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WATER RESOURCES RESEARCH PROGRAM

TRANSPORT AND DISPERSION OF OIL-REFINERY WASTES
IN THE COASTAL WATERS OF SOUTHWESTERN LAKE MICHIGAN
(EXPERIMENTAL DESIGN--SINKING-PLUME CONDITION)

by

D. L. McCown, W. Harrison,
and W. Orvosh

GREAT LAKES PROJECT

ARGONNE NATIONAL LABORATORY

ENERGY AND ENVIRONMENTAL SYSTEMS DIVISION

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Great Lakes Project

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FOREWORD

The U.S. Energy Research and Development Administration (ERDA) was formed in January, 1975. Shortly thereafter, certain energy-related research programs being conducted by the U.S. Environmental Protection Agency (EPA) were transferred to the ERDA's jurisdiction. Funding for the programs was also transferred ("passed through") from EPA to ERDA, giving rise to the designation of such research programs as "pass-through" programs.

One of the EPA-to-ERDA pass-through programs was entitled "Offshore Oil Extraction and Related Problems." A task within this program was entitled "Transport and dispersion of refinery wastes in freshwater coastal regions." This research task fell for execution to Argonne's Energy and Environmental Systems Division (EES). The task was further assigned to the Great Lakes Project, in the EESD's Water Resources Research Program.

The present report is the first of a series that will be devoted to the transport and dispersion of oily wastes discharged into the coastal waters of southwestern Lake Michigan by flow from the Indiana Harbor Canal (IHC). The IHC discharge forms a thermal plume in the lake because the canal receives copious volumes of steel-mill processing water. Two modes of discharge of canal water into Lake Michigan will be treated over the planned five-year study period:

1. The surface-plume mode (operative between about mid-March through mid-December), and
2. The sinking-plume mode (operative from about mid-December through mid-March).

Initial reports in this series will treat methods for tagging and tracing oil-refinery wastes and associated receiving waters of the IHC. Later reports will treat modeling of the dynamics of oily-pollutant transport and dispersion.

Technical monitoring of this research task is being conducted jointly by EPA and ERDA under EPA Interagency Agreement Number D6-E681.

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ABSTRACT

The field phase of the experimental design was implemented on February 14-16, 1976, and consisted of (1) tagging 170 ℓ of simulated refinery waste with 1.4 kg of a 50-percent acid solution of dysprosium acetate and spreading the tagged waste on the water surface at the entrance to the Indiana Harbor Canal (IHC), (2) tagging 3600 m³ of water at the IHC mouth with 13.6 kg of samarium complexed with DTPA, (3) sampling the surface and subsurface waters of the lake downflow for 10 km using three boats with submersible pumping systems, and (4) sampling raw-water from the shore and Dunne Crib intakes at Chicago's South Water Filtration Plant (SWFP). The laboratory portion of the experimental design involved neutron activation analysis of the samples after evaporation of the water phase. Reactors and low-energy, photon spectrometers at Argonne and Ames, Iowa were used for sample irradiation and counting.

Results indicate that the methodology, with appropriate changes, can be used successfully to study the transport and dispersion of simulated refinery waste injected into the IHC's sinking plume. Deficiencies in the original experimental design are discussed, and recommendations are given for their remedy. More-frequent sampling at the SWFP, and the use of an underway water-sampling system that will permit sampling coverage farther offshore, are the principal improvements required for the 1976/1977, full-scale, sinking-plume study.

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I. INTRODUCTION

A. Purpose and Scope of Study

There is at present an inadequate understanding of the processes of transport and dispersion of oil-refinery wastes in coastal waters. It is the purpose of the present program

1. To develop methods for tagging and tracing refinery wastes discharged to fresh coastal waters,
2. To apply these methods to specific, contaminated coastal waters, and
3. To develop and verify a numerical model that will permit prediction of the transport and dispersion of such oily wastes.

Initially, the studies by Argonne National Laboratory (ANL) will be devoted to a series of experiments conducted on refinery wastes that move into the coastal waters of southwestern Lake Michigan from the Indiana Harbor Canal (Fig. 1). The canal water moves into the lake as a thermal plume, sinking during much of the time in winter, and forming a surface plume during the remainder of the year. Significant differences in the oil-transport regime are expected during surface and sinking-plume conditions. The most difficult transport/dispersion regime for analysis is that of the sinking plume, because it is difficult to follow and sample a tagged mass of canal water that forms only a thin layer (commonly 1- to 5-m thick) as it spreads over the bottom. Nevertheless, the importance of sinking-plume transport in carrying contaminants from the Indiana Harbor Canal (IHC) to municipal water intakes in southwestern Lake Michigan dictates devoting significant efforts and resources to the tagging and tracing of IHC water in winter. This first report of a continuing series, therefore, is concerned with the design and implementation of a tagging and tracer technique, applied over a limited period of time (1 day) to the sinking plume emanating from the IHC.

B. Approach

It is important to distinguish between the dynamics of waste-receiving waters and the motions of the associated oily wastes within and upon these waters. Adequate understanding of these separate but complementary motions is essential for the development of predictive models.

Fig. 1. Location map for study area in southwestern Lake Michigan.

Accordingly, it was necessary to develop a method for the simultaneous tagging and tracing of oil and water, by means of which concentrations of tags as low as 10^{-10} g/sample could be determined.

Traditionally, there have been two classes of substances that have been used to tag water or pollutants for tracing: fluorescent dyes and radionuclides. Fluorescent dyes have several drawbacks. Some fluorescent dyes bleach in the sunlight. Others that do not bleach may become adsorbed onto suspended particles, which then settle out of the water column. A further drawback is that all of the fluorescent dyes emit radiation of approximately the same wavelength and distinguishing between different dyes is seldom feasible. Radionuclides have several advantages for water and contaminant tracing, but they have a significantly high radiation hazard for all but very short-term studies.

The approach to tracing used in the present study is based on earlier work by McCown involving the use of stable-element tags and neutron-activation analysis (NAA). Among the advantages of this method are the following:

1. there is no radiation hazard to the environment,
2. detection is possible to at least one nanogram per liter of rare-earth concentration in the tagged water or oil,
3. it is possible to use multiple tracers and to distinguish between them,
4. there is negligible tracer loss to suspended matter and sediments, and
5. the stable-element tags themselves can be chosen to be nontoxic to the environment.

Certain rare-earth elements (REEs), such as dysprosium, samarium, lanthanum, europium, and ytterbium suggested themselves as likely candidates for tags. The availability of a high-flux reactor and of superior radiation-counting equipment at Argonne, and the existence of precision boat-positioning equipment within the Great Lakes Research Project at ANL, made it possible to design a relatively sophisticated experiment for studying the transport and dispersion of oil-refinery waste in a sinking-plume situation.

C. Area of Investigation

A comprehensive background report (Snow, 1974) was prepared by the Illinois Institute of Technology Research Institute (IITRI) on the water pollution situation in southwestern Lake Michigan as it relates to effluents from the Indiana Harbor Canal. The Great Lakes Project in Argonne's Energy and Environmental Systems Division assisted IITRI in field and analytical studies of the dispersion of effluents from the IHC. Snow (1974, v. 1, p. 129) listed the following mechanisms of transport and dispersion from the canal into the lake:

1. Turbulent vertical mixing of IHC water in the canal with intruding lake water (flowing inward along the bottom in summer and inward along the surface in winter),
2. Initial jet flow near the canal mouth,
3. Gravity spreading of canal water moving into the lake,
4. Vertical mixing of the plume due to turbulent eddies in the lake,
5. Plume transport by ambient lake currents,
6. Mixing of plume margins by turbulent eddies in the lake (important only over a distance of two miles or more), and
7. Shearing and dispersion of the plume by lake currents.

