and Recording Package	29
17	Computer Graphical Output of Processed Data from In-Situ Current Meters	30
18	In-Situ Thermograph Showing Electronics, Battery, and Thermistor Probes	32
19	Metal Encased and Potted Thermistor for Thermographs and Current Meters	33

LIST OF FIGURES (Contd.)

<u>No.</u>	<u>Title</u>	<u>Page</u>
20	Thermistor Leads Spliced and Potted to Waterproof Plug	34
21	Temperature-Profiling Equipment	35
22	Temperature-Calibration Equipment	36
23	Mechanical Meteorological Station	38
24	Shipboard Instruments Used for Ambient Measurements	39
25	Schematic Diagram of Dye Sampling Manifold	42
26	Dye Sampling Manifold and Sampling Syringes	43
27	Aerial Photograph of Dispersing Dye "T"	45
28	Components of Instrumented Drogue	46
29	Small, Open Cabin Survey Boat	48
30	Data Acquisition System, Mark II	50
31	Block Diagram of Mark IV Data Acquisition System	51
32	Cassette Reader and 7-Track Recorder	52
33	Ekman-Merz Current Meter	54
34	Braincon Current Meter with Savonius Rotor Sensor	56
35	Ducted-Impeller Current Sensor Developed at Argonne National Laboratory	57
36	Endeco Ducted-Impeller Current Sensor	58
37	Ryan Thermographs	59
38	Weather Measure Meteorological Station	60
B.1	Schematic Diagram of Towed Thermistor-Chain Variables and Coordinate System Used in Analysis	B2
B.2	Measured and Smoothed Fin-Depth Data	B4
B.3	Measured and Smoothed Tension Data at the Water Surface	B5

LIST OF FIGURES (Contd.)

<u>No.</u>	<u>Title</u>	<u>Page</u>
B.4	Measured and Predicted Angle of Chain at the Water Surface	B6
B.5	Predicted Chain Shape at Various Towing Speeds for a Fixed Amount of Chain in the Water	B7
B.6	Maximum Error Resulting from the Assumption That the Chain is Linear	B9
B.7	Forces on Infinitesimal Chain Segment	B10
B.8	Drag Coefficient, C_D , Obtained by Fitting the Mathematical Analysis to the Smoothed Calibration Data	B14
B.9	Tangential Loading Coefficient, f_o , Obtained by Fitting the Mathematical Analysis to the Smoothed Calibration Data	B15

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
A.1	Instrument Specifications	A4
B.1	Cable-Tension Parameters	B16

ARGONNE NATIONAL LABORATORY'S THERMAL PLUME
MEASUREMENTS: INSTRUMENTS AND TECHNIQUES

by

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ABSTRACT

Instrumentation and techniques have been developed at Argonne National Laboratory for measuring the three-dimensional temperature structure of thermal plumes from power plants, along with the limnological, meteorological, and plant operating conditions affecting their behavior. The equipment and procedures were designed to provide field data for use in evaluating predictive models that describe thermal plume behavior, and over 100 sets of these data have been collected. The evolution of the instrumentation and data-handling techniques from early manually-operated systems to the present highly automated systems are discussed.

The instrument systems and techniques employed in a typical thermal discharge survey are highly integrated. Continuous monitoring of ambient and plant conditions is coupled with plume mapping from a moving survey boat. The instantaneous location of the boat together with subsurface temperature measurements from a towed thermistor chain provide a quasi-synoptic view of the plume structure. Real-time, onboard display of the boat path and vertical temperatures supply feedback to investigators for determining the extent and spatial resolution of measurements required.

The unique design, reliability, accuracy, calibration, and historical development of the components of these integrated systems are described. Survey system interfaces with data handling and processing techniques are also explained. Special supportive studies to investigate plume dynamics, values of eddy diffusivities, time-temperature histories of water parcels in thermal plumes, and rapid changes in plume shape are also described along with instrumentation used.

1 INTRODUCTION

The Energy and Environmental Systems Division (EES), formerly the Center for Environmental Studies, of Argonne National Laboratory (ANL) has been studying the physical effects of power-plant, waste-heat discharges into the Great Lakes since 1970 -- under the auspices of a progressively superseded federal sponsorship, beginning with the Atomic Energy Commission and on up through the U.S. Energy Research and Development Administration to the U.S. Department of Energy. One of the primary objectives of the Argonne

program is the evaluation of the various modeling techniques used to predict the fate of the waste heat from power plants. Since prototype data were needed to evaluate these models, a review of existing data was carried out.¹ The review indicated a paucity of detailed field data of good quality describing thermal plumes under various environmental conditions. Because it was clear that such data were needed to evaluate the various predictive techniques, ANL began an extensive field program of measurements of the physical phenomena related to waste-heat discharges into the Great Lakes.

Initially, research was centered on thermal plumes from power plants with once-through condenser cooling using shoreline surface discharges. More recently, the effort has switched to studies of plumes from similar plants using high-velocity submerged discharges or multiport diffusers.

During the early days of the field program, thermal plume data collection, reduction, and handling were usually accomplished with minimal sophistication in both equipment and techniques. For example, temperatures were measured at various stations and recorded manually. The position of the survey boat was determined using a sextant and known landmarks. However, these techniques did not lend themselves to the collection of the quantities of data necessary to evaluate predictive models adequately. Consequently, data collection and handling methods became more and more automated each year to the point where the temperature data, boat position, bottom depth, clock time, etc., are now collected and recorded on magnetic-tape cassettes. In addition, the path of the survey boat is plotted on board during the field survey.

One of the purposes of this report is to describe the present Data Acquisition System (DAS) in detail with a developmental perspective. The system, designed for use aboard a small boat, is interfaced with a towed thermistor chain or thermistor bar, a navigational ranging system, a depth sounder, and a real-time boat-position plotting system. Temperature and water-depth data, are recorded by the system as a function of time and boat position on both paper tape and magnetic-tape cassettes. The sampling time interval is variable and the data acquisition system allows the collection of data at approximately 1500 points over a linear distance of 8 km in one hour for a 4-second sampling interval. These data are processed by computer to yield temperature plots in the horizontal and vertical planes. The real-time plotting system permits the boat pilot to know the boat location at any time allowing him to adjust the course of the boat to map the study area completely.

The six chapters of the report are disposed as follows. A brief discussion of the measurements and measurement strategies used at Argonne for the mapping of the thermal plumes from power plants on the Great Lakes is given in Sec. 2 and detailed descriptions of the equipment and instrumentation currently used for the mapping are provided in Sec. 4. Special field studies undertaken in support of the plume mapping and model evaluation efforts and the equipment for those studies are discussed in Secs. 3 and 5, respectively. A summary of earlier data acquisition systems and instrumentation and the evolution to the present systems is given in Sec. 6.

2 DESCRIPTION OF A TYPICAL THERMAL PLUME SURVEY

2.1 Thermal Plume Mapping

The objective of the thermal plume mapping procedure is to obtain as complete a description as possible of the thermal field produced by the power-plant discharge. Hence, temperature measurements are made in three dimensions in the receiving water body, producing maps of isothermal contours in horizontal and vertical planes through the water body.

Temperature measurements are made at as many as seven depths, by means of fast-response linearized thermistors, from a small boat driven back and forth throughout the region of interest. The temperatures are displayed on board the boat so that the experiment director can assess the mapping procedure while it is in progress. The thermistors are mounted either on a rigid aluminum bar that allows measurements only to a depth of 3 m; or on a flexible, faired cable that allows them to a depth of 12 m. The bar is easier to handle in shallow water and is usually adequate for shoreline surface discharges where the plume floats near the surface. The cable is needed for the deeper, submerged discharges where the bottom receiving water is affected, at least in the near-field region of the plume.

The location of the boat at any instant can be fixed from range-range information obtained from a Motorola Mini-Ranger system on board the boat. Distance is ascertained by a time-of-flight technique from two fixed shore-based transponders whose location must be known or determined before the thermal plume survey is performed. The position of the boat is then computed onboard by a small programmable calculator and the results are plotted on an x-y plotter. The plotter is so mounted that it can be seen by both the boat pilot and the experiment director. The boat path plot and the display of the seven water temperatures permit the experiment director to alter the boat course to obtain maps of as much detail as required of any particular region of the survey area.

A data acquisition system aboard the boat collects temperature, range, and depth data, displays them, and records them on paper tape and a magnetic-tape cassette. The rate at which data are collected and recorded is selectable by the experimenter and is varied during the mapping procedure to collect more data in the near field where temperature gradients are usually large.

When mapping a thermal plume, the normal procedure is to begin near the discharge where the plume is easily distinguishable from the ambient water. The boat is then driven in a serpentine path through the plume and adjacent ambient waters. More closely spaced boat paths and higher acquisition rates are used near the discharge where larger temperature gradients are expected. The entire mapping procedure generally takes from one to three hours, with an experiment crew consisting of the boat driver, the experiment director, who operates the data acquisition system, and an attendant for the bar or cable.

2.2 Ambient Receiving-Water Conditions

In order to evaluate the effect of the thermal discharge from a power

plant on the ambient receiving water and to determine the effect of the environment on the dispersal of the heated effluent, certain characteristics of the ambient environment need to be measured. The parameters normally measured during a thermal plume survey are lake water temperatures, lake currents, and wind velocity, which serve as guides to the interpretation of the thermal plume map and as input information for predictive model comparisons. Lake currents are measured by one or more in-situ current meters throughout the period of a series of plume mapping surveys. These in-situ meters include recording packages that record current speed and direction every eight minutes on magnetic-tape cassettes. Typically, a string consisting of two current meters is moored in the lake at a depth and distance offshore comparable to the position of the power-plant outfall. One of these is located a few meters below the surface and the second, a few meters above the bottom for monitoring currents that interact with the thermal discharge in the near-field region. A third meter is often placed farther offshore and also a few meters below the surface to measure the currents that influence the far field of the thermal plumes and give an indication of current shear. The records from these in-situ meters provide a time history of the currents in the study region. In addition, before and/or after each plume mapping, the currents are measured at various depths at fixed survey boat locations, which are usually in the vicinity of the in-situ current meters. The current profiling is accomplished by securing the boat with two anchors and lowering a current meter over the side. Speed and direction are recorded from a deck readout at 1-m intervals from the surface to the bottom, yielding information on the spatial variation of the currents.

