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FINAL REPORT ON
DISSOLVED GAS SATURATIONS IN THE INSHORE MARINE WATERS OF CAPE COD BAY AND INCIDENTS OF GAS BUBBLE DISEASE AT PILGRIM NUCLEAR POWER STATION
1973-1985

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FINAL REPORT ON DISSOLVED GAS SATURATIONS IN THE INSHORE MARINE WATERS OF CAPE COD BAY AND INCIDENTS OF GAS BUBBLE DISEASE AT PILGRIM NUCLEAR POWER STATION 1973-1985

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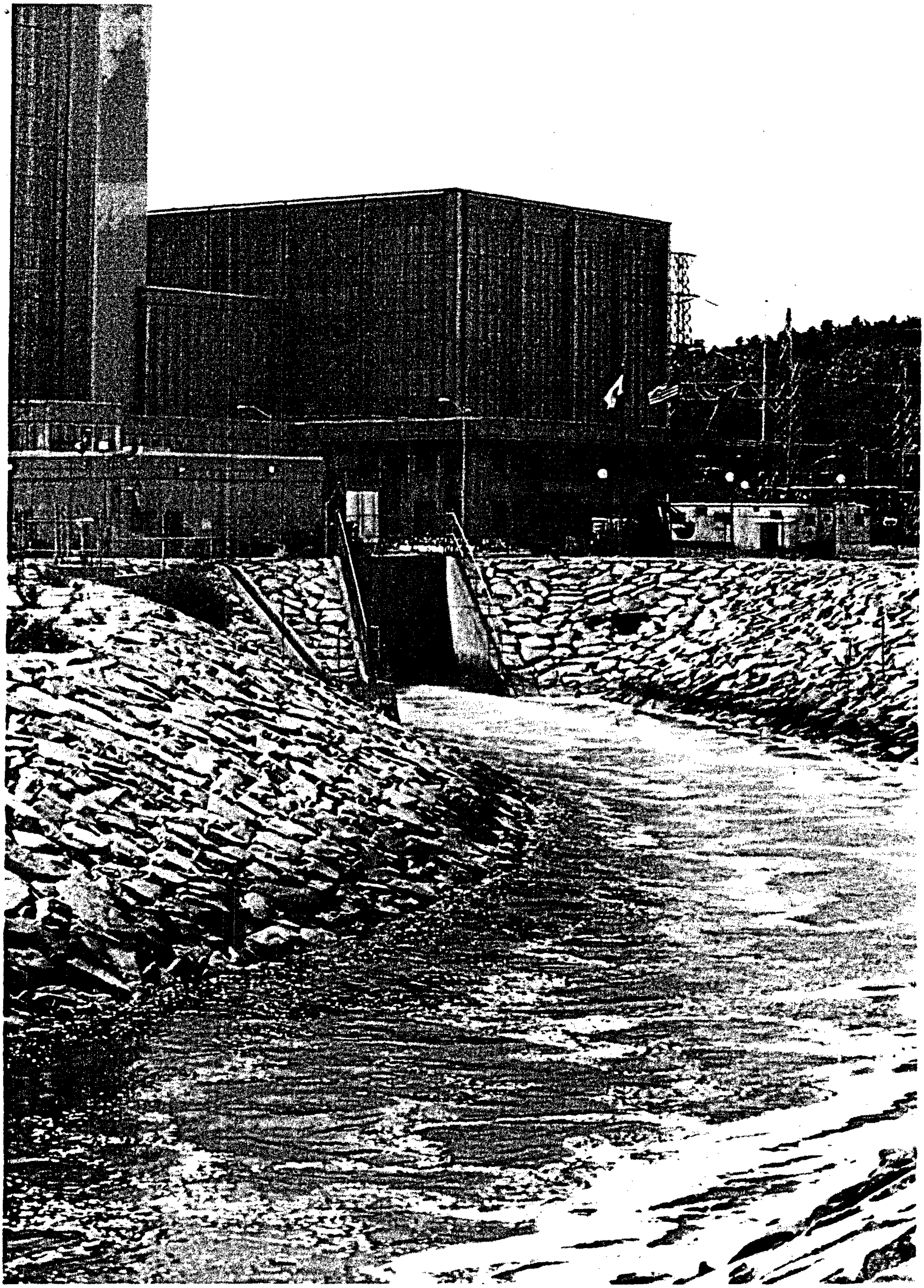

FRONTISPIECE.-Thermal effluent as it emerges from the Pilgrim Nuclear Power Station in the discharge canal.