Lake currents in winter are occasionally to the north just off the IHC. There is some evidence (P. A. Reed, 1975, written communication) that if conditions are right for development of a sinking plume, plume-borne pollutants may be transported as far north as the City of Chicago's Central Water Filtration Plant (CWFP), which draws its water from the Dever crib (located 3.2 km NE of CWFP). According to P. A. Reed, plume water is commonly transported as far as the intake crib for Chicago's South Water Filtration Plant (SWFP) during winter months. During January, 1975, for instance, the SWFP experienced a period of hydrocarbon odors in its raw water that lasted two weeks. The severity of the odors was greater in the SWFP's raw water from its shore supply than in the raw water from its crib (Fig. 1). The odors were accompanied by elevated concentrations of ammonia-nitrogen, and there can be little doubt that a significant percentage of these

hydrocarbon odors originated from waters of the IHC. According to permit data (Snow, 1974, v. 1, p. 200), for example, the ARCO refinery, Inland Steel, Youngstown Sheet and Tube (Fig. 2), and others contribute up to 22,680 kg/day (50,000 lb/day) of oil and grease to the IHC. If the lake temperature is appropriate ($\approx 2^{\circ}\text{C}$), strong development of a pronounced sinking plume occurs when

- a) there is significant rainfall in the area (0.64 cm [0.25 in] of rain in a day will cause some combined sewers that enter the IHC to overflow), and
- b) there are brisk winds from southerly quadrants.

D. Previous Work

Although the environmental fate of crude oil has been studied (cf. Harrison, 1974), the authors have been unable to find any literature treating the transport and dispersion of oil-refinery wastes in fresh coastal waters. Nor have any publications been found that discuss tagging or tracing of petroleum (refined or unrefined), or of coastal waters, using REEs and NAA. A Ph.D. thesis (Channell, 1971) was found on the tagging and tracing of estuarine waters, however, using REEs and NAA.

Published information on coastal currents in the vicinity of Chicago is scanty. Monahan and Pilgrim (1975) made a Savonius-rotor, current-meter study, summarized previous research, and concluded that currents off Chicago are typically weak (< 0.6 knots).

LAKE MICHIGAN

Fig. 2. Indiana Harbor Canal and Associated Major Industries.

II. EXPERIMENTAL DESIGN

A. Analytical Procedures

It was necessary to develop an analytical procedure that would permit rapid activation and counting of a large number of samples. Elements with short half-lives were chosen. It was expected that the short reactor irradiations necessary for high detectability of the REEs selected would not result in overriding interference from naturally occurring elements such as sodium. Also desired was elimination of all sample preparation other than drying. Availability of a high-resolution gamma detector, with an excellent peak-to-background ratio in the low-energy (≈ 0.1 MeV) part of the spectrum, made this possible.

B. Tagging Agents

Dysprosium (Dy) was selected as one of the tags because of its very high, thermal-neutron-capture cross section and its short half-life (see Table I). Samarium (Sm) was selected as the other tag because it too has a relatively short half-life, and the energy of its major gamma is close enough to dysprosium's major gamma to permit simultaneous detection and quantification of both tags. Unfortunately, the thermal-neutron-capture cross section of Sm is considerably lower than that of Dy so that Sm is approximately two orders of magnitude less detectable than Dy.

C. Tagging Procedures

A tagging procedure which would insure minimal loss of a tagging agent from the refinery waste had to be developed. Investigation of the loss was made in a series of bench tests in which tagged oil was spread on samples of lake water in beakers. The water was sampled periodically over a several-day period to determine the amount of REE moving from the oil to the water.

Waters of the IHC are turbid and highly polluted. Introduction of an REE tag into the IHC water column in the ionic form would hazard removal of the REE from solution by any of several mechanisms. Two examples are:

TABLE I. Neutron Activation Characteristics of Dysprosium and Samarium (from Lederer, 1967)

Reaction	$^{164}\text{Dy} (n,\gamma) ^{165m}\text{Dy}$	$^{154}\text{Sm} (n,\gamma) ^{155}\text{Sm}$	$^{152}\text{Sm} (n,\gamma) ^{153}\text{Sm}$
Half-life ($T_{1/2}$)	75 sec	22.5 min	47 hr
Thermal neutron-capture cross section (σ)	2000 barns ^a	5 barns	210 barns
Isotopic abundance	28%	23%	27%
Major gamma energy ^b	0.1082 MeV	0.1043 MeV	0.1032 MeV
Approximate sensitivity as determined by experiment	$5 \times 10^{-10} \text{ g}^c$	$5 \times 10^{-8} \text{ g}^c$	$5 \times 10^{-9} \text{ g}^d$

^abarn = 10^{-24} cm^2

^bFrom Bowman, 1974

^cIrradiation time - 180 s, delay to count - 30 s, count - 180 s (live time).

^dIrradiation time - 1 hr, delay to count - ≈ 5 days, count - 1 hr.

- 1) the formation of insoluble compounds by reaction with some of the many species in solution in the IHC or on the bottom of the canal, and
- 2) removal from solution by adsorption on suspended solids.

Channel (1971) shows that the persistence of lanthanum in waters that are in contact with bottom sediment is almost doubled for lanthanum complexed with EDTA¹ than for lanthanum dissolved in acid. Channel suggests that chelation would be advantageous for an injection into an area where suspended solids were flocculating or where the water depth would allow significant contact of the tagged water mass with bottom sediments. IHC waters contain an abundance of suspended solids and, in a sinking plume, this water remains in contact with bottom sediments. Chelation of REE tags, by complexing with DTPA was, therefore, considered necessary.

D. Sampling Procedures

Documentation of transport and dispersion in a sinking plume requires a large number of data points. This requirement dictates extraction of water samples from several depths and at many locations in the lake. In addition, it is of great importance to know to a high degree of accuracy the position of the sampling boat. Clearly, electronic boat-positioning equipment as well as several boats would be required to cover the area of interest in a reasonable time frame.

It was decided to sample at least five depths in the lake. This task required a weighted hose that could be raised and lowered to specific levels and a pump system for delivering water above-deck in a continuous stream.

A minor objective of this study was to determine whether IHC water entered the water-intake system at the City of Chicago's South Water Filtration Plant (SWFP). City chemists at the SWFP were requested to draw raw-water samples from the Dunn crib (Fig. 1) and their shore intakes so that it could be determined whether the REE tags had, in fact, entered the plant.

¹EDTA is Ethylenediaminetetraacetic acid

E. Weather Controls on Execution of Field Work

Tagging and subsequent overwater sampling of the sinking plume requires fairly specific weather conditions, as follows:

- 1) air temperature above 0°C to prevent icing on the survey boats, and
- 2) brisk southerly winds, to force water out of the IHC and cause the sinking plume to move to the north along shore and into the area of the pre-determined sampling grid and the SWFP's water intakes.