The temperature structure of the ambient receiving water is established before and/or after each plume mapping by driving the boat along a line perpendicular to the shoreline from a location several thousand meters offshore to as close to shore as possible with the thermistor bar or cable in the water and the data acquisition system in operation. To sample the temperature of the water being brought into the plume area by the ambient lake current, these measurements are carried out upcurrent of the plume itself. Temperature measurements as a function of depth are also made from the anchored boat at the same time that the current is being profiled. The in-situ current meters also measure and record water temperature at the position of the meter to provide a time history of the lake temperature at that point.

Wind speed and direction as well as air temperature are recorded with a portable meteorological station throughout the period of the series of plume-mapping surveys. This mechanical device produces a strip-chart record and is generally installed on a breakwater or in an unobstructed area onshore to obtain an estimate of over-the-water wind speed and direction.

While the survey boat is anchored to obtain the lake current and water temperature profiles, several other environmental parameters are observed and recorded. These include wave height, period, and direction; wind speed and direction; wet and dry bulb temperatures; and sky cover. These data are used to provide as complete a record as possible of the environmental conditions that prevailed during the mapping of the thermal plume.

2.3 Measurement of Plant-Discharge Conditions

The heat rejection rate of the power plant must be known in order to interpret the thermal plume maps, to evaluate the effectiveness of a particular discharge design in diluting the heated effluent, and to carry out comparisons with model predictions. In particular, it is necessary to know the discharge flow rate and the discharge and intake temperatures. The discharge flow rate is sometimes measured by profiling with a current meter at the outfall. When these measurements cannot be made, as in the case of a submerged diffuser, the value of the flow rate is obtained from power-plant personnel who use pump performance curves or other pump calibration studies. The discharge and intake temperatures are measured and recorded throughout the period of a series of plume mapping surveys by thermograph packages installed in the discharge and intake pipes or canals. The thermograph records the water temperatures on magnetic-tape cassettes to provide a continuous record of discharge and intake temperatures.

Discharge and intake temperature data are often collected at power plants by utility personnel and are usually available. These data, however, are not considered to be sufficient because of the occasional lack of power plant data, and occasional discrepancies in instrument calibration. The self-contained thermograph packages can be calibrated against the same secondary standard as the other temperature measuring devices used in the thermal plume surveys. The data can be reduced in the same manner as data from current meters and the DAS. Data handling is discussed in more detail in the following section.

2.4 Instrument Calibration and Data Handling

All the thermistors used to map the plume, measure ambient lake temperatures, and measure the discharge and intake temperatures are calibrated against a common secondary standard, a platinum wire resistance temperature device (RTD). Calibration is carried out periodically in the laboratory by placing the thermistors and the RTD probe in a well-stirred water bath at 8-10 different temperatures in the normal operating range of 0-35°C. Using a single secondary standard assures the accuracy of the relative calibration of all the thermistors and the consistency of the resulting data.

Calibrations of the current meters, the Mini-Ranger, and ambient instruments are performed one or more times a year.

The magnetic-tape cassettes from the DAS, the in-situ current meters, and the thermographs are transcribed onto computer-compatible 7-track magnetic tapes. These tapes are reduced by computer to provide a graphical representation of a thermal plume and to produce plots of current speed and direction versus time, and temperature versus time. The data on the strip charts from the meteorological station must be read and plotted by hand.

3 SPECIAL SUPPORTING STUDIES FOR THERMAL PLUME SURVEYS

In addition to the major field activities of thermal plume mapping, special supportive studies are carried out to look at specific parameters addressed by various predictive techniques.

3.1 Aerial Infrared Photography

Mapping thermal plumes with a boat permits the measuring of temperatures at a number of depths. Unfortunately, the boat technique yields a time-distorted picture of the plume. The distortion is a function of the sampling course chosen and the temporal variability of the environmental conditions influencing the plume relative to the time required to complete a mapping. If ambient-lake and plant-operating conditions remain constant during a boat plume survey, the time distortion is likely to be minimal. However, with changing conditions, problems in analyzing the boat thermal plume data can arise. Thermal scanning, on the other hand, offers a synoptic picture of the surface temperature. In addition, this technique offers the capability of generating much more data in less time than that required for boat measurements. Scanning has been used by ANL in addition to the boat technique to collect thermal plume data.² Data collected in this manner have yielded information on the dynamics of thermal plume behavior and have resulted in a comparison of boat- and infrared-measurement techniques as well.³

Thermal scanning measures temperatures within only a few tens of microns of the surface. On very calm days, the surface-layer temperature structure can be considerably different than that of the rest of the plume. In addition, meteorological conditions have to be ideal for an infrared overflight. Experience has shown that for routine monitoring of surface plumes, both the infrared and boat techniques are valuable. For situations in which three-dimensional temperature data are required or when simultaneous measurements of other physical, chemical, and biological parameters with temperature are needed the boat technique is the only feasible method.

3.2 Velocity and Temperature Measurements in the Near-Field Region of Thermal Plumes

Many analytical modeling techniques have been developed to predict velocity and temperature structure in the near-field region of thermal plumes. Studies were conducted whereby near-field velocity and temperature profiles were made from a securely anchored boat, and data collected in this manner were used in the evaluation of near-field models.⁴

3.3 Jet-Dynamics Measurements

Wavelike temperature variations have been inferred from aerial infrared scans of cooling water discharges at power plants,⁵ and hydraulic model studies have indicated temperature and flow fluctuations near the simulated outfall.⁶ Because modeling techniques fail to include unsteady temperature and flow fields, ANL made measurements of short-period velocity and temperature fluctuations to explore further these phenomena and to attempt to understand some of the mechanisms involved.²

3.4 Eddy-Diffusivity Measurements

The dispersal of warm-water effluents in large lakes is governed largely by processes of mixing with the ambient water. In models of the far-field region of the thermal plume, the mixing process is usually treated analytically as a diffusion phenomenon (Fick's law), with an unknown diffusion coefficient. Most of the available analytical and numerical models of far-field thermal mixing require the input of the diffusion coefficient. The diffusion process describes the convective transport of heated water by turbulent eddies at scales much smaller than those resolved by current-meter measurements.

Only limited data are available on turbulent diffusivities in large lakes, and the scarcity is partly attributable to some of the complications in the experimental measurements. Argonne attempted to obtain measurements for the determination of the horizontal and vertical diffusion coefficients in both thermal-plume and ambient-lake waters.²

3.5 Bathymetric Measurements and Location of Submerged Structures

Bottom profile data are routinely collected in the vicinity of power plants being studied by ANL. These bathymetry data are a necessary input to some of the mathematical models developed for prediction of thermal plume behavior. Continuous recording depth sounders also have been used to locate the submerged intake and jets from submerged discharges and multiport diffusers. The jet turbulence can be identified and used to verify the position of the diffuser.

3.6 Drogue Studies

Drogues that move essentially with the water mass in which they are placed provide a Lagrangian measure of currents in contrast to the Eulerian measure of the moored current meters. A drogue may be considered analogous to an organism drifting with a discharge or ambient current. Time-temperature measurements are useful in determining the temperature regime to which organisms may be subjected as they are drawn into a plant intake or entrained from ambient receiving water into a thermal plume. Of main concern in the intake-discharge passage are planktonic organisms, small fish in the egg or larval stage, and juveniles that may have limited mobility. The time-temperature data curves obtained using drogues instrumented with thermographs can be used in conjunction with temperature tolerance studies (usually done in the laboratory) to help assess any biological impact of the heated discharge on the organism of interest. The time-temperature data collected with instrumented drogues also can be used for mathematical model evaluation.

Uninstrumented drogues have proved useful in qualitative studies dealing with ambient water entrainment by thermal plumes and in studies examining the possibility of reentrainment of discharge waters by a power-plant condenser cooling-water intake. In addition, during plume mapping when the temperature differences between thermal plume water and ambient-receiving water are small, drogues can be used to indicate the trajectory of the thermal plume.

4 DESCRIPTION OF EQUIPMENT AND INSTRUMENTATION USED FOR THERMAL PLUME SURVEYS

4.1 Survey Boat and Related Equipment

The boat (ERDA I) used for studies of thermal discharges is an all-aluminum work boat of 7.6-m length. It has a trihull design and is powered by a 225-hp (168-kW) inboard/outboard engine with a closed-circuit cooling system. The boat has a fully enclosed heated cabin for operation and protection of equipment during cold and rainy weather. ERDA I also has, as permanent equipment, a VHF Marine Radio for maritime communications, a VHF radio for private communications among field personnel, a digital depth sounder, and an auxiliary power system. The digital depth sounder is a Data Marine Model 2300 (Appendix A), which has been modified to provide binary coded decimal (BCD) information output to be used by the data acquisition system (DAS) (Sec. 4.5). The auxiliary power system consists of a 24-volt alternator/regulator that charges two standard 12-volt automobile batteries in series. This system is used as the primary power source for the DAS and powers two Flite-Tronics PC16 inverters to produce 117 V ac for the boat position system (Secs. 4.4 and 4.6).

In addition, the ERDA I is equipped with a small crane and an "A" frame lifting rig, both equipped with winches, to handle over-the-side measurements and deployment of in-situ equipment (Fig. 1).