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I. SUMMARY

Mortalities of Atlantic menhaden (Brevoortia tyrannus) attributable to gas bubble disease (GBD) occurred in the spring of both 1973 and 1975 at Pilgrim Nuclear Power Station (PNPS) coincident with increasing ambient seawater temperatures, 80 to 100% PNPS operating capacity, dissolved gas supersaturations, and attraction of fish to the thermal effluent. During the first fish kill, oxygen was supersaturated in the power plant's discharge canal, averaging 126%. Discharge levels of total dissolved gas saturation, and the saturations of nitrogen plus argon and oxygen during the latter mortality exceeded 115%. When the power plant was operating, discharge gases were supersaturated (exceeding 100%) and often above the recommended 96 hour LD_{50} tolerance level of menhaden for nitrogen (112% at 22 C or 72 F). Discharge water temperatures usually exceeded the maximum preferred temperature (20 C or 68 F) of menhaden in summer and early fall which apparently negated attraction to the thermal effluent at these times.

Although there have been no substantial gas-related fish kills at PNPS since 1975, there is the potential for future problems. A fish barrier net is currently utilized in the discharge canal for the purpose of lessening the magnitude of mortalities if they should occur again. Two other alternatives may also be employed if mortality is significant, namely - reduction of plant operation and unit outage. Stripping dissolved gases from the thermal effluent by means of an air diffuser (degassification) has also been investigated and considered for implementation.

II. INTRODUCTION

Water supersaturated with dissolved gases can adversely affect fish and other aquatic biota via a phenomenon known as gas bubble disease (GBD), a pathological condition ascribable to physical causes analogous to "caisson disease" in man. Gas bubbles form in the blood and tissues causing blockage, rupture, and possible death. Various reports indicate that fish appear to tolerate mild cases of this affliction, but severe GBD has caused mortalities (Marsh and Gorham 1905; Woodbury 1941; Renfro 1963; Ebel 1969; Beiningen and Ebel 1970; DeMont and Miller 1971; Marcello and Strawn 1972; Marcello and Fairbanks 1976; Fairbanks and Lawton 1977). Literature reviews by Rucker (1972), Weitkamp and Katz (1973 and 1975), and Bouck (1975) summarize past studies on gas supersaturated water and GBD in fish.

Dissolved gases that occur in aquatic systems are primarily derived from the atmosphere. Barring an outside force, the dissolved gas pressure is equal to the atmospheric (barometric) pressure just above the air-water interface (760 mm Hg at sea level). Natural and man-made conditions occur that can upset this balance. Supersaturated conditions in aquatic environments resulting from natural causes include: solar and geothermal heating (Harvey 1967; Boyer 1974; Bouck 1975), high photosynthetic activity and algal blooms (Woodbury 1941; Ruckavina and Varenika 1956; Renfro 1963), waterfalls (Harvey and Cooper 1962), and high stream velocities (Lindroth 1957; Boyer 1974). Man's activities have contributed to the problem of gas saturation and resultant GBD in fish below spillways of dams and hydroelectric facilities (Harvey and Cooper 1962; Ebel 1969; Beiningen and Ebel 1970; Merrill et al. 1971); in fish hatcheries and other facilities where there may be infusion of air at water pump intakes, leaking pipelines, pipe joints, bleeder valves, and into turbines (Marsh and Gorham 1905; Rucker and Tuttle 1948; Erdman 1961; Harvey and Smith 1961; Dennison and Marchyshyn 1973; Wold 1973; Penrose and Squires 1976); and more recently in thermal effluent from electric power generating stations located on lakes (DeMont and Miller 1971; Miller and DeMont 1974; Otto 1976), estuaries (Marcello and Strawn 1972), and coastal areas (Marcello and Fairbanks 1976; Fairbanks and Lawton 1977; Bridges and Anderson 1984).