Additionally, if more than 0.25 in. (0.63 cm) of rainfall occurs during a 24-hr period, the combined sewers discharge into the Grand Calumet River overflow producing a hydraulic head that strengthens sinking-plume development.

F. Ancillary Environmental Data

Continuous data of the following types are required during a sinking-plume study:

1. Current speed and direction for bottom currents in the path of flow,
2. Water temperature just above the lake floor in the path of flow, and
3. Overwater wind speed and direction.

III. IMPLEMENTATION OF DESIGN REQUIREMENTS

A. Tagging Procedures

1. Oil-refinery waste

The bench tests mentioned above required obtaining a sample of typical refinery waste. Because access to the ARCO refinery (Fig. 2) could not be obtained, a sample of refinery waste was simulated by mixing equal parts of motor oil (30W), diesel fuel (#2), and engine drain oil. Initially, a 200-cm³ sample of this waste was tagged with a given REE and placed, as a floating slick, upon a 2-l volume of Lake Michigan water. A later series of bench tests varied the amount of tagged oil on the surface from 100 to 10 to 1 ml. Samples were taken of the oil and water prior to the tagging and at regular daily intervals thereafter for a period of about 5 days. The oil/water phases were subjected to various degrees of agitation during this period, including mixing with an electric mixer to examine the effect of turbulence on the samples. In addition, the acidity, chemical nature, and concentration of the tagging solutions were varied to determine their effect upon the loss-rate of tagging element. After the samples had been irradiated in the normal manner (see Sec. III.C.2), it was found that in all but one case less than 1% of the tagging element had passed into the water and, in some instances, less than 0.001%. Figures 3 and 4 are plots of the percent of an REE transferred from the oil to the water as a function of time for various concentrations, amounts of tagged oil, acidities, and compounds. Figure 4 is a more realistic appraisal of an oil slick under environmental conditions, because the thickness of the oil on the water surface is more indicative of the very thin surface-film conditions of a true oil slick than is the thick (≈ 2 cm) film (Fig. 3) used in the initial bench tests. Sampling of the water in the beakers of Fig. 4 was subject to less contamination by the surface oil film (an automatic pipette was passed through the oil film to draw samples) because the films were thinner and in one case, the 1 ml beaker, the oil film did not cover the water surface completely. It should be noted that the element detected in the water could have been carried into the water in small amounts of dissolved oil, rather than actually passing out of the oil solution.

Fig. 3. Percent of Rare Earth Elements Transferred from Oil to Water Phase as a Function of Time.

Fig. 4. Percent of Rare Earth Elements in Oil Transferred into Water as a Function of Time and the Amount of Oil.

Dysprosium acetate, in 50% acetic-acid solution, was chosen for tagging the simulated oil-refinery waste, because this formulation has a small tendency to transfer from the oily waste into the water (Figs. 3 and 4) and Dy is detectable at concentrations approximately two orders of magnitude less than that at which Sm is detected.

The final volume of tagged oil-refinery waste was prepared by combining 1.36 kg (3 lb) of the 50% acetic-acid solution of dysprosium acetate with 170.4 l (45 gal) of the synthetic refinery waste described above. Mixing prior to injection was accomplished by bubbling air through the solution for several hours.

2. Canal water

IHC water was tagged in situ with 13.6 kg (30 lb) of samarium. The samarium had been complexed with DTPA¹ prior to seeding. As previously mentioned, it was necessary to complex the samarium with a strong chelating agent (DTPA) to insure persistence in the water column.

The samarium/DTPA tag was dispersed in IHC water by pumping it through a pipe with small holes drilled along one side. The pipe was lowered over the rail of the boat and the samarium solution was pumped into the pipe and dispersed at various depths between the surface and -1.0 m through the holes in the pipe. During the 21-minute dispersion process ANL's boat, the ERDA 1, ran back-and-forth across the canal mouth six times. Each transect of the mouth was approximately ninety meters long and perpendicular to the lakeward flow of canal water. The flow speed at the entrance, 0.04 m/s, was calculated from current-meter measurements taken at the narrowest point in the canal upstream of the entrance, at the Elgin, Joliet, and Eastern (EJ&E) railroad bridge (Fig. 2). In this manner, a volume of IHC plume water approximately 90 by 40 by 1 m deep was seeded with a reasonably homogenous concentration of samarium ($C_I \approx 3.8 \times 10^{-3}$ g/l).

The transects for dispersing the tags were run at the lake entrance of the IHC (at the horn, Fig. 2). On February 14, 1975, the line of transects was approximately 100 m upflow from the point where the canal water was sinking. The zone of convergence of canal and lake water was easily

¹DTPA is Diethylenetriamine-pentaacetic acid

recognized. As the ERDA 1 proceeded lakeward, the surface water temperature dropped from 7.5° to 1.8°C within a few meters. Canalward of the sinking zone, the water temperature was vertically isothermal. Just lakeward of the sinking zone, however, the temperature profile showed warm ($\approx 4.0^{\circ}\text{C}$) water near the bottom, overlain by colder ($\approx 1.8^{\circ}\text{C}$) water.

B. Sample and Data Acquisition

1. General considerations

During planning of the sinking plume experiment, weather data from previous years were investigated to determine if a three-day experiment was feasible. The weather data indicated that a three-day period of southerly winds, with air temperatures above freezing, was a fairly regular occurrence. Some local meteorologists even refer to a "January thaw." The January thaw is credited with a protracted period of high hydrocarbon odors that occurred at the SWFP in January, 1975, as reported by P. A. Reed (1975, written communication). The winter of 1975-76 had no January thaw. In fact, this was a very unusual winter because temperatures were abnormally high through mid-December. Air temperatures then dropped very quickly to give the Chicago area its severest January in forty years. Air temperatures then rose very quickly in February, giving the area one of the warmest Februarys on record. In February the weather was controlled by a fast west-to-east flow in the upper atmosphere. This flow had the effect of speeding the passage of frontal systems through the area. These fast-moving frontal systems had two effects. First, the systems produced rapidly varying wind conditions, which, in turn, produced rapidly varying coastal currents. Second, the steep atmospheric temperature gradients developed abnormally strong winds for that time of the year.

The above-described meteorological conditions rather profoundly affected the conduct of the experiment for several reasons, including the following:

- 1) the interval during which a sinking plume could occur was over one month shorter than during a normal winter,
- 2) when favorable winds occurred in January, the air temperature was too cold for safe operation of the survey boats, and

- 3) trajectories of the rapidly-moving weather systems were very difficult to predict and their duration was too short for more than a one-day operation.

The sampling effort of February 14-15, 1976, was conducted on perhaps the only suitable day during the 1975-76 winter. Even so, the extent of the operation had to be drastically cut because the two smaller boats could not operate under the adverse wave conditions. Sampling was restricted mainly to the VERSLUIS over water and to the raw water taps for the crib and shore intakes at the SWFP.

The VERSLUIS was able to make 17 stations, the ERDA 1 made two, and Launch 7 made one. Samples were also taken from the raw-water taps for the SWFP's shore and Dunn-Crib intakes.

2. Ship positioning

The three sampling boats used Motorola Mini-Ranger positioning equipment. This equipment consists of two shore-based transponders, and a receiver/transmitter and range console on the boat. The consoles provide visual, digital displays of the distance, in meters, to each of the two shore stations (Fig. 5). Personnel on board each boat employ a chart of the area, which is overprinted with distances from each transponder (a "cyclic, range/range chart), to pinpoint the boat's position.