4.2 Thermistor Bar

The thermistor bar (Fig. 2), which can be used to measure temperatures in the upper 3 m of the water column, is supported from the gunwale of ERDA I (Fig. 3). It is constructed from a 1.27 x 6.35 x 370-cm solid aluminum bar, which has the leading edge shaped and the trailing edge milled to allow a hollow aluminum fairing to be screwed in place along its length. Six thermistors are mounted in holes drilled through the bar (6.45-mm diameter) from leading edge to trailing edge (into hollow space in fairing). The holes are spaced 55.6 cm apart, positioning the six thermistors 0.5 m apart when the bar is in normal running attitude. When the bar is in the normal measurement position, the six thermistors are then at 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 meters below the water surface. An additional thermistor is mounted on an outrigger with a spring-steel arm to follow the upper 1 cm of the water surface (Fig. 4).

The seven thermistors are specially mounted Yellow Springs Instruments (YSI), type 700 series, linear (when used in YSI thermilinear linearization network) thermistors (Appendix A). The bead is self-supporting on three-wire leads epoxied in a stainless steel tube of 6.35-mm diameter by 25-mm length and is waterproofed with a thin epoxy coating. This mounting technique results in a sensor with a time constant of 0.6 s or less, and allows the tube to be inserted in the holes of the bar where they are set-screwed in place. The thermistor leads (neoprene jacketed) that leave the small mounting tube are spliced to a waterproof connector (Electro-Oceanics 56B4-U) so that sensors may be interchanged or replaced easily. The changing is accomplished via a service panel (Fig. 5) on the hollow fairing that exposes the bar wiring. A matching

Fig. 1. Survey Boat Equipped with A-Frame Hoist and Fowed Overboard Chain

Fig. 2. Thermistor Bar

Fig. 3. Diagram of Survey Boat with Thermistor Bar and Surface-Following Thermistor

Fig. 4. Surface-Following Thermistor

centimeters

Fig. 5. Thermistor Bar Service Panel

connector at each service panel allows field personnel to change defective thermistors.

When in place, the thermistor bead is approximately 3 mm in front of the leading edge of the bar. Each sensor is surrounded by a small piece of stainless steel mesh that is fastened to the bar for protection of the bead (Fig. 5).

The bar tracks the boat path very well but exhibits some ruddering when the boat turns too sharply. The ruddering is not severe enough to cause damage but some flexing of the hollow fairing is evident.

4.3 Towed Thermistor Chain

The bar described above is adequate for measurements to depths of 3 m. For measurements at greater depths a towed chain array for sensors is used. The chain developed at ANL was patterned after similar devices used at the Canada Centre for Inland Waters (CCIW).⁷ Consultation with CCIW engineers and scientists regarding their experiences with towed chains allowed ANL to develop a working system in less than six months.

The towed thermistor chain (TTC) built at ANL is designed to be compatible with the existing DAS. The thermistor sensors are the same YSI 700 series thermistors; however, they are mounted and epoxied in a specially designed plug (Figs. 6 and 7). The plug is designed to mate with a Glenair (GL20G3S-F) waterproof connector. The thermistor bead (YSI part 44018) is soldered in the three-prong plug and is supported by its leads above the epoxy potting. The bead and exposed leads are coated with epoxy to complete the waterproofing of the assembly. These sensors exhibit a time constant of about 0.2 seconds.

Although the existing DAS accepts only seven thermistor inputs, the cable was constructed with nine sensors for flexibility in choice of sensor depth during a plume survey. The electrical cable used is a 27-wire cable jacketed in polyurethane. The sensor *breakouts* are made by slitting the cable at the appropriate points and pulling three leads from the cable. The Glenair connector is spliced to the three leads and the connection is placed in an aluminum mold and cast with polyurethane. The casting is hydrodynamically shaped with the sensor connector at the trailing edge of the breakout. A preliminary analysis of the chain shape for various towing parameters was performed. It was determined that a breakout spacing of 1.1-m was needed to produce a 1-m sensor separation under normal towing conditions. This chain array was designed to be used with a dynamic-depressor fin (Endeco type 166 V-fin) and is supported on a wire-rope external strain member. Flexmore fairing units (Flexmore type 1042-900) are used over the strain member and chain to reduce drag. This system is stored on an 0.87-m diameter rotating wheel mounted on the port side of ERDA I where it is deployed and retrieved by a small winch and crane assembly, (Figs. 1 and 8). When under tow, the strain member is supported from a fixed hook on the crane thus relieving strain on the storage wheel. The system has performed very well at speeds up to 5 m/s with no evidence of chain strum or unacceptable drag. The chain when under tow exhibits a curved shape similar to that in Fig. 9. A complete analysis of the chain dynamics under tow appears in Appendix B.

Fig. 6. Section of Towed Thermistor Chain with Molded Breakout, Thermistor Plug, Plug Extraction Tool, External Strain Member, and Fairing

Fig. 7. Diagram of Section of Towed Thermistor Chain

Fig. 8. Diagram of Survey Boat with Towed Thermistor Chain and Surface-Following Thermistor

Fig. 9. Diagram of Thermistor Chain Under Tow

4.4 Survey-Boat-Position System

Fixing of the boat's position on a continuous basis during a plume survey is accomplished by means of a Motorola Mini-Ranger. This device is a microwave range-range positioning system. The system consists of two battery-powered (24 V dc, 0.75 A) shore-based transponders (Fig. 10), an onboard receiver/transmitter unit, and a mobile range console (117 V ac, 105 watts) (Fig. 11) used on the survey boat. The range console interrogates the transponders and obtains range-range information that can be used to determine boat position. The Mini-Ranger is interfaced with the DAS and the real-time position-plotting system so that the range-range information can be recorded and/or used to produce immediately an onboard plot of boat position relative to power plant and shoreline. Figure 12 shows the x-y plotter with a typical plot of the boat path during a survey.

The Mini-Ranger ranges are also displayed on the range console front panel and on the DAS front panel. Appendix A contains all specifications for the Mini-Ranger.

4.5 Data Acquisition System

The data acquisition system (DAS) (Figs. 11 and 13) used for thermal discharge studies was designed and built by ANL's Electronics Division. It accepts analog signals from the seven thermistors or other analog signals ranging from 0-5 V dc. The signals are converted to digital form and shown by light emitting diode (LED) displays. Direct digital information in binary coded decimal (BCD) form is also accepted by the DAS and is shown by LEDs on the front panel. For thermal plume studies, the normal inputs are the seven thermistor inputs (analog), the two range inputs from the Mini-Ranger (BCD), and the depth information (BCD) from the Data Marine depth sounder. In addition to being displayed, all inputs to the DAS are printed on paper tape and recorded on magnetic-tape cassettes.

The printer built into the DAS is an Anadex 650, which is a 21-column printer. By using the technique of shifting from black to red ribbon, the 21 columns can be used for temperature information followed by 21 columns for the clock, range, special information flag, and depth data. The same information is recorded by a Memodyne model 201 digital-stepping, magnetic-tape cassette recorder. The inputs to the DAS are displayed and recorded on command of the DAS internal clock. The recording interval may be selected by front-panel controls. At command, all data (including clock) are updated, printed, and recorded. The option of recording all information on either paper or cassette tape, or both, may be selected on the front panel. Provision is made for entering information such as date and experiment number manually via thumbwheel switches on the front panel. A switch that may be used as a special information flag such as indication of thermistor-bar position (full depth or half depth, etc.) or some other special condition, is also provided.

The magnetic-tape cassettes containing data from the DAS are transcribed onto computer-compatible 7-track magnetic tapes. These data along with calibration and site survey data are then processed by the computer and used to produce maps of temperature as a function of position in both the horizontal

Fig. 10. Shore-Based Transponder for Survey-Boat-Position System

Fig. 11. Data Acquisition System, Mini-Ranger Console, and Programmable Calculator

Fig. 12. Position Plotter with Typical Survey Plot

Fig. 13. Block Diagram of Data Acquisition, Mini-Ranger, and Position-Plotting Systems

and vertical planes. Isothermal contours are then drawn on the maps either by hand or by means of a computer contouring program. Figure 14 is an example of a horizontal section at the lake surface after isotherms have been drawn. The boat path is indicated by what appears to be a dotted line but is actually the temperature data posted along the boat path. The DAS requires 24-V dc at 5.5 A, which is provided by the ERDA I auxiliary power system. Appendix A contains the specifications of the DAS.

4.6 Real-Time Boat-Position-Plotting System

The real-time position-plotting system consists of a Hewlett-Packard programmable calculator (HP 9810A), an x-y plotter (HP 9862A), and an interface unit (HP 11203A) as an interface to the Mini-Ranger. The calculator (Fig. 11) controls the Mini-Ranger and accepts its range-range information to calculate the x-y coordinates to be displayed on the x-y plotter. The chart paper for the x-y plotter is usually prepared prior to the survey to include the locations of the shoreline, discharge and intake structures, and other features of interest (Fig. 12). Although this position-plotting system can be used alone, it is generally used in conjunction with the DAS.

When the DAS operates without the position-plotting system, the Mini-Ranger acquires range data at a free-running rate determined by a front panel control on the Mini-Ranger. The Mini-Ranger supplies this range-range information as needed. The sampling rate is determined by the DAS internal clock, which is independent of the Mini-Ranger.

Use of the Mini-Ranger to supply range-range information to the calculator-plotter system, without interruption of the data flow from the Mini-Ranger to the DAS, required several changes to the Mini-Ranger and an interface to the calculator. The Mini-Ranger required modification to allow for acceptance of control from an external trigger. It was also desirable to provide *automatic zero output* for those times when the Mini-Ranger did not obtain valid range information from its shore-based transponder to prevent the Mini-Ranger-calculator system from becoming *hung up*.