Cooling water passing through a power plant condenser system is confined from the atmosphere and subjected to temperature elevation which may result in the effluent being discharged with dissolved gases at supersaturated levels. The return to ambient saturation by gaseous diffusion across the air-water interface is a relatively slow process involving cooling of the water to ambient (Marcello and Fairbanks 1976).

Noteworthy incidents of GBD in fish have been documented at Pilgrim Nuclear Power Station (PNPS) since the plant commenced commercial operation in 1973 (Marcello and Fairbanks 1976; Fairbanks and Lawton 1977). In April 1973, an estimated 43,000 adult Atlantic menhaden (Brevoortia tyrannus) died of this affliction in the discharge canal and thermal plume at the power station. Two years hence, again in April, about 5,000 adult menhaden succumbed to GBD in the same locale (Marcello and Fairbanks 1976). Another occurrence involved a school of adult striped mullet (Mugil cephalus) in the discharge canal in the late fall-early winter of 1975. Symptoms of GBD were evident in some of the mullet, but no mortalities were substantiated (Fairbanks and Lawton 1977). Atlantic silverside (Menidia menidia) have also been noted with GBD symptoms in the PNPS discharge canal on a few occasions. One incident involved an estimated 600 silversides and 300 juvenile clupeids: menhaden and river herring (Alosa spp.), which were afflicted with GBD in the PNPS discharge canal in August 1985. No mortality was observed in the latter case, but there were individuals that appeared severely stressed.

Because of past GBD-induced fish mortalities at PNPS and the potential for recurrence, we implemented a systematic program to measure dissolved gas saturations at the site in March 1975. Routine measurements were collected through November 1981, with gas saturations monitored generally throughout the year under ambient conditions and in the thermal cooling water discharge to ascertain seasonal and/or annual trends. A study was conducted in the thermal plume in 1983; measurements have been taken in the discharge canal, as needed, since 1981. The specific environmental conditions, power plant design features, modes of operation, and saturation levels were important considerations regarding GBD mortalities in the discharge canal and thermal plume.

III. METHODS AND MATERIALS

Weekly dissolved gas measurements were taken in the discharge canal under the access bridge (surveillance location) and at two reference sites on the north side of the intake embayment (Fig. 1). Total dissolved gas pressure (mm) in the water was measured with a Weiss saturometer (ECO Enterprises, Seattle, WA), a portable field instrument which operates essentially as an artificial fish gill via the membrane-diffusion method, employing a coil of semi-permeable silastic tubing, enclosed in a protective metal case, as a sensing membrane (Plate 1).

Silastic is permeable to dissolved gases in water including water vapor and allows their passage from the water to the interior chamber of the tubing for readout. When immersed in water, the total pressure of the gases diffused