Cruise plans that were developed prior to the sampling program were ineffective because only the larger of the three boats, the VERSLUIS, could operate for any length of time. The VERSLUIS, therefore, commenced running the sampling patterns for all three boats, continuing on February 15 as long as feasible.

3. Water samples

Water samples were drawn from five depths as follows:

- 1) 1/2 m above the bottom,
- 2) 2-1/2 m above the bottom,
- 3) 5 m above the bottom,
- 4) 3 m below the surface, and
- 5) 1 m below the surface.

Fig. 5. Sampling and Transponder Locations of February 15, 1976.

Sampling was accomplished by lowering a plastic garden hose through a pipe that extended 1 m below the water surface. The hose was marked at 0.5-meter intervals and had a 4.5-kg trolling weight suspended 0.5 m from the end. The water depth was recorded and the bottom sample drawn while the weight was resting on the bottom and the hose was taut. The hose end was then raised successively to the other four sampling depths. The pipe did not allow the underwater hose nozzle to rise above 1 m below the water surface. This prevented sample contamination by a possible surface slick.

On the small boats, a given water sample was pumped on board with a pump whose flow rate was measured to be approximately 18.9 l/min (5.0 gal/min). On the VERSLUIS, the same hose was used as in the small boats. Each time the hose was raised to a new depth, the system was run long enough to ensure that water from the previous depth had been evacuated from the hose. A polyethelene "Baggie" was then filled with water from the particular sampling depth. A final sample was collected by completely immersing a 15 ml polyethylene vial, which had been soaked in alcohol, in the water and by snapping closed the vial's cap while the vial was still immersed. After being filled, the polyvials were placed in trays in predetermined slots according to the sample boat's position and the sampling depth.

4. Water temperatures

Water temperatures at the lake surface and each sampling depth were recorded using an electronic, digital thermometer (Digitec Model #581). A temperature sensor was inserted through a waterproof fitting, into the hose immediately before the pump. The temperature for each level was recorded while the sample was being drawn into the Baggie. Surface water temperature was determined by a second sensor held over the side of the boat.

5. Water-intake samples

Duplicate water samples (two, 15-ml polyvials) were taken by personnel at the SWFP, from water taps for both the shore and crib intakes, according to the following schedule:

<u>Date</u>	<u>Time (hr)</u>	<u>Interval (hr)</u>
Feb. 15	0200-0600	every 1
Feb. 15	0630-2000	" 1/2
Feb. 15	2100-2400	" 1
Feb. 16	0100-1200	" 1
Feb. 16	1400-1800	" 2
Feb. 16	2200 m	" 4
Feb. 18	0200-1000	" 4

6. Ancillary-environmental data

Wind data were recorded during the experiment with a recording meteorological instrument placed at the end of the Calumet Harbor breakwater (Fig. 6) on a tower approximately 15 m above the water.

Three thermographs and three Bendix Q-15 current meters were moored about one meter above the bottom at each of the three locations shown on Fig. 6. The Bendix meters were fitted with ducted impellers for sensing the speed and direction of lake currents. Water temperature was sensed with Yellow Springs Instruments thermistors that had a time constant of ≈ 30 s.

C. Sample Analysis and Data Processing

1. General considerations

Analytical procedures explained in subsequent sections of this section were developed for rapid sample insertion into, and retrieval from, a nuclear reactor. Speed of sample exchange was possible because ANL's CP-5 reactor has a fast pneumatic system ("rabbit tube") that allows insertion and retrieval lasting no more than a few seconds. Unfortunately, the rabbit tube presented mechanical difficulties that sometimes affected performance. Apparently, there is a rough spot somewhere in the tube that will stop the capsule before it is inserted into the reactor. The capsule is not stopped on every insertion, but, when it is, a several-hour delay is incurred until the capsule is freed. This problem has been time consuming and costly; most frustrating of all, reactor-operations personnel have been unable to remedy the problem. The last irradiation performed in the rabbit system, on March 15, 1976, resulted in the rabbit capsule breaking apart. Half of the

Fig. 6. Location of Current-meter Moorings.

capsule could not be found. The reactor had to be shut down and the pneumatic system opened from the reactor end. It was discovered that the end-stop for the rabbit tube was completely deteriorated and had to be replaced. The end-stop could not be replaced until the reactor was shut down for fuel on April 18, 1976.

It was necessary to travel to the Ames reactor at Iowa State University (ISU) to analyze samples. ISU facilities could be used for only three days because of prior commitments, but 140 samples were run. The remainder of the samples were irradiated after the rabbit tube was repaired.

2. Sample preparation, irradiation, and counting

Lake water in the polyvial samples was evaporated by placing trays of 104 polyvials into an oven, set at 80°C, for approximately 48 hours. Evaporation of the water eliminates ^{19}O gamma interference, the polyvials do not have to be sealed prior to insertion into the reactor, and no allowance is necessary for sample expansion or hydrolysis during irradiation.

Immediately before irradiation, the outside of each polyvial was washed several times with alcohol to remove NaCl or other surface contamination. The polyvial was packed into the rabbit capsule for insertion into the reactor and was irradiated for three minutes (timed by stopwatch) in a flux of $2.5 \times 10^{13} \text{ n/cm}^2/\text{s}$. During the thirty seconds that elapsed between the end of irradiation and the commencement of counting several steps were performed: (1) the rabbit capsule was removed from the rabbit tube and taken to a hood where the polyvial was extracted, (2) the cap of the polyvial was popped open in the hood to allow the air flow to remove radioactive argon from the polyvial, and (3) the polyvial was recapped and placed in a sample holder for counting. All of the samples were counted for at least 180 s of live time, which commenced 210 s after insertion of the sample into the reactor flux.

Making the time interval for irradiation, delay, and counting the same for all samples permitted direct comparison of peak areas of particular gammas with the peak areas of calibration samples. This simplified quantification of the amounts of dysprosium and samarium in the lake-water samples. Because the time intervals were of equal duration, the ratio of the number of counts (N_c) in a calibration sample's peak to the amount of element (W_c)

contained was equal to the ratio of the number of counts in the unknown peak (Nu) to the amount of unknown element (Wu) contained in the sample, or

$$\left(\frac{N_c}{W_c} = \frac{N_u}{W_u} , \text{ or } W_u = \frac{N_u W_c}{N_c} \right) .$$

(When time intervals are not equal, the radioactive delay must be accounted for with an exponential decay term and the calculation becomes more difficult.)

The irradiated samples were counted with an Ortec, solid-state, lithium-drifted germanium [Ge(Li)], low-energy, photon spectrometer (LEPS). This detector (Model #8013-25400) had an active surface area of 500 mm². The signal from the detector was fed into a Canberra (Model #1468) live-time corrector and then to an Ortec (Model #452) spectroscopy amplifier for pulse shaping. Finally, the signal went to a Nuclear Data (Model #560), 4096-channel, multi-channel analyzer that had a CRT display and a teletype for hard copy. The CRT display had two line markers that could be moved independently through the spectrum for bracketing any particular area of interest. A hard-copy output could be extracted in two modes. The first mode was a totalizing function that averaged the number of counts in the two channels designated by the markers, then subtracted that average from each channel between the markers, and then totaled the remaining number of counts between the markers. The hard copy in this first mode gave a total number of counts between the markers and a net number of counts. The second mode of output was a channel-by-channel printout of the number of counts in each channel between the markers.