The HP 11203A BCD interface unit was installed according to information supplied in Motorola Application Note 6131-250. After the modifications were completed, the Mini-Ranger could be controlled by the calculator.

Upon instruction from the calculator, the Mini-Ranger obtains range readings and supplies them to the calculator (in parallel to the DAS), where the necessary calculations are performed to transform the ranges into x and y coordinates for use by the plotter. The calculator is programmed, before going to the field site, with all the information needed to control the Mini-Ranger and to perform the necessary calculations to obtain a plot at the site to be studied. The information is stored on a magnetic card and fed to the calculator at the start of a survey. This system provides a real-time plot of boat position without interrupting range information being recorded by the DAS.

Fig. 14. Typical Isotherm Plot of Thermal Plume

4.7 Shipboard Current Meter

Measurements of the ambient current from the survey boat with a Bendix Q-15 current meter (Fig. 15) during a field study is a routine procedure. Current speed is sensed by a 5-bladed impeller enclosed in a duct and direction is sensed by a 3-m vane connected to the duct. A small magnet is imbedded in each impeller blade, and as the blades pass near two reed switches in the duct housing, the switches sense the direction and the number of impeller rotations. Vane direction relative to magnetic north is sensed by a potentiometer fixed to the main duct shaft, with its *wipers* coupled to a geomagnetic compass. The effects of wave motion and oscillatory boat motion on current speed determinations are minimized by the presence of the duct, by the counting of net impeller rotations, and by electronic averaging of the signal over a selectable range of 2 to 30 seconds. Current speed and direction are displayed on deck by means of a Bendix S-232 deck readout unit connected to the current meter by a four-conductor cable. Provision is made for coupling the analog signals from the S-232 deck readout to the DAS analog inputs to allow onboard digitizing and recording of currents during long-term experiments. Specifications for this instrument are listed in Appendix A.

4.8 In-Situ Current Meter

Current meters are deployed near a power plant for continuous, in-situ measurements during thermal surveys. Bendix Q-15R (inverted Q-15) in-situ current meters are used with a data recording package designed by ANL's Electronics Division (Fig. 16 and Appendix A). The recording package contains the electronics necessary to digitize the direction signal from the Q-15R and two thermistor input signals. The direction signal is digitized and recorded four times during a sampling interval of eight minutes. The package also contains the scaling circuitry to average the Q-15R impeller signal and an internal crystal-controlled clock for timing. All data are recorded on a Memodyne Model 201 magnetic-tape-cassette recorder at a preselected sampling interval of eight minutes as mentioned. All circuitry uses low-current-drain integrated circuits. The standby current drain is less than 0.5 mA and the pulse current when recording is about 80 mA. A cylindrical PVC pressure vessel, 15 cm in diam. x 50 cm in length, houses the recording electronics and battery supply. Interconnection to the Q-15R is via a 6-m long cable terminated with an Electro Oceanics type B51F6M waterproof connector. Nine alkaline "D" cells power the package for more than four months at the 8-min sampling rate (tape capacity at that rate is about three months). The package was designed to be serviced by a diver who unplugs it, removes two bolts, delivers it to boat personnel for tape and battery changes, and then reinstalls it. Data are transcribed from the cassette onto 7-track tapes for computer reduction. A representation of the graphical output produced from these data is shown in Fig. 17.

Detailed calibration studies of the Bendix Q-15R current meter showed a strong nonlinear relationship between the observed count-rate and the true water speed in the range 0.0-0.1 m/s. An empirical response curve was fitted to the data and fitted coefficients were determined for all Q-15R current meters calibrated by ANL. Separate calibrations of every current meter are recommended whenever possible. If this is not possible, use of the composite fitted curve is recommended in preference to the manufacturer's conversion factor.⁸

Fig. 15. Shipboard Current Meter, Direction Vane, and Deck Readout

Fig. 16. In-Situ Current Meter and Recording Package

Fig. 17. Computer Graphical Output of Processed Data from In-Situ Current Meters

4.9 In-Situ Thermographs

In-situ measurements of water temperatures in the vicinity of power plants are made with a modified electronics package similar to the one used with the Q-15R current meter described in Sec. 4.8 and shown in Fig. 18. These thermographs are sometimes used in the intake forebay and cooling water discharges at power plants. The recording package is modified slightly from the current meter package by deleting the impeller signal scaling circuitry and adding one additional analog input. The modification produces a thermograph with four thermistor inputs that record data in a format that is similar to the in-situ current meters.

The thermistors used as sensors in both the current meter and thermographs are YSI two-lead type 44012. These beads are spliced to a two-wire, neoprene-jacketed electrical cable and inserted into a 0.8-cm diam. x 15-cm long stainless steel tube. The assembly is sealed by hot-molding the cable and tube together with neoprene (Fig. 19). The four small electrical cables from the thermistors are spliced and then molded with neoprene to an Electro Oceanics B51F6M waterproof connector (Fig. 20). The lead lengths are typically 12, 8, 3, and 3 m to allow variability in sensor placement. The recording interval, servicing and data reduction techniques, and battery and cassette life are similar to those of the in-situ current meter packages. The graphical representation of temperatures is similar to the temperature chart shown in Fig. 17 for current meters. Appendix A contains the complete specifications for these thermographs.

4.10 Temperature-Profiling Equipment

Part of the *ambient-conditions* measurements include temperature profiling at the same time and location as current profiling. A Digitec model 580C electronic thermometer is used for this measurement (Appendix A). The Digitec has rechargeable batteries for portable use, but it can be powered by the boat auxiliary power system. The unit uses the YSI series 700 thermistor as a sensor, thereby allowing a direct interchange with the various temperature probes used with the DAS. The sensor commonly used for profiling is the same thermistor mount used in the thermistor bar described in Sec. 4.2. The thermistor is spliced and molded to the end of an electrically-shielded, PVC-jacketed, three-lead cable of 20-m length where it is contained in a weighted protective mount (Fig. 21). The cable has sufficient strength to support the weight of the mount and is used therefore without an additional supporting strain member when profiling.

4.11 Temperature-Calibration Equipment

The secondary standard used for calibration of all temperature sensors is a Stolab model 911 PL electronic thermometer. This device uses a platinum resistance wire as a sensor and has the necessary electronics to produce an output signal of 10 mV/C° that is directly read as temperature by a Data Precision model 245 digital voltmeter (DVM) (Fig. 22). By calibrating the DVM with a standard voltage source and by using a Stolab PL100C calibration device (designed to be used with the 911 PL), the 911 PL and Data Precision Model 245 combination can be calibrated to better than ± 0.05 C° for the range 0-100°C. The DVM

Fig. 18. In-Situ Thermograph Showing Electronics, Battery, and Thermistor Probes

Fig. 19. Metal Encased and Potted Thermistor for Thermographs and Current Meters

Fig. 20. Thermistor Leads Spliced and Potted to Waterproof Plug

Fig. 21. Temperature-Profiling Equipment

Fig. 22. Temperature-Calibration Equipment

is battery powered and the 911 PL has been modified to accept external battery power to allow portable use as a standard to check the temperature devices used in the field. This combination is also the secondary standard used for calibrating the TTC, thermistor bar, and other temperature devices in the laboratory. Specifications for these units appear in Appendix A.

4.12 Meteorological Measurements

Wind speed and direction, and air temperature are monitored during a field study with a Meteorology Research Inc. (MRI) model 1071 portable, mechanical weather station (Fig. 23 and Appendix A). The device contains a cup anemometer, a directional vane, and a helical coil thermometer, all outputs of which are recorded on pressure sensitive strip chart paper. The clock that drives the chart uses two "D" cell batteries to wind its drive spring and can run continuously for thirty days. An optional gear train allows modification of the station for 60-day records with the same clock and batteries but different chart paper. The data from the strip chart must be reduced by hand.

4.13 Shipboard Ambient Instruments

Wind speed and direction and relative humidity are measured onboard the survey boat during the time the lake currents are profiled. The instrument used for measurement of wind speed is a Science Associates type 444 hand-held cup anemometer and a hand bearing compass is used to estimate wind direction. Relative humidity is measured by a VWR Scientific 35545 sling psychrometer -- dry bulb temperature is also recorded from this instrument. Figure 24 is a photograph of these instruments.

Fig. 23. Mechanical Meteorological Station

Fig. 24. Shipboard Instruments Used for Ambient Measurements

5 EQUIPMENT FOR SPECIAL SUPPORTING STUDIES

5.1 Aerial Infrared Photography

Aerial infrared overflights were conducted as a cooperative effort with the University of Wisconsin, using their infrared equipment. The heart of the University's thermal scanning system is a Texas Instruments (TI) RS-18A thermal scanner employing a liquid-nitrogen-cooled HgCdTe detector. Operated as a single-channel system, the RS-18A detects 8-14 μm wavelength radiation emitted from the first few tens of microns of the water's surface. The field of view of the scanner is 100° (50° on either side of nadir); its instantaneous field of view (resolution) is 2.5 mrad based on 30% modulation. For real temperature measurement, 100% modulation is necessary, so the effective resolution of the RS-18A was about 10 mrad. The scanner is electronically roll-stabilized resulting in a lightweight, easily mountable system. (See Ref. 9 for complete details of the University of Wisconsin system.)

5.2 Velocity Measurements in the Near-Field Region of Thermal Plumes

Water-velocity measurements near power-plant cooling-water discharges were made with the Bendix Q15 current meter and S232 deck readout interfaced with the DAS or a strip-chart recorder. The results of near-field velocity measurements and comparisons with model predictions are given in Ref. 4.

5.3 Jet-Dynamics Measurements

Jet dynamics studies involve the use of many of the instruments described in Sec. 4. The wavelike temperature variations mentioned in Sec. 3.3 were measured by using the DAS, the thermistor bar, two thermistors each with 30-m long leads, and the Q15 current meter. The boat was anchored in front of a discharge with the long-lead thermistors positioned at some distance on either side of the boat and the bar and Q15 deployed over the side. All data from these devices were recorded by the DAS. A complete description of the technique and equipment used for these measurements is contained in Ref. 2.