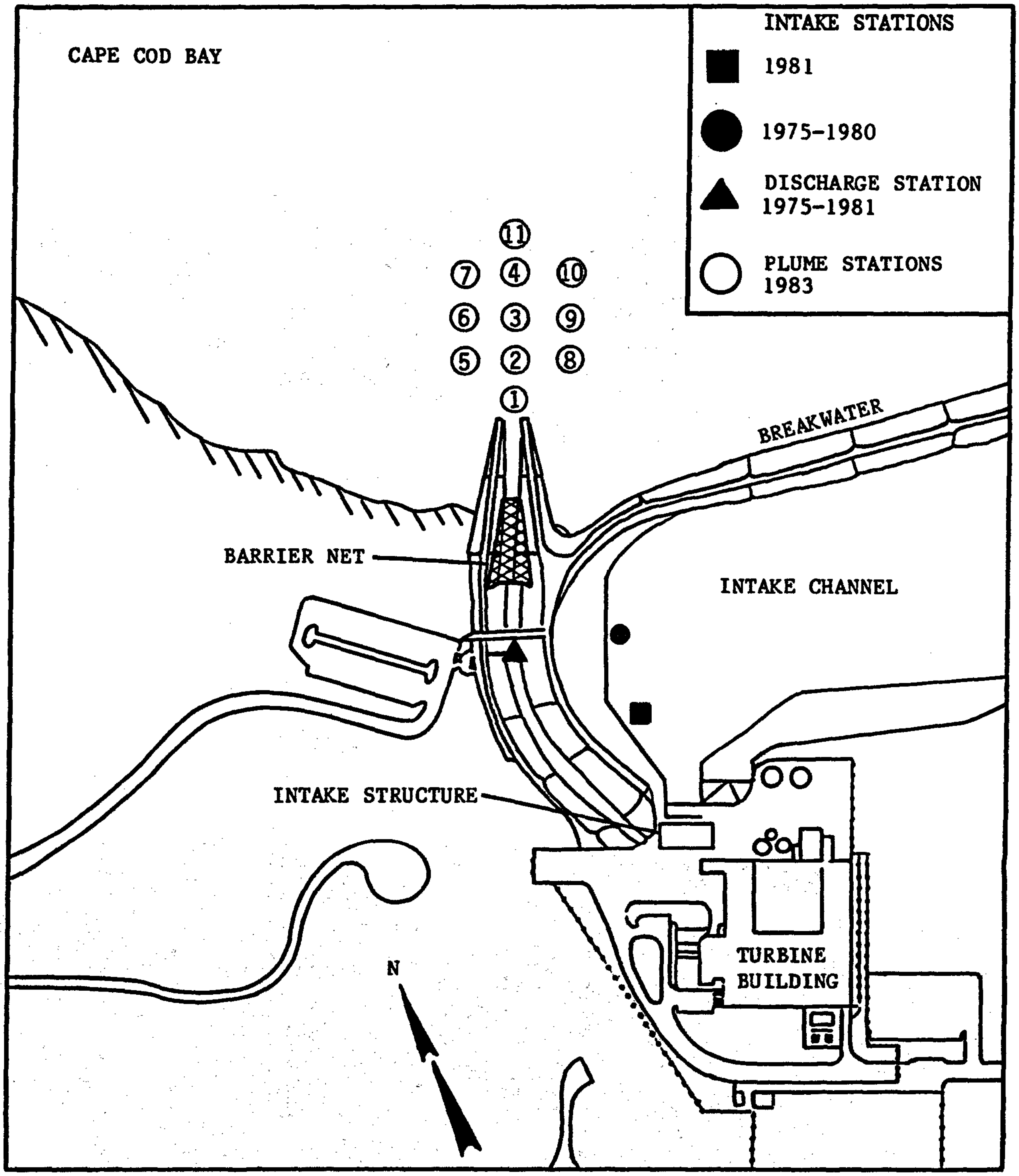

Figure 1. Station locations for saturated dissolved gas plume mapping (April and September, 1983) and intake and discharge sampling stations for gas saturations (1975-1981) at Pilgrim Nuclear Power Station.

Plate 1. Weiss (ECO) saturometer is used at Pilgrim Station to measure gas saturations in the marine environment.