During the 180-s counting period, the analyzer operator observed the CRT display for evidence of gamma peaks at the energies indicative of dysprosium and samarium. If a peak or peaks developed, the operator extracted the data by the totalizing mode when the count had finished. If there were no peaks, the spectrum was erased for the next sample. In instances in which both the dysprosium and samarium peaks were in evidence, the spectrum recorded for the initial 180 s was stored and the count was continued for up to 540 s additional. The above procedure was necessary because the short half-life (75 s) of dysprosium would be buried in the background when counting continued for longer than three half-lives (225 s) but the samarium peak

would continue to build due to its longer half-life (22.5 min). The data could then be extracted from both spectra and the number of counts in the samarium peak from both spectra could be totaled.

Samples analyzed at Ames were done in the same manner as described above, except that a 45-s delay was necessary between extraction from the reactor and commencement of counting. This delay was necessary because the multi-channel analyzer could not be moved into the rabbit lab and it required 15 s more to place the sample on the counter. The counting equipment utilized at Ames was Nuclear Data and Ortec, similar to the equipment at ANL; however, the Ames detector had an active surface area of only 250 mm². The effect of the smaller detector was to require sample placement closer to the detector.

The above-described procedures allowed analysis of approximately ten samples per hour, whenever it was possible to irradiate one sample while the previous one was still being counted.

The decision to employ samarium as the second REE gave a somewhat unexpected and important advantage. Referring to Table I, it can be seen that Sm^{152} has a thermal-neutron-capture cross section of 210 barns and a half-life of 47 hours. Ultimately, the 47-hour isotope of samarium is approximately one order of magnitude more detectable than the 22.5-minute isotope, if a one hour irradiation is employed. This feature allows quick determination (by standard short irradiations and counts) of samples with evidence of samarium, although the amounts may be approaching the limits of detectability. Re-irradiation of those samples, and others in that region of time or space, is then done for a longer period (one hour). The longer irradiation is followed by a decay period of approximately 5 days, to allow the sodium ($T_{1/2} = 15 \text{ hr}$) interference to decay away, and then a recount of one or more hours. The associated gamma peak thus becomes higher and better defined allowing a lower statistical error and a better determination of the amount of samarium in that sample. Clearly, the longer irradiation and counting periods are much too time-consuming and expensive to be used with all of the samples we collect; however, they are practical to use for a few samples, as indicated by the shorter irradiations.

D. Error Analysis

1. Flux variation

The neutron flux in the CP-5 reactor was controlled automatically to vary no more than $\pm 0.5\%$. During the first series of bench tests (Sec. III. A.1), the deteriorated end stop of the rabbit system caused the location of the capsule to vary slightly from run to run while in the reactor. This variation exposed the capsule to a different flux during each irradiation. The error induced by the varying position of the capsule was largely undetermined and presumed random. Analysis of repeated runs of calibration samples indicated, however, that the error approached 10% for concentrations greater than 10^{-7} g/sample.

The defective end stop was replaced after running the first series of bench tests (Fig. 3) and before running (1) the second series of bench tests, and (2) the environmental samples from Lake Michigan.

2. Sample-volume variation

Ten water samples taken in the field were selected at random and weighed to determine volume variation. The volume variation error (1σ) was found to be $< 3\%$ by weight. The weight variation of empty polyvials was $< 0.3\%$.

3. Counting statistics

The statistical counting error is generally accepted as

$$e = \sqrt{N} = \sigma \quad \text{with } e = \text{error}$$

$$N = \text{number of counts}$$

$$\sigma = \text{one standard deviation}$$

This error reflects the Poisson distribution related to the random nature of radioactive decay. For a detailed analysis, the reader is referred to Livezey's textbook (1966, p. 146-149). The summation of counts under a peak is subject to two statistical errors. The first is the error in determination of the total number of counts in the peak (T). The second error is in the determination of the number of counts in the background (B) that must be subtracted from T to obtain the net number of counts (N) in the peak. That is,

$$N = T - B .$$

The error in N is due to the error in T, denoted by ϵ_T , and the error in determining B, denoted by ϵ_B . The percent total error in N, e_N , is

$$e_N = \frac{\sqrt{(\epsilon_T)^2 + (\epsilon_B)^2}}{N} \times 100.$$

The statistical error increases with decreasing elemental concentration (lower peaks) and, generally, only becomes a significant factor, considering other errors, when elemental concentrations are approaching the minimum detectable amounts.

4. Calibration solutions

The errors involved in making up a calibration solution are as follows:

- (1) water volume measurement error:

$$\frac{0.5 \text{ ml}}{500 \text{ ml}} = 0.1\%$$

- (2) REE weighing error:

$$\frac{0.009 \text{ g}}{1.0 \text{ g}} = 0.9\%$$

(weighed on electronic balance)

- (3) pipette error: $\pm 1\%$ (from manufacturer's specifications)

The total error of the first undiluted solution equals

$$\sqrt{(0.9)^2 + (0.1)^2 + (1)^2} = 1.3\%.$$

With each dilution, errors numbers 1 and 3 may be a factor so that the total error of each subsequent solution can be calculated as

$$e_T = \sqrt{(0.9)^2 + N(0.1)^2 + N(1)^2} \quad (N = \text{numbers of dilutions}).$$

The largest number of dilutions used was four ($N=4$), giving a maximum error of 2.2%.

5. Counting geometry

The geometric counting error is generally the largest error in activation analysis and one of the most difficult to quantify. This error occurs because an REE, upon drying, becomes distributed in places other than the center of the bottom of the polyvial. The geometric error was estimated in the following manner:

- (1) Seven calibration samples with different amounts of REE were made up by filling the polyvials as full as possible to simulate field samples. (Normally, calibration samples contain only one ml, to improve geometry).
- (2) Each of the seven polyvials was split into top and bottom halves.
- (3) Each half was irradiated and counted. (Top halves were counted at the same distance from the detector as bottom halves; refer to Table II).
- (4) The percentage of Sm that had dried in each half was calculated

$$\% = \frac{C_T}{C_T + C_B} \quad \text{and} \quad \frac{C_B}{C_T + C_B}$$

C_T = counts in top-half of polyvial

C_B = counts in bottom-half of polyvial

- (5) Each polyvial half was considered to be a point source centered above the detector and the loss of counts due to moving the top-halves (which had been counted in the same position as if they were bottoms) to the position they would normally occupy at the top was estimated by using the geometric-factor equation. [See the Radio-logical Health Handbook (U.S. Dept. HEW, 1970, p. 35).]

$$G = 0.5(1 - \cos \alpha),$$

where

$$\alpha = \arctan \frac{r}{d}$$

r = radius of detector window

d = distance between counter and source

G = geometric factor,

then

$$\begin{aligned}
 G &= \frac{\text{Projection of the area of the detector onto sphere}}{\text{Total area of sphere with center at distance } d \text{ from detector}} \\
 &\approx \frac{\text{number of gammas striking detector } (C)}{\text{total number of gammas emitted } (\Sigma)} \\
 &= \frac{C}{\Sigma}
 \end{aligned}$$

That is,

$$G_{\text{lower}} = G_L \approx \frac{C_T}{\Sigma_T}; \quad G_L = G \text{ at bottom of polyvial in normal counting position } (d = 76 \text{ mm})$$

and

$$\frac{G_U}{G_L} = \frac{\frac{C_{T'}}{\Sigma_T}}{\frac{C_T}{\Sigma_T}} = \frac{C_{T'}}{C_T}$$

$$C_{T'} = \frac{G_U}{G_L} C_T = K C_T = \text{estimated number of counts if the top-half of polyvial was counted in its normal position}$$

so that the estimated loss of counts due to moving the source from bottom to top position is,

$$\text{lost } C_T = C_T - K C_T = C_T - C_{T'}$$

and the percent loss is,

$$\% \text{ loss} = \frac{C_T - K C_T}{K C_T + C_B} = \frac{1 - K}{k + \frac{C_B}{C_T}}$$

The four appropriate G's were calculated to be the following:

$G_U = 0.002288$, $d = 130$ mm (corresponds to point source at top of polyvial when bottom is 76 mm above detector - normal counting position).