5.4 Eddy-Diffusivity Measurements

Measurements performed by ANL for the determination of diffusion coefficients involved specialized equipment and techniques. Two separate techniques were used to determine horizontal diffusivities. The first technique required the continuous injection of sodium fluorescein dye into the lake at 1.5-m depth at a test site while the survey boat crossed the dye plume with the temperature measuring bar lowered into the water. Six copper tubes of 0.6-cm diameter were attached to the bar, with each tube opening at a point adjacent to a temperature sensor. This arrangement permitted sampling at the six different water depths corresponding to the typical temperature-measuring depths. Aboard the boat, all tubes were connected to a manifold that was pumped by a water pump of 290 cm^3/s capacity at 30 kPa (Fig. 25). The manifold was equipped with delay lines to provide equal transit times for each sampling tube and a special gland for each tube to allow simultaneous grab samples to be obtained by using six 15- cm^3 syringes (Fig. 26). These grab

Fig. 25. Schematic Diagram of Dye Sampling Manifold

Fig. 26. Dye Sampling Manifold and Sampling Syringes

samples were immediately discharged into sample bottles for laboratory analysis and yielded information for the calculation of the vertical diffusivity. Data for determination of horizontal diffusivities were obtained by diverting one sampling tube through a Turner Associates model 111 fluorometer (Appendix A). Fluorometer output was recorded simultaneously on a strip chart recorder and digitized and recorded on the DAS along with temperature information. The Mini-Ranger positioning system also was used with the DAS to record the boat sampling path.

The second technique involved the rapid injection of dye in the shape of the letter "T" from a fast moving boat. Each segment of the T was typically 300 m in length. The T-shaped patch was then photographed periodically from a Cessna 180 airplane equipped with a Zeiss aerial-mapping camera, model RMK 15/2323, using a Wratten 61 filter to enhance contrast of the dye on standard Tri-X black and white film. The series of photographs recorded the dispersal of the T patch (Fig. 27). The film was developed and the image of the dye on the negative was scanned with a densitometer to obtain information on the dye concentration, from which horizontal diffusivities were calculated. A more detailed description of the equipment and the analysis techniques used is contained in Ref. 2.

5.5 Location of Submerged Structures

A continuously recording depth sounder (Raytheon Model DE719B) has been used for detecting intake structures and turbulent jets from submerged diffusers, as well as diffuser ports. If used with the real-time position-plotting system, this technique provides verification of the position of submerged structures for maps used on the x-y plotter. See Appendix A for specifications of this depth sounder.

5.6 Drogue Studies

For a time-temperature history of condenser cooling water discharged from a plant, instrumented drogues are used. Those used by ANL are cruciform style with styrofoam floats and attached instrument packages.¹⁰ To minimize wind effects on the drogue, the styrofoam float is small with a ratio of drogue area influenced by the water to the area influenced by the air of 100:1. The drogue is constructed so that the instrument package is housed in the center of the vanes. The package consists of a 12-V battery pack having a life of 20 hr, a Rustrak model 288 strip chart recorder that allows for 3.3 hr of continuous use, and a mercury switch placed in an ordinary 4-liter paint can (Fig. 28). A thermistor extends from the bottom of the can through a water-tight seal. The mercury switch turns on the instrument package when the drogue is placed in the water in its normal position.

The drogue is placed in or near the cooling water outfall and its progress is determined with the boat by checking position periodically with the Mini-Ranger ranging system. Such experiments are normally performed in conjunction with thermal plume mapping.

The drogues are sometimes used without instrument packages to ascertain the discharge or ambient-water movement only.

Fig. 27. Aerial Photograph of Dispersing Dye "T"

Fig. 28. Components of Instrumented Drogue

6. EQUIPMENT AND INSTRUMENT DEVELOPMENT

6.1 Survey Boats

When ANL's studies of waste-heat discharges began, a 2.5-m fiberglass boat, the *Aha*, (Fig. 29) was purchased and equipped with a 65-hp (48-kW) outboard engine. It was outfitted with a canvas cabin that proved to be inadequate for the protection of equipment and the safety of personnel. Hence, during the second field season, the boat was outfitted with an aluminum cabin and equipped with two 50-hp (37-kW) outboard engines.

During the 1973 field year, a Zodiac inflatable rubber boat and a 25-hp (19-kW) engine were purchased to assist in supportive studies such as the deployment of current meters, thermographs, drogues, and dye. Measurements of thermal discharges were being attempted in colder and more inclement weather than previously, prompting the purchase of a new workboat with an enclosed, heated cabin. The new boat, ERDA 1, arrived in early 1975 from the Mon Ark Boat Company. It is an all aluminum boat, 7.6 meters long, and has a 225-hp (168-kW) inboard outboard engine with a closed circuit cooling system (Figs. 1 and 3).

6.2 Systems for Establishing Survey Boat Position

Early boat positioning techniques involved establishing a grid of buoys in the vicinity of a power plant to provide known location markers. The locations of the buoys were determined with the aid of a sextant on the boat or transits at known locations on shore. In 1972, the Mini-Ranger positioning system described earlier was purchased and has been used for all positioning since that time.

6.3 Data Acquisition Systems

6.3.1 Mark I

The original data acquisition system (DAS) (1970 field year) used a Digitec Model 8500-1 digital thermometer (Appendix A), with a manual switching device to sequentially sample five thermistors. Four Yellow Springs Instrument No. 409 thermistors were mounted on a 3.0-m aluminum bar attached at one end to the gunwale of the survey boat. The bar was lowered into the water for a temperature survey, and when in this position, it extended to 2.7-m below the surface. The thermistors were so positioned along the bar that their average depths below the water surface were 0.3, 0.9, 1.8, and 2.7-m. A fifth sensor was mounted on a towable float to monitor surface temperature.

The recording technique used involved manual switching from one thermistor to another and manual transcription of the temperature displayed on the digital thermometer. Sampling was done at 15-s intervals while running at a constant speed between the buoys in the grid system. Since the digital thermometer required 115 V ac, it was powered from an inverter connected to two standard 12-V dc automobile batteries. During a typical survey, approximately 200 sampling locations were sampled (five temperatures at each location).

Fig. 29. Small, Open Cabin Survey Boat

This data was reduced by hand and used to produce five maps of the thermal plume at the surface and at the 0.3, 0.9, 1.8, and 2.7-m levels.

6.3.2 Mark II

To eliminate some of the obvious problems involved in taking data by hand, a second generation DAS was developed in 1971. This system used a Digitec Digital Main Frame Model 251A with Thermistor Plug-In Module Model 551-2 (Appendix A) to sample Yellow Springs Instrument type 709, three-lead, linearized thermistors. A new thermistor bar was constructed with positions for mounting the new thermistors located at 0.5-m intervals to a depth of 3 m. The digital thermometer was interfaced to an electronic timer that sequentially sampled seven thermistors, and the sampling interval could be selected by the operator (Fig. 30). At the time of sampling, the timer would step through the seven thermistors and the digital thermometer would display a temperature for each thermistor and present that number in binary coded decimal (BCD) format to an interface for an IBM Selectric Typewriter. The interface accepted the parallel BCD information in shift registers and then, via an *autofinger* attachment to the typewriter, printed elapsed time and the temperatures in sequence across the data page. One sequence of time and seven temperatures required approximately seven seconds to accumulate and type. Calibration of the sensors was performed at the beginning and end of each plume survey by immersing the bar in ambient water and comparing the readout with a mercury-in-glass standard thermometer. Boat positioning for this system and data reduction was the same as for the Mark I system.

6.3.3 Mark III and Mark IV

Three refinements in plume mapping occurred in the 1972 field year. The first was the addition of the Motorola Mini-Ranger to the acquisition system (Mark III). The second was the development of a completely new acquisition system. The third refinement was the development of a computer program to display the data.

The Motorola Mini-Ranger was interfaced with the Mark II acquisition system in mid-1972. Two range readings for each data point were added to the typewriter output.

During this period, a new data acquisition system, Mark IV, was designed by ANL's Electronics Division. The new system made possible the measurement of temperature as a function of depth from a moving boat at about 1500 known locations in about one hour, typically covering about eight linear kilometers as described in Sec. 2. The block diagram in Fig. 31 shows the essential components of the system (Fig. 11 is a photograph of the system). This system employed the same thermistor bar that was used with the Mark II system, digitizing and recording electronics, and positioning and depth-sounding instrumentation. A tape reader is part of the laboratory gear that transcribes the cassette tape onto a 7-track IBM compatible tape for computer processing (Fig. 32).

The third refinement in 1972 to the overall data gathering and handling

Fig. 30. Data Acquisition System, Mark II

Fig. 31. Block Diagram of Mark IV Data Acquisition System

Fig. 32. Cassette Reader and 7-Track Recorder

procedure was the development of a computer program to process and display the data. At the beginning of the field year, the data contained on the typewriter printout of the Mark II and III systems were keypunched manually onto IBM cards. After the completion of the new acquisition system, the plume data were transcribed from the magnetic-tape cassettes onto an IBM compatible tape. In either case, the plume data and additional calibration data were used in the computer program to produce seven horizontal plots with a Calcomp Digital Incremental Plotter. The isotherms and centerlines were drawn by hand on this output. Vertical cross sections of the plume were obtained by identifying, on the horizontal sections, the boat transects of interest. Index numbers associated with the data points were identified and used as input for another computer program, which plots the data in vertical sections. A more complete explanation of the data handling techniques may be found in References 2, 11, and 12.