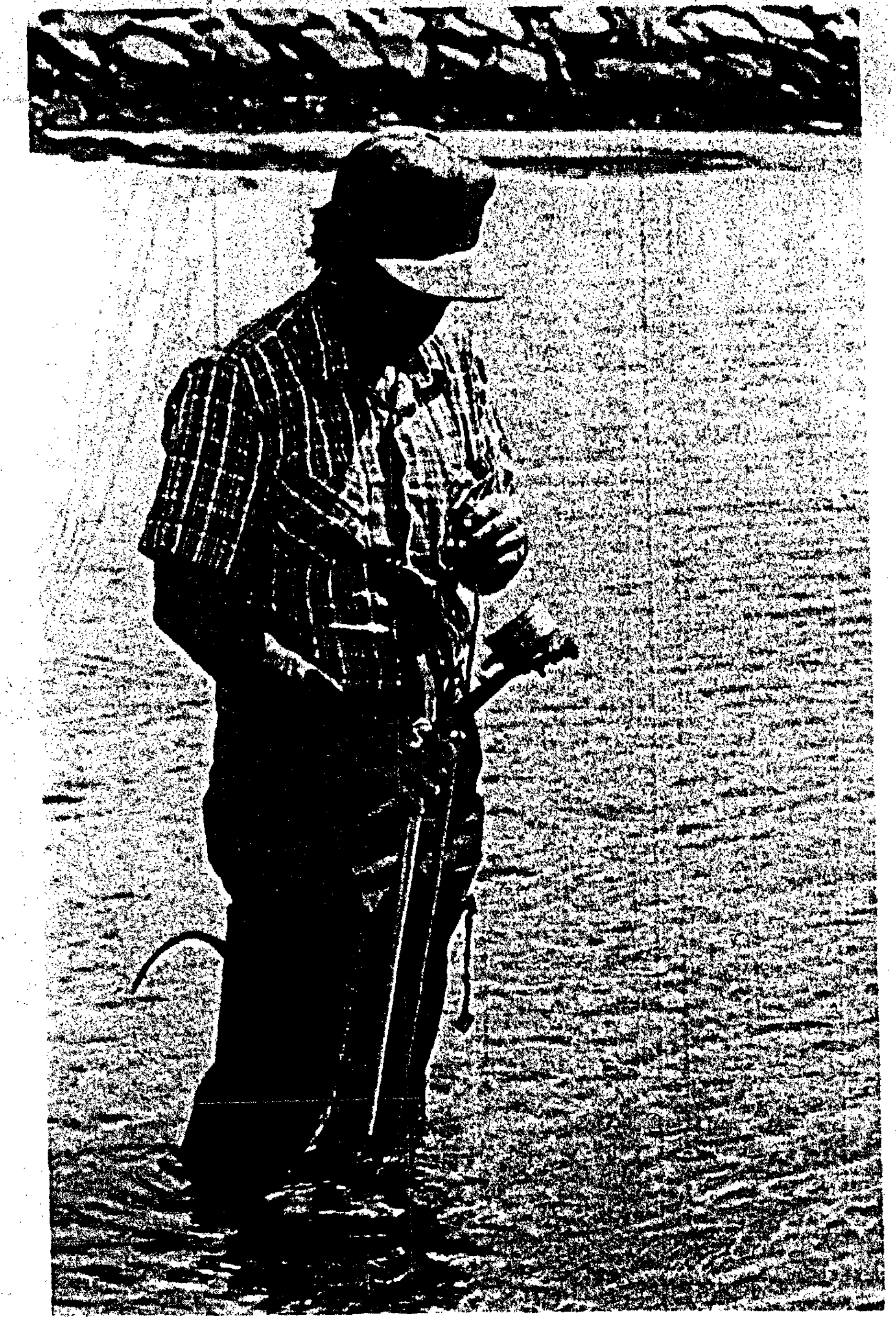

Plate 2. Operation of the Weiss (ECO) saturmeter at Pilgrim Station

into the tubing eventually reaches equilibrium with the respective partial pressures in the water. Pressure (differential) was read directly from a gauge attached to the tubing. Immersion and agitation over a 15-20 minute period were generally sufficient to achieve equilibrium (Plate 2). Water temperature and barometric pressure were measured concurrently. When total dissolved gas pressure exceeds barometric pressure the water is supersaturated. Two 250 ml water samples were collected and chemically fixed in the field for subsequent determination of dissolved oxygen concentrations (ppm) in the laboratory by azide modification of the Winkler titration method (American Public Health Association et al. 1971; Strickland and Parsons 1972). Values for water-vapor pressure were taken from Weast and Selby (1962) and those for oxygen saturation were from Weiss (1970). Measurements were taken just below the water's surface.