$G_L = 0.006797$, $d = 76$ mm (corresponds to point source at bottom of polyvial - (normal counting position)).

$G_{U'} = 0.01861$, $d = 80$ mm (corresponds to point source at top of polyvial if polyvial is sitting on detector).

$G_{L'} = 0.3143$, $d = 5$ mm (corresponds to point source sitting on detector).

To further illustrate this geometric effect, consider the percent loss of the number of counted gammas if the point source were moved from 76 mm to 130 mm.

$$\frac{G_L - G_U}{G_L} = 66\% \text{ loss}$$

- (6) The mean (μ) and one standard deviation (σ) percent loss due to an REE drying in the top of a polyvial was then calculated and the same estimation was done for a polyvial sitting directly on the detector ($d = 5$ mm).

Results of the above six steps are shown in Table II.

The correction associated with the above counting geometry exhibits a peculiarity because this correction for geometry always produces a gain of counts. That is, the corrected counts will always be $N + \mu N$ because the samples are being compared to calibration samples where it is known that the solution dried within a few mm of the bottom (since they contain only one ml). In order to report this error in a manner consistent with other errors, the mean % loss is first added to the recorded counts, then it is reported as $\pm \sigma$ (one standard deviation appropriate to the counting position of the polyvial). As an example, if a recorded peak has 1000 counts, and it was counted at 76 mm, then the following is done:

1000 ct + ($\mu \pm \sigma$) 1000
 1000 ct + (0.145 ± 0.158) 1000
 1000 ct x (1.145 ± 0.158)
 1000 ct x ($1.145 \pm 13.8\%$)
 1145 ct $\pm 13.8\%$

TABLE II. Measurements and Calculations for Estimating the Counting Error Due to the Geometry of the Distribution of Dried REE's in Polyvials

Polyvial No.	C_T	C_B	$C_T + C_B$	$\% C_T$	$\% C_B$	% Loss @ 76 mm $\frac{1 - K_1}{K_1 + \frac{C_B}{C_T}}$	% Loss @ 5 mm $\frac{1 - K_2}{K_2 + \frac{C_B}{C_T}}$
1	322	1710	2032	15.8	84.2	11.7	18.3
2	440	1441	1881	23.4	76.6	18.4	29.8
3	54	13,437	13,491	0.4	99.6	0.26	0.39
4	120	136,050	136,170	0.1	99.9	0.07	0.10
5	2460	2885	5345	46.0	54.0	43.9	82.2
6	6722	16,674	23,396	28.7	71.3	23.5	39.2
7	7033	139,300	146,333	4.8	95.2	3.3	4.94
mean (μ)						14.5	25.0
one standard deviation (σ)						15.8	29.4

$$K_1 = \frac{G_T}{G_B} = 0.3366$$

$$K_2 = \frac{G_A}{G_D} = 0.0191$$

C_T = counts in top-half of polyvial

C_B = counts in bottom half of polyvial

$$\% \text{ loss} = \frac{C_T - C_T K}{C_T K + C_B} = \frac{1 - K}{K + \frac{C_B}{C_T}}$$

6. Sampling procedures

Undoubtedly, there are errors associated with the sampling procedure; however, no way is known of putting a numerical value on these errors. The method of tagging in no way insures a homogeneous mixture, although with time it should become more homogeneous, so that it is possible for samples taken in close proximity to differ markedly from each other and not be indicative of the average concentration in the general area. This type of error is inherent in any type of tracing experiment and is usually neglected, not because it does not exist, but because it generally cannot be quantified.

7. Error summary

Of the six types of errors discussed above, three are relatively minor, one is basically undetermined, one increases with decreasing tracer concentration, and one, the geometric error, is large. For the purpose of reporting results, the errors due to calibration solution, sample volume, and flux variation will be considered insignificant compared to the other errors and results will be reported as follows:

$$\text{sample weight (g)} \pm \left[(\% \text{ geometric error})^2 + (e_N \text{ of field sample})^2 + (e_N \text{ of calibration sample})^2 \right]^{1/2}$$

E. Results

1. Lake currents, winds, and water temperatures

Of the three current meters and thermographs moored off south Chicago during the study, only the two innermost meters (Fig. 5) returned data on near-bottom currents. All three thermographs returned water-temperature data however. The meteorological wind instrument (Fig. 6) functioned well prior to and during the study.

Lake-current data obtained during the study are listed in Appendix A, together with wind and water-temperature data. Figure 7 presents progressive-vector plots for wind and currents during the study period. It can be observed that transport of bottom water was toward the southeast just prior to

the beginning of the study period. After the switch in the wind at approximately 0400 hrs on February 14 (Appendix A), however, the current direction at the outermost meter (no. 8, Fig. 6) switched to a flow toward the northwest. The current direction at meter 5, however, remained directed toward the southeast. The speed of the current at meter 5 was 20% higher than that at meter 8 during the period of peak flow recorded at both meters (Appendix A, February 15, 1200-1400 hrs).

Such strong, diametrical currents, at two meters only 1.3 km (0.7 n.m.) apart, were completely unexpected and prompted a search of the current-meter records for the entire recording period (Dec. 19, 1975 - April 10, 1976). No less than 22 instances of this reversal in lake-current flow were observed during the 120-day interval and each current reversal was concurrent with a wind switch to southerly quadrants. The opposing currents (Fig. 7) observed on February 14 and 15 were, therefore, consistent with flows occurring earlier in the winter months under similar wind conditions. The significance of these currents for the design of an optimum sampling pattern is discussed later.

2. Tracer concentrations in survey area

Neither the samarium nor the dysprosium tracer was found in water samples taken from the boats on February 15, 1976. This was due to the fact that the sampling pattern did not adequately engage the sinking plume, for reasons discussed below. Neither tracer was found in samples taken from the SWFP's shore intake, but three samples drawn from the SWFP's raw-water tap for the Dunn Crib contained significant concentrations of Sm (Table III). (The duplicate water sample [Sec. III.B.5] for 2200 hr leaked from its polyvial and was, therefore, not analyzed.)

Fig. 7. Progressive-vector Diagrams for Currents Recorded by Current Meters and Winds Recorded by Wind System (Fig. 6) Beginning at 0000 Hr February 14 and Ending 0000 Hr February 16, 1976. Distances are in Meters. Each Vector is a 2-hr Average.