A problem inherent with all data acquisition systems, like the ones described above, was the response time of the YSI type 709 thermistors. The thermistor response was slow enough (2.5 s) to cause a displacement in the temperature data that became apparent when crossing a temperature interface in one direction followed by a crossing of the same interface in the opposite direction. Faster response thermistors were desirable, and in 1973, Yellow Springs Instrument Company agreed to furnish their 700 series thermistor in a special mount that minimized thermal mass. This bead, although quite fragile, had a time constant of less than 0.6 s (typically 0.3 to 0.4 s). A new thermistor bar was constructed that would mount these thermistors on the bar's leading edge and had a better hydrodynamic shape (Sec. 4.2). The new thermistors had several failures that were traced to poor waterproofing of the leads supporting the bead. Each device was then coated with a thin layer of epoxy to eliminate the problem. Coating in this manner did eliminate the electrical leakage, but it also added to the thermal mass of the bead causing the time constant to increase to approximately 0.6 s.

The newest version of the acquisition system, Mark IV, is fully described in Sec. 4.5.

6.4 Current Meters

6.4.1 Survey Boat Measurements

During the first two years of the project, an Ekman-Merz current meter was used (Fig. 33) for current measurements from the survey boat. This ducted current meter has an eight-bladed impeller with a vane about 0.75-m long, which orients the impeller (Appendix A). The meter is actuated and deactuated by messenger weights on the supporting line. An average current speed is obtained from the total revolutions of the impeller over a known time. Direction is found by averaging the locations in which small metal pellets are found in the vane-oriented directional compartment. This meter required resetting after each measurement and suffered from occasional failure of the pellet distribution mechanism. For these reasons, in 1972, the Bendix Q-15 geomagnetic ducted meter with a Model S-232 deck readout unit was chosen as the meter to be used for current measurements from the survey boat.

Fig. 33. Ekman-Merz Current Meter

6.4.2 In-Situ Current Measurements

In-situ measurements of currents near power-plant discharges began in 1971. Three Braincon model 381 film-recording current meters were used from 1971 through 1973. The original units used Savonius rotors (Fig. 34) as the current sensing elements and, hence, were suitable only for deep-water application. Since they were used in the near-shore zone, the Savonius rotors were replaced by ducted impellers designed and built at ANL during the winter of 1971. The modified meters were used during 1972 and 1973 with satisfactory results. The *homemade* impellers (Fig. 35) were somewhat difficult to maintain due to fragile sapphire bearings and were replaced in 1973 when Endeco marketed ducted impeller units (Model 132) (Fig. 36) of similar design to those originally built at ANL (Appendix A).

The modified Braincon 381 meter produces images on 16-mm film corresponding to average current speed, current direction, and water temperature. Data reduction was done by hand and proved quite tedious. However, in 1972, reduction of these films was automated using ANL's image processing computer system. This device scans the image and converts the data to computer form for easy reduction. In 1973, development began on the in-situ Bendix Q-15R current meters described in Sec. 4.8.

6.5 Thermographs

In the early years of the program, Ryan model F-8 strip chart thermographs were used. These thermographs were wind-up devices with Bourdon tube sensors that produced a stylus deflection across a small strip chart proportional to temperature (Fig. 37). The wind-up clock allowed an 8-day, in-situ recording. These devices suffered from problems such as poor time base, poor resolution, and package leaks. Data reduction from the Ryans was done manually. For these reasons, the electronic thermographs (described in Sec. 4.9) were designed and built in 1974.

6.6 Meteorological Instruments

Meteorological information for periods of plume mapping were usually obtained from power plant personnel. These data were not always available due to equipment failure, etc., and a Weather Measure wind speed and direction indicator was used as a backup device. Wind speed was sensed by a 3-cup anemometer; direction by a 30-cm long vane (Fig. 38 and Appendix A). These measurements were made from the anchored boat as part of ambient environmental observations. In 1972, the Science Associate type 444 hand-held anemometer, mentioned in Sec. 4.13, replaced the Weather Measure device. The type 444 was much easier to use aboard the boat. Also during 1972, the Meteorological Research Incorporated (MRI) type 1071 described in Sec. 4.12 was purchased to be used for continuous monitoring of wind.

0 10 20 30 40 50 60
centimeters

1. The object is a dark, rectangular piece of equipment, possibly a book cover or a piece of equipment, with a metallic component visible on the left side.

Fig. 36. Endeco Ducted-Impeller Current Sensor

Fig. 37. Ryan Thermographs

Fig. 38. Weather Measure Meteorological Station

ACKNOWLEDGMENTS

The characterization of the behavior of thermal plants, steam power plant, for the evaluation of predictive models requires an integrated system for data acquisition, processing, and analysis. A high rate of data transfer for large amounts of data collected is important. Use of existing and present facilities or instruments and equipment is desirable for studies at several different sites. The systems described in this paper have evolved to meet the needs where these requirements have been satisfied for Advanced Studies on the Great Plains.

The thermopile measurement system developed here has been employed successfully at the Lawrence National Laboratory in the collection of thermopile data for temperatures ranging from approximately 100°K down to 4°K at different pressures. The system is capable of making scans in the x-y plane at about 1000 points per second, at each rate two channels of data, with an accuracy of 0.05 percent, are sampled simultaneously. Both the thermopile and the data amplifier have been fully tested to be rugged and easy to handle. In the experimentally established optimal system, of the great data collection, guaranteed the flexibility necessary for changing studies from pressure and temperature changes, where the temperature measurements can be replaced from the surface depth of up to 1000 microns and a position plotting system, is providing a real time plot of data plot, has enhanced the ability of the experiment even to direct the scan to regions where detection data collection is desirable. Adjustment of the experiment plans to meet variable field conditions, is also aided by the display of temperature and depth supplied by the data acquisition system. The current meter and thermopile are interfaced to the common recording package, have been shown to be suitable for about three years. Data returns from the experimental system have been at 90% or better.

3. The reliability of the system and the accuracy of the data collected depend both on the integrated design of the systems and the careful, periodic calibration procedures. In particular, the calibration in all temperature range of a permanent system using the same temperature standard and technique yields consistent sets of measurements of ambient-lake, plant discharge, and thermal-plume temperatures. The Argonne instruments and techniques have provided thermal-plume data of the quality required by its model evaluation efforts. A list of the publications and reports describing the data collected and the model evaluation effort at ANL using the equipment and techniques described in this report is contained in Appendix C. In addition, the data have been used extensively by others in independent investigations.

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APPENDIX A

INSTRUMENT SPECIFICATIONS

Specifications for most of the instruments discussed in the text of this report are listed in Table A.1. A discussion of each instrument is given below including details of calibrations leading to the accuracies listed in Table A.1 where applicable.

Bendix Q15 Current Meter and S232 Deck Readout

The specifications for this instrument are those of the manufacturer. The S232 deck readout has been modified by ANL to provide switch selected time constants of 2, 5, 10, 15, 25, and 30 seconds. The Q15 current meter is normally calibrated at a tow-tank facility at the same time as the Q15R in-situ current meters. The S232 deck readout is calibrated with a pulse generator (for speeds) and a potentiometer (for direction) per instructions detailed in the Operation Manual for the device.

Towed Thermistor Chain, Data Acquisition System

The TTC and DAS are calibrated for temperature as a system. Each thermistor probe is immersed in a well-stirred water bath whose temperature is monitored with the Stolab 911 PL/Data Precision 245 DVM platinum resistance temperature standard. Calibration is performed for temperatures in the range of 0-35°C, usually in approximately 3 degree intervals. The thermistor probes are allowed to equilibrate for about 1 min and then are monitored by the standard and recorded by the DAS on magnetic-tape cassette also for about 1 min at a 4-s sampling interval yielding about 14 values to be averaged for each calibration temperature. The system resolution is 0.01 C° and system noises and digitizing errors combine so that, after calibration, all temperatures fall within 0.1 C° of the temperature indicated by the standard.

The time constant of a thermistor is determined by introducing a step-function temperature change to the probe and monitoring the time required for the thermistor to reach 63% of the final temperature.

Motorola Mini-Ranger

The specifications listed for this instrument are those given by the manufacturer. It is typically calibrated against a known range of 1900 meters. This distance is similar to the usual ranges encountered at a survey site. The calibration correction is determined from an average of approximately 25 range readings. Following this calibration, any one range reading falls within the manufacturer's specification of ± 3 meters.

Data Marine Depth-Sounder

This digital reading depth sounder is permanently mounted on the survey

boat, ERDA I, with its transducer mounted in the hull about one foot below water level. It is electronically calibrated in the laboratory for the speed of sound in fresh water ignoring water temperature, draft of the survey boat, etc. Actual depth readings are checked periodically with a lead line in order to correct any depth reading that is recorded by the DAS during bathymetry surveys. All specifications listed in Table A1 are those of the manufacturer.

MRI Mechanical Meteorological Station

This instrument is returned periodically to the manufacturer for calibration. Table A.1 lists the manufacturer's specifications. It is checked at ANL periodically by comparison with wind speed, direction, and temperature recording instruments at ANL's meteorological tower. It has shown evidence of timing errors during field use where it is typically "spiked" daily. There seemingly is no explanation for these errors and they may be peculiar only to this particular instrument.

Bendix Q15R Current Meter and ANL Recording Package

The Bendix Q15R current meter is an inverted version of the Q15 mentioned earlier and has identical specifications. The current meters are calibrated once a year at a tow-tank facility. The ANL electronic recording package is used with the Q15R to record water speed, direction, and temperature on a magnetic-tape cassette. The thermistors used for temperature measurements are calibrated in a stirred-water bath and typically exhibit the specifications listed in Table A.1. The 0.3 C° accuracy figure is due to the worst case digitizing error which occurs at warmer temperatures (20-30°C).

ANL Thermographs

The ANL Thermograph uses a recording package and thermistors similar to those mentioned above. The temperature measurement accuracy is due to the same digitizing error at warmer temperatures.

Digitec 581C

There are three Digitec 581C digital thermometers available for use during field surveys. The thermistors used with these instruments are Yellow Springs Instrument (YSI) series 700, and therefore the Digitec can accept inputs from other ANL instruments using YSI 700 series thermistors. The specifications listed in Table A1 reflect total errors as given for Digitec 581C digital thermometers by the manufacturer and total errors associated with this instrument after calibration with the platinum resistance standard (Stolab 911PL and Data Precision DVM).

Stolab 911PL and Data Precision DVM

This combination of instruments is used as the temperature standard (laboratory and field) for all temperature measuring devices mentioned in this

report. The specifications in Table A.1 are derived by calibration of the Data Precision DVM against a voltage standard, and calibration of the Stolab 911PL temperature measuring electronics with a Stolab platinum resistance standard (Stocal PL100). The specification of ± 0.05 C° accuracy reflects the manufacturer's specification of maximum platinum resistance temperature probe error in the range of 0-100°C.

Turner Fluorometer, Model 111

The manufacturer does not list accuracy specifications for this instrument. It is calibrated daily with known standards when used.

Braincon Current Meter Type 381

All specifications listed in Table A.1 are those of the manufacturer. This device is calibrated (for speed only) at a tow-tank facility at the same time that the Q15R current meters are calibrated.

Digitec Model 8500-1 Digital Thermometer

The Digitec Model 8500-1 Digital Thermometer was used in an early DAS and the specifications in Table A.1 are the manufacturer's except for the accuracy shown as after calibration. This calibration was performed in a stirred-water bath using a mercury-in-glass thermometer as the standard.

Digitec Model 251A/551-2 Digital Thermometer

This digital thermometer was used in an early DAS and its specifications were determined in a manner similar to the Digitec 8500-1.

Ekman-Merz Current Meter

The specifications listed in Table A.1 are those determined from measurements made by the manufacturer.

Weather-Measure Cup Anemometer

This instrument was used for estimation of wind speed and direction from the survey boat early in the thermal-plume measurements program. The specifications are estimated.

Ryan Model F8 Thermograph

All specifications listed for this instrument were estimated from calibrations performed at ANL.

Raytheon Model DE719B Fathometer

The specifications listed in Table A.1 are those of the manufacturer. Verification of depth is routinely done with a lead line.

TABLE A.1. Instrument Specifications

Instrument	Sensor	Accuracy	Threshold	Range	Resolution	Time Constant	Remarks
Bendix Q-15 Current Meter and S 232 Readout	Speed; Impeller Direction; Vane	$\pm 3\%$ of full scale $\pm 12^\circ$	0.04 knot -	0-1.0 knot/ 0-5.0 knot 0-360°	0.02 knot/ 0.1 knot 5°	2-30 s; selectable	Low/high range Vane has adjustable length; 0.3-3.0 m.
Towed Therm Chain and Data Acq System	Thermistor	$\pm 0.1^\circ\text{C}$	-	0-50°C	0.01 °C	0.2 s	Thermistor YSI 44018 specially made with 0.2 s time constant.
Motorola Mini-Ranger	-	$\pm 3\text{ m}$	-	0.1-35 km	1 m	-	Accuracy applied to each range mea- surement. System accuracy varies with position of transponders rela- tive to boat. For most measurements, $\pm 3\text{ m}$ applies.
Data-Marine Depth-Sounder	Model 2301 (Transom Mounted)	$\pm 1\text{ ft}$; low range $\pm 1\text{ fathom}$; high range	2 ft; low range 2 fathoms; high range	2-99 ft; low range 2-99 fathoms; high range	1 ft 1 fathom	-	
MRI Mechanical Meteorological Station	Speed; 3 Cup Anemometer Direction; Vane Temperature; Bi- metallic Coil Clock	$\pm 2\%$ $\pm 5^\circ$ 1.7°C $\pm 60\text{ s}/24\text{ hrs}$	0.35 m/s 0.35 m/s - -	0.35-45 m/s 0.35-45 m/s -35 to +50°C 32 days	0.9 m/s 5° 0.5 °C -	5.5 m (response distance) 2 m (response distance) unknown -	Clock specifications are open to question.
Bendix Q15K plus ANL Electronics	Speed; Impeller Direction; Vane Temp.; Thermistor	$\pm 3\%$ of full scale $\pm 12^\circ$ $\pm 0.3^\circ\text{C}$	2.0 cm/s - -	0-250 cm/s 0-360° 0-30°C	0.2 cm/s 0.3 °C	- 6 s	Tow tank calibrations typically show a threshold of 2.5-3.0 cm/s.
ANL Thermograph	Thermistor	$\pm 0.3^\circ\text{C}$	-	0-30°C	0.3 °C	6 s	Four thermistor sensors - YSI 44012 $\pm 0.3^\circ\text{C}$ specification is due to dig- itizing error at warmer temperatures.
Digitec 581C	Thermistor	$\pm 0.45^\circ\text{C}^{\text{a}}$ $\pm 0.15^\circ\text{C}^{\text{b}}$	-	-30 to +100°C	0.1 °C	0.6 s	This instrument when used in the field is calibrated at each use against the platinum standard. Accuracy should be $\pm 0.15^\circ\text{C}$.
Stolab 911 PL	Platinum Resistor	$\pm 0.05^\circ\text{C}$	-	0-100°C	0.01 °C	1 s	Calibrations of these devices are done on a voltage standard and a platinum resistance standard.
Data Precision DVM	-	$\pm 100\text{ }\mu\text{V}$	-	0-1.0 V	100 μV	-	
Turner Fluorometer Model 111	-	-	-	0-100 arbi- trary units	.25 unit	-	Comparison type instrument must be calibrated with known standards. Sensitivity changed by neutral density filters in the light path.

TABLE A.1. Instrument Specifications (Contd.)

Instrument	Sensor	Accuracy	Threshold	Range	Resolution	Time Constant	Remarks
Braincon Current Meter Type 381	Speed; ducted impeller	$\pm 3\%$ fs	.04 kts	0-5 kts	.01 unit	-	
	Direction; magnetic compass	$\pm 1\%$	-	0-360°	2°	-	
	Savonius Rotor	± 0.07 m/s	-	.06-2.6 m/s	0.005 m/s	-	
Ryan Model F8 Thermograph	-	± 2.0 C°	-	0-30°C	± 1.0 C°	-	Values estimated.
	Chart Advance	$\pm 4\%$	-	-	-	-	Values estimated.
Digitec Model 8500-1 Digital Thermometer	YSI No. 409 Thermistor	± 0.25 C° ^a	-	0-100°C	0.02 C°	-	YSI No. 409 thermistors have a 2.2-sec time constant in well-stirred water.
		± 0.1 C° ^b					
Digitec Model 251A/551-2 Digital Thermometer	YSI No. 709 Thermistor	± 0.3 C° ^a	-	(-30.0) -(+100.0)°C	0.01 C°	-	YSI No. 709 thermistors have a 2.2-sec time constant in well-stirred water.
		± 0.1 C° ^b					
Ekman-Menz Current Meter	Impeller	± 0.05 m/s	-	0.05-2.0 m/s	-	-	
	Direction Vane	$\pm 15^\circ$	-	0-360°	-	-	Directional accuracy estimated.
Weather-Measure Cup Anemometer	Cup Anemometer	± 2 mph	-	0-100 mph	1 mph	-	Values estimated.
	Direction Vane	$\pm 15^\circ$	-	0-360°	15°	-	Values estimated.
Raytheon DE719B Fathometer	Transducer	$\pm 0.5\%$	-	0-205 ft	± 1 ft	-	
	Model 200T5HAD			(4 ranges)			

Conversion factors:

1 knot = 0.514 m/sec; 1 ft = 0.305 m; 1 fathom = 1.829 m

^a Before calibration^b After calibration

APPENDIX B

ANALYSIS OF THE TOWING PROPERTIES OF
THE TOWED THERMISTOR CHAINB.1 Calibration Procedure

In order to use the towed thermistor chain (TTC) to map the temperature field of a thermal plume, it is necessary to determine the depth of each thermistor breakout as a function of length of chain deployed and towing speed. As the chain is towed through the water, the shape of the chain is determined by the dynamic properties of the V-fin and the drag forces acting on the faired chain. A mathematical analysis of the forces acting on the towed chain was carried out to determine its shape and thus the depths of the thermistor breakouts. Figure B.1 is a schematic diagram of the TTC and the coordinate system used in the mathematical analysis. The coordinate system has its origin at the V-fin and moves with the chain through the water. Several parameters used in the analysis are indicated on the figure and are defined as follows:

- V = towing speed,
- s_o = length of chain in water,
- b_o = horizontal distance between surface point and bottom of chain,
- h_o = depth of bottom of chain,
- T_o = tension in chain at lower end,
- α_o = angle of chain at lower end,
- T_s = tension in chain at surface of water,

and

- α_s = angle of chain at surface of water.

The quantities V and s_o are considered to be the independent variables specified by the experimenter. They correspond to the boat speed and the amount of chain payed out (in the water). The quantities T_o and α_o are properties of the V-fin and are functions of V only. Values for T_o were obtained from the manufacturer of the V-fin (ENDECO) and values for α_o were obtained from results of calibration tests performed by CCIW (Sec. B.2). If the precise details of the drag forces on the chain were known as a function

Fig. B.1. Schematic Diagram of Towed-Thermistor-Chain Variables and Coordinate System Used in Analysis

of V and s_o , the shape of the chain could be calculated. Because they are not known, it is necessary to express the drag forces in terms of assumed functional forms and two unspecified drag coefficients. Numerical values for these coefficients, assumed to be functions of V and s_o , must then be determined by fitting the results of the theoretical analysis to field calibration data.