TABLE III. Concentration of Samarium in Raw Water from
Dunn Crib and Isotope Dilution Ratio

Time of Raw-water Sampling (hr CST)	Place of Sample Irradiation	Activated Isotope	Isotope Concentration in Raw Water	Isotope Dilution Ratio (C_I/C_F)
1530	Argonne	^{155}Sm	$9.5 \times 10^{-7} \text{ g/l} \pm 18\%$	3.8×10^3
1530	Argonne	^{155}Sm	$4.3 \times 10^{-7} \text{ g/l} \pm 26.6\%$	1.1×10^4
2200	Argonne	^{155}Sm	$1.4 \times 10^{-6} \text{ g/l} \pm 17\%$	2.7×10^3

IV. DISCUSSION

A. Adequacy of Tagging Techniques

1. Oil-refinery waste

Bench testing indicated that the Dy tag tended to remain in the oil phase. The fact that no Dy was detected in the three crib samples that contained Sm could be due to the fact that (1) the oil tag was not spread over as large an area as the water tag (so that the samples with Sm concentrations were not coincident in space with the oil tag), or (2) the oil tag may have been, within the ≈ 24 -hour period, entirely a surface slick.

One possible change in procedure might be to inject the tagged oil-refinery waste into the water column in the same manner as the water tag. Most refinery waste may enter the IHC by submerged discharges. Thus, submerged injection of tagged, simulated refinery waste is being evaluated for use in the next sinking-plume study.

2. Canal water

The technique for tagging canal water is adequate. The fact that the Sm tag was detected at the Dunne Crib (≈ 10 km from IHC entrance), after there had been dilution by a factor of approximately 10,000, clearly seems to indicate that: (1) complexing of Sm with DTPA keeps the Sm in solution, (2) that Sm is detectable in field samples after the initial concentration has been diluted by at least four orders of magnitude, and (3) IHC water is entrained into the City of Chicago's municipal water intakes. The sample drawn at 2200 hr (Table III) may indicate a tendency for the sinking-plume water to remain in the crib area after the fast currents have ceased. The recorded currents, by 2040 hr on February 15, had dropped to less than 0.05 kn (2.6 cm/s) and there may have been some oscillatory type water movement. There is no reason to believe that the tracer-injection technique used was not a suitable one.

B. Adequacy of Field Procedures

1. Ship positioning and sampling pattern

The Mini-ranger positioning system, without a doubt, gave adequate overwater fixes. It also was easy to use and not time-consuming.

The sampling pattern on February 15, 1967 (Fig. 5), did not extend far enough offshore. The sinking plume, emanating from the IHC, was considerably farther from shore than had been expected because of the unusual reverse currents that occurred on that day. If wave conditions had allowed the operation of all three boats, as planned, it is quite probable that the plume area would have been sampled because the original sampling pattern extended farther offshore.

2. Shipboard sampling

The use of small boats during the winter sinking-plume condition proved to be impractical. It probably always will be, because of the adverse meteorological conditions that generally occur.

The hose/pump system employed for drawing water samples requires a significant improvement. This system takes samples too slowly and it requires too many boats for adequate coverage of an area. A sampling system that will not require stopping at discrete stations, and which can operate continuously as the boat moves, is being developed. The present conception of the experimental system (Fig. 8) is a cable with a depressor fin that will remain at a constant depth below the water surface while being towed at a constant speed. A second cable would be attached approximately 1 m above the depressor fin. This cable would terminate in a small, heavy, spherical weight that would drag on the bottom. The cable would be considerably longer than the distance from the depressor fin to the bottom (Fig. 8) to allow for adjustment to changes in bottom topography. The master steel cable would have five small, semi-rigid, plastic hoses attached around it. Each of these hoses would extend to a different sampling depth and one would extend down the second cable to a depth approximately 0.5 m above the bottom. The top four hoses would be approximately fixed, at a constant speed, with regard to depth but the bottom sampling hose's intake would vary depending on bottom depth. The entire cable would be faired to minimize drag. The Great Lakes Project has experience with a towed-depressor/thermistor array (Frigo, Paddock, and McCown, 1975) and the knowledge gained from its research and development efforts will be utilized in designing the system.

The smaller-diameter hoses proposed for the underway sampling system would require a different type of pumping equipment; five, positive-

Fig. 8. Schematic of Proposed Underway Sampling System.

displacement pumps would be used. Flow of sample water would be significantly lower (≈ 400 ml/min) than with impeller type pumps, but, since the flow would be continuous and the samples only 15 ml in volume, no problems are expected.

3. Water-intake samples

The method of drawing samples from the SWFP's raw-water tap for the Dunn Crib is adequate; however, to better define the tagged slug of IHC plume water, sampling of raw water must be performed over shorter time intervals than used heretofore. A good estimate of the rate of travel of the tagged water can now be made so that for the next experiment samples may be drawn over a much smaller time interval. The greater frequency of sampling will permit better resolution of peak concentration, time-of-passage, and the concentration-vs.-time profile for the tagged refinery waste as it moves past the Dunn Crib.

4. Ancillary environmental data

Equipment performance and quality of data from the Q-15 current meters and the MRI wind instrument were satisfactory. Current meter No. 7 did not return data because its directional fin was sheared off by a passing ship. The improvement to be made in this operational area is the employment of additional current meters so that wider coverage of the area of investigation can be realized. As many as seventeen current meters will be available for the winter, 1976/1977 sinking-plume study.

C. Adequacy of Analytical Techniques

The only problems that developed with the analytical techniques were the aforementioned malfunctioning rabbit system and the deteriorated end stop. The sensitivity and rapidity of analysis that is essential to the project can be consistently achieved. An area of some concern is the large error that must be accepted due to geometry in order to achieve the rapidity of analysis; however, continuing attempts to better quantify and lower this error are being made.

V. RECOMMENDATIONS FOR FUTURE STUDIES

Implementation of the experimental design for this project has revealed inadequacies in the original design. In addition, the effort has uncovered an unexpected current regime that must be carefully evaluated and worked with in the future. The next sinking-plume experiment may be carried out with the expectation of fully accomplishing the project objectives. Accordingly, the following recommendations are made for the winter, 1976/1977, study:

1. Sm complexed with DTPA should be used to tag canal water;
2. Dy should be used to tag the simulated oil-refinery waste;
3. Tagged, simulated refinery waste should be injected directly into IHC water about to form a northerly-moving sinking plume;
4. The time interval for taking raw-water intake samples from the Dunne Crib should be decreased from 30 min to about 5 min;
5. An underway water-sampling system should be used to allow coverage of a larger area extending farther offshore; and
6. REE samples should be analyzed by the methods discussed in this report.