To evaluate the two drag coefficients, two additional parameters need to be determined by means of field tests. A sensitivity study of the mathematical analysis indicated that, of the parameters that could be easily measured in the field, the two drag coefficients are most sensitive to h_o and T_s . A series of field calibration tests were carried out to determine h_o and T_s as a function of V and s_o . A total of 24 runs were made at four different towing speeds (V) and with six different lengths of chain in the water (s_o). During these runs, a pressure transducer, housed in a body that minimizes the influence of dynamic pressure, was attached to the bottom breakout of the chain just above the V-fin. The signal from the pressure transducer indicated the depth of the bottom of the chain (h_o). The tension in the chain at the surface (T_s) was measured with a spring balance attached to the strain member. In addition, the angle the chain made with the vertical (α_s) was determined with a scale attached to the gunwale of the boat. The results of these calibration measurements are plotted in Figs. B.2 and B.3 as a function of $s_o - h_o$ for various values of V . To expand the vertical scale, the quantity $s_o - h_o$ is plotted instead of h_o . Estimated experimental error limits on the measured values of h_o and T_s are indicated. These limits correspond to ± 0.1 m for h_o and $\pm 10\%$ for T_s .

Smooth curves were fit to the depth and tension data to obtain h_o and T_s as continuous, smoothly varying functions of V and s_o (see Sec. B.2 for details). These curves are indicated on Figs. B.2 and B.3. The two drag coefficients were then determined (as a function of V and s_o) by fitting the results of the theoretical analysis to these curves. The resulting predictions for α_s are plotted in Fig. B.4 along with the measured values. This comparison should be considered as a check as to whether the mathematical description of the chain is reasonable. It is clear that the trends are predicted; the measured values deviate from the predictions by 5° at most.

Figure B.5 shows a sample prediction of chain shape, with the break-out positions indicated, for a fixed amount of chain in the water at various

Fig. B.2. Measured and Smoothed Fin-Depth Data

Fig. B.3. Measured and Smoothed Tension Data at the Water Surface

Fig. B.4. Measured and Predicted Angle of Chain at the Water Surface

Fig. B.5. Predicted Chain Shape at Various Towing Speeds for a Fixed Amount of Chain in the Water

boat speeds. Results such as these can be used to determine the depths of the thermistors during a plume survey.

To demonstrate the necessity of this detailed analysis of the shape of the chain, Fig. B.6 shows the maximum error in the depth of a breakout, $\Delta z_{\max}$, that would result if it were assumed that the chain were a straight line between the surface and the appropriate depth h_0 . This maximum deviation between a curved configuration versus a linear one becomes significant at higher speeds and longer chain lengths. With 12 m of chain in the water and a speed of 4 m/s (7.8 knots), the deviation corresponds to 0.5 m. Some plume-mapping investigators who are using towed thermistor chains assume a linear chain shape, and, for many speeds and chain lengths, this assumption will lead to incorrect thermistor depths and the specification of erroneous plume-temperature contours. The current ANL prototype/model comparison studies require very precise temperature contours for submerged-diffuser plumes.

B.2 Mathematical Analysis

An analysis of the forces on a chain towed through a fluid can be used to develop a set of ordinary differential equations that describe the resulting shape of the chain. Consider a small segment of chain of length ds as depicted in Fig. B.7. The fluid can be considered to be moving past the chain at a constant speed V in the direction of the negative x axis. Let T be the tension in the segment at one end and α be the angle the chain makes with the z axis. The tension and angle will both, in general, vary with s , the distance along the chain. Let W be the weight (in the fluid) per unit length of chain, P be the drag force per unit length normal to the chain, and Q be the drag force per unit length tangential to the chain. The chain segment is undergoing uniform motion with respect to the fluid; therefore, the net external force on the segment must be zero. Resolving the forces on the segment into components normal and tangential to the segment and setting the net force in each of these directions equal to zero, yields the following equations:

$$Pds - W \sin \alpha \, ds - (T+dT) \sin(d\alpha) = 0,$$

and

$$Qds + W \cos \alpha \, ds + T - (T+dT) \cos(d\alpha) = 0.$$

Fig. B.6. Maximum Error Resulting from the Assumption That the Chain Is Linear

Fig. B.7. Forces on Infinitesimal Chain Segment

These equations are only valid in the limit as ds approaches zero so that P and Q may be considered constant over the segment. Using series expansion for the trigonometric functions of $d\alpha$, neglecting terms of second order or greater in infinitesimal quantities, dividing by ds , and letting ds approach zero, the equations become

$$\frac{d\alpha}{ds} = \frac{P - W \sin \alpha}{T},$$

and

$$\frac{dT}{ds} = Q + W \cos \alpha.$$

It is convenient to write the drag forces per unit length in the following forms.

$$P = R g(\alpha),$$

$$Q = R f(\alpha),$$

and

$$R = (1/2)\rho C_D d V^2,$$

where:

$g(\alpha)$ and $f(\alpha)$ = functions yet to be determined,

R = the drag force per unit length when the chain is perpendicular to the flow ($\alpha=0$),

ρ = density of the fluid,

C_D = nondimensional drag coefficient, and

d = width of the leading edge of the chain.

Tests reported by Day and Michailidis¹³ indicate that the general functional forms of $g(\alpha)$ and $f(\alpha)$ are essentially the same for a variety of fairings and various towing speeds. For the purposes of this analysis, these functions have been approximated by

$$g(\alpha) = \cos^2 \alpha$$

and

$$f(\alpha) = f_0 \sin(2\alpha); \quad 0 \leq \alpha \leq \pi/4,$$

$$= f_0 (1/2 + 4\alpha/\pi - 8\alpha^2/\pi^2); \quad \pi/2 \geq \alpha \geq \pi/4,$$

where:

f_o = nondimensional tangential loading coefficient.

The coefficients C_D and f_o are the two drag coefficients referred to in Sec. B.1, which must eventually be determined by fitting to data.

The differential equations for dT/ds and $d\alpha/ds$, along with the equations of geometry,

$$\frac{dx}{ds} = \sin \alpha$$

and

$$\frac{dz}{ds} = \cos \alpha ,$$

can be integrated (numerically on a computer) to yield T , α , x , and z as functions of s . The values of these four quantities must first be specified at some initial points. If s is chosen to be zero at the bottom of the chain (at the V-fin), then initially $T = T_o$, $\alpha = \alpha_o$, $x = 0$, and $z = 0$. As discussed in Sec. B.1, T_o and α_o are properties of the V-fin and depend only on the towing speed V . Performance specifications, supplied by the manufacturer of the fin, contain performance curves of tension versus towing speed. In the range of speeds of interest in this work, the curve can be approximated by

$$T_o = c_1 + c_2 V = c_3 V^2$$

where

$$c_1 = 75.6 \text{ N} ,$$

$$c_2 = 52.8 \text{ N s/m} ,$$

and

$$c_3 = 17.17 \text{ N s}^2/\text{m}^2 .$$

Calibration tests with similar V-fins at CCIW⁷ indicate that the angle at the fin may be approximated by

$$\alpha_o = c_4 \left(1 - e^{-c_5 V} \right)$$

where

$$c_4 = 0.17 \text{ radians}$$

and

$$c_5 = 0.88 \text{ s/m.}$$

The integration is carried out from $s = 0$ at the fin to $s = s_0$ at the water surface. At this point, $T = T_s$, $\alpha = \alpha_s$, $x = b_0$, and $z = h_0$. The values of C_D and f_0 are adjusted by an iterative search procedure so that h_0 and T_s match the smooth curves fit to the experimentally measured values of cable tension at the surface and V-fin depth.

The experimentally measured values of h_0 and T_s were discussed in Sec. B.1 and appear on Figs. B.1 and B.2. The smooth curves fitted to the data and plotted on these figures are specified mathematically by the formulas given below. The depth of the fin is given by

$$h_0 = s_0 \left(1 + c_6 V s_0 + c_7 V^2 s_0 \right)$$

where

$$c_6 = -0.00586 \text{ s/m}^2$$

and

$$c_7 = 0.000544 \text{ s}^2/\text{m}^3.$$

The tension in the chain at the surface is given by

$$T_s = T_\infty - (T_\infty - T_0) e^{-c_8 s_0}$$

where

$$c_8 = 0.42 / \text{m}$$

$$T_0 = \text{Tension at the V-fin,}$$

and

T_∞ is obtained by linear interpolation of the values listed in Table B.1.

The quantities T_0 and T_∞ are both functions of V . The tension in the chain at the surface for large values of s_0 is represented by T_∞ . The values obtained for C_D and f_0 by fitting the results of the mathematical analysis to these expressions for h_0 and T_s are plotted in Figs. B.8 and B.9 as functions of s_0 for various values of V .

Fig. B.8. Drag Coefficient, C_D , Obtained by Fitting the Mathematical Analysis to the Smoothed Calibration Data

Fig. B.9. Tangential Loading Coefficient, f_0 , Obtained by Fitting the Mathematical Analysis to the Smoothed Calibration Data

At this point, a sensitivity analysis was carried out to determine how the precise choice of C_D and f_o affects the predicted shape of the chain. It was found that, as long as h_o is correctly predicted, the shape is independent of the choice of C_D and f_o , provided reasonable values are chosen.

Table B.1. Cable-Tension Parameters

V (m/s)	T_∞ (N)
0	144
1.03	229
1.93	344
2.70	490
3.34	726

APPENDIX C

ANL PUBLICATIONS RELATED TO THERMAL PLUME STUDIES
LISTED CHRONOLOGICALLY

1. Asbury, J.G., *Effects of Thermal Discharges on the Mass/Energy Balance of Lake Michigan*, Argonne National Laboratory Report ANL/ES-1 (July 1970).
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