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APPENDIX A

WIND, LAKE-CURRENT, AND WATER-TEMPERATURE DATA FOR THE PERIOD FEBRUARY 14-16, 1976

Date/Time (hr CST)	Wind ^a		Lake Current ^b				Water Temp. ^c		
	Speed (m/s)	Direct. from (°T)	Meter 5		Meter 8		Meter 5 (°C)	Meter 7 (°C)	Meter 8
			Speed (cm/s)	Direct. toward (°T)	Speed (cm/s)	Direct. toward (°T)			
14 Feb.									
0120	3.5	37	8.94	144	8.10	119	1.5	1.9	1.4
0200	3.9	37	8.64	138	7.10	190	1.5	1.2	1.4
0240	3.6	37	10.12	138	7.67	140	1.5	1.2	1.4
0320	4.7	51	7.60	145	6.03	140	1.5	1.2	1.4
0400	6.5	74	8.93	139	7.72	184	1.5	1.2	1.5
0440	7.6	92	8.65	146	7.15	132	1.5	1.2	1.5
0520	8.5	104	7.47	172	6.08	216	1.5	1.2	1.5
0600	8.0	114	5.50	153	5.91	204	1.5	1.2	1.4
0640	7.3	122	7.14	136	6.04	192	1.5	1.2	1.3
0720	7.0	122	4.05	130	2.83	148	1.5	1.5	1.4
0800	5.1	146	3.68	137	2.77	167	1.5	1.1	1.4
0840	3.8	138	4.13	148	3.11	184	1.5	1.1	1.4
0920	6.5	144	3.55	140	3.67	191	1.5	1.1	1.4
1000	6.2	158	0.73	164	0.70	180	1.5	1.1	1.4
1040	6.5	154	0.73	164	0.71	172	1.5	1.1	1.5
1120	6.3	142	1.25	151	0.78	130	1.5	1.2	1.5
1200	7.9	140	0.58	149	0	0	1.5	1.2	1.5
1240	7.6	153	0	0	0	0	1.5	1.2	1.5
1320	7.7	153	0	0	0	0	1.6	1.2	1.5
1400	8.9	151	0	0	0	0	1.6	1.2	1.5
1440	9.3	140	0.20	0	0	0	1.6	1.2	1.5
1520	8.5	143	0.60	0	0.20	0	1.6	1.2	1.5
1600	9.6	137	1.10	0	0.40	0	1.6	1.2	1.5
1640	11.2	139	0	0	0	0	1.6	1.2	1.5
1720	11.4	140	3.36	150	1.60	356	1.6	1.2	1.5
1800	13.9	138	3.85	152	1.71	339	1.6	1.2	1.5
1840	13.5	140	5.57	170	2.81	356	1.6	1.2	1.5

APPENDIX A (Continued)

Date/Time	Wind ^a		Lake Current ^b				Water Temp. ^c		
	Speed	Direct. from	Meter 5 Speed	Direct. toward	Meter 8 Speed	Direct. toward	Meter 5	Meter 7 (°C)	Meter 8
(hr CST)	(m/s)	(°T)	(cm/s)	(°T)	(cm/s)	(°T)			
14 Feb. (contd.)									
1920	12.0	144	6.26	167	2.38	345	1.5	1.2	1.5
2000	14.5	146	7.22	137	5.08	350	1.5	1.2	1.6
2040	13.2	150	12.24	137	7.42	356	1.5	1.2	1.5
2120	15.8	156	10.54	135	6.29	342	1.8	1.2	1.5
2200	15.7	159	9.56	143	7.28	351	1.5	1.2	1.5
2240	14.2	161	13.79	136	10.85	348	1.5	1.6	1.5
2320	12.9	171	11.51	129	8.82	356	1.5	1.2	1.5
15 Feb.									
0000	13.6	177	12.41	139	9.32	356	1.5	1.2	1.5
0040	15.1	179	12.93	148	9.00	352	1.5	1.2	1.5
0120	13.9	181	14.35	129	9.33	355	1.8	1.2	1.5
0200	14.9	180	13.15	134	10.02	356	1.5	1.2	1.5
0240	15.2	180	13.72	133	11.50	345	1.4	1.2	1.5
0320	15.6	192	13.59	141	11.53	356	1.5	1.2	1.5
0400	15.2	192	14.63	155	10.11	332	1.6	1.8	1.5
0440	14.6	198	14.65	150	10.88	324	1.5	1.2	1.5
0520	13.6	209	15.10	131	12.53	321	1.5	1.6	1.5
0600	16.0	213	13.59	137	10.54	325	1.5	1.2	1.5
0640	15.3	214	11.90	153	9.69	352	1.5	1.2	1.5
0720	17.3	214	10.68	135	8.85	362	2.0	1.2	1.5
0800	16.5	215	9.14	138	8.63	328	1.5	1.4	1.5
0840	15.1	219	7.94	149	6.90	294	1.5	1.4	1.6
0920	14.3	222	9.13	137	8.14	296	1.6	1.5	1.6
1000	13.7	225	7.60	153	6.52	306	1.6	1.5	1.8
1040	15.1	231	8.13	146	5.75	320	1.6	1.5	1.6
1120	15.4	233	8.35	163	6.94	335	2.1	1.5	1.8
1200	15.5	231	5.20	157	6.44	314	1.7	1.5	2.0
1240	15.8	240	2.90	180	7.22	356	1.8	1.7	2.0

APPENDIX A (Concluded)

Date/Time	Wind ^a		Lake Current ^b				Water Temp. ^c		
	Speed	Direct. from	Meter 5		Meter 8		Meter 5	Meter 7	Meter 8
			Speed	Direct. toward	Speed	Direct. toward			
(hr CST)	(m/s)	(°T)	(cm/s)	(°T)	(cm/s)	(°T)	(°C)		
15 Feb. (contd.)									
1320	14.4	245	3.08	216	5.51	348	1.9	1.9	2.1
1400	14.6	243	2.12	188	5.19	332	1.9	1.9	2.1
1440	13.9	243	2.42	204	4.49	328	1.9	1.9	2.1
1520	14.6	245	0.76	203	4.08	338	1.9	1.9	2.2
1600	13.5	248	5.20	179	6.76	322	1.9	2.0	2.3
1640	12.9	258	2.83	188	3.55	350	1.9	2.2	2.3
1720	11.8	256	2.63	189	4.55	351	1.9	2.2	2.3
1800	9.2	250	4.78	196	4.06	280	2.0	2.2	2.3
1840	9.0	243	2.91	184	4.08	338	2.0	2.2	2.3
1920	9.8	256	3.54	188	2.94	342	2.0	2.2	2.4
2000	9.7	263	2.35	192	2.59	332	2.0	2.2	2.4
2040	7.9	271	1.60	184	1.61	330	2.2	2.2	2.4
2120	6.0	262	0.76	203	1.06	319	2.0	2.2	2.4
2200	4.4	269	0.72	236	1.43	282	2.0	2.2	2.4
2240	4.2	272	0.22	206	1.08	326	2.0	2.2	2.4
2320	1.8	246	0	0	0	0	2.1	2.2	2.3
16 Feb									
0000	1.9	288	0	0	0	0	2.1	2.2	2.3
0040	3.1	321	0.45	206	0	0	2.2	2.2	2.3
0120	2.5	13	0.22	206	0	0	2.2	2.2	2.3
0200	2.0	36	0	0	0.40	0	2.2	2.2	2.3
0240	1.4	48	0	0	0	0	2.2	2.2	2.3
0320	2.8	31	1.20	95	0	0	2.2	2.2	2.3
0400	3.0	64	0.60	90	0.58	301	2.2	2.2	2.3

^aSpeed: integrated over 8 min. and 5 such readings averaged over 40 min.;
Direction: 40-min. average from 8 instantaneous recordings

^bSpeed: integrated over 40 min.; Direction: 40-min. average from 4 instantaneous recordings

^cInstantaneous recording every 40 min.