The formulae utilized to calculate percent saturation values of total dissolved gas (S_{tot}), nitrogen plus argon (S_{N_2+Ar}), and oxygen (S_{O_2}) were obtained from Weiss (1970), revised after Fickeisen et al. (1975), and modified by New England Aquarium (1975) to correct for salinity influence on gas solubility.

Revised formulae follow:

$$\text{Total dissolved gas \% saturation} = \frac{P_{atmos} + P_{sat} - P_{H_2O}}{P_{atmos}} \times 100$$

$$\text{Nitrogen plus argon percent saturation } (S_{N_2+Ar}) = \frac{P_{atmos} + P_{sat} - P_{H_2O} - \left(\frac{O_2}{O_{2\,sat}} \times .2094 \times P_{atmos}\right)}{(P_{atmos} - P_{H_2O})\ (.7902)} \times 100$$

$$\text{Oxygen percent saturation } (S_{O_2}) = \frac{O_2}{O_{2\,sat}} \times 100$$

where: P_{atmos} = barometric pressure (mm Hg)

P_{sat} = saturometer gauge pressure (mm Hg) reading, which is the difference between the barometric pressure and total dissolved gas pressures.

P_{H_2O} = water vapor pressure at ambient water temperature (mm Hg)

O_2 = oxygen concentration (ppm)

$O_{2\,sat}$ = oxygen saturation value at ambient water temperature and salinity (ppm).

We undertook a short-term project in 1983, relative to regulatory concerns as to the extent of potentially lethal gas saturations in the thermal plume at PNPS, because of concern for possible problems downstream of the barrier net installed in the discharge canal. Our objective was to define the levels of nitrogen saturation - specifically the 115% surface nitrogen isopleth in the discharge plume as it emanates from the effluent canal. Our work was conducted bracketing the plume from outside the discharge jetties seaward for about 183 m. Field measurements were collected in April and September of 1983 on both flood and ebb tides when the plant was operating at or near full capacity. We sampled 11 stations (Fig. 1) during offshore winds in order to measure maximum distal effect of the plume on nitrogen saturations at the water's surface. Two Weiss saturometers were used to measure total gas pressure. Dissolved oxygen samples were collected, fixed, and returned to the laboratory for titration analyses. Temperature, salinity, and barometric pressure were recorded.

IV. RESULTS AND DISCUSSION

1) Gas Saturations

Based on seven years (1975-1981) of systematic data collections, seasonal trends in dissolved gas parameters were evident. Although saturation levels in the thermal effluent varied with cooling water temperatures, cyclic seasonal patterns occurred in both ambient and discharge waters (Fig. 2). Ambient surface seawater temperatures increased during the spring and summer, peaking in late August or early September. Over the seven years of study, water temperatures in the intake embayment were measured from -1.5 C to 24.0 C (29.3 F to 75.2 F). Discharge temperatures fluctuated generally above ambient commensurate with changes in plant operating load, which ranged from 0-100% of capacity. At 100% plant operating output, 4.7 x 10" J/hr of heat are removed from the station's condensers resulting in a maximum temperature rise (Δ T), within the system, of 16.1 C (34.1 F) above ambient. The highest discharge water temperature recorded while sampling was 34.8 C (94.6 F) obtained in August 1980.

Dissolved oxygen (DO) concentration (ppm), which was inversely related to water temperature, peaked during the winter when temperatures were lowest (Fig. 2). Levels in both the intake and discharge canal were relatively similar, with discharge values often just slightly lower. An exception was during plant outages when, with a reduction in plant pump output, oxygen concentration typically declined markedly below ambient in the discharge canal with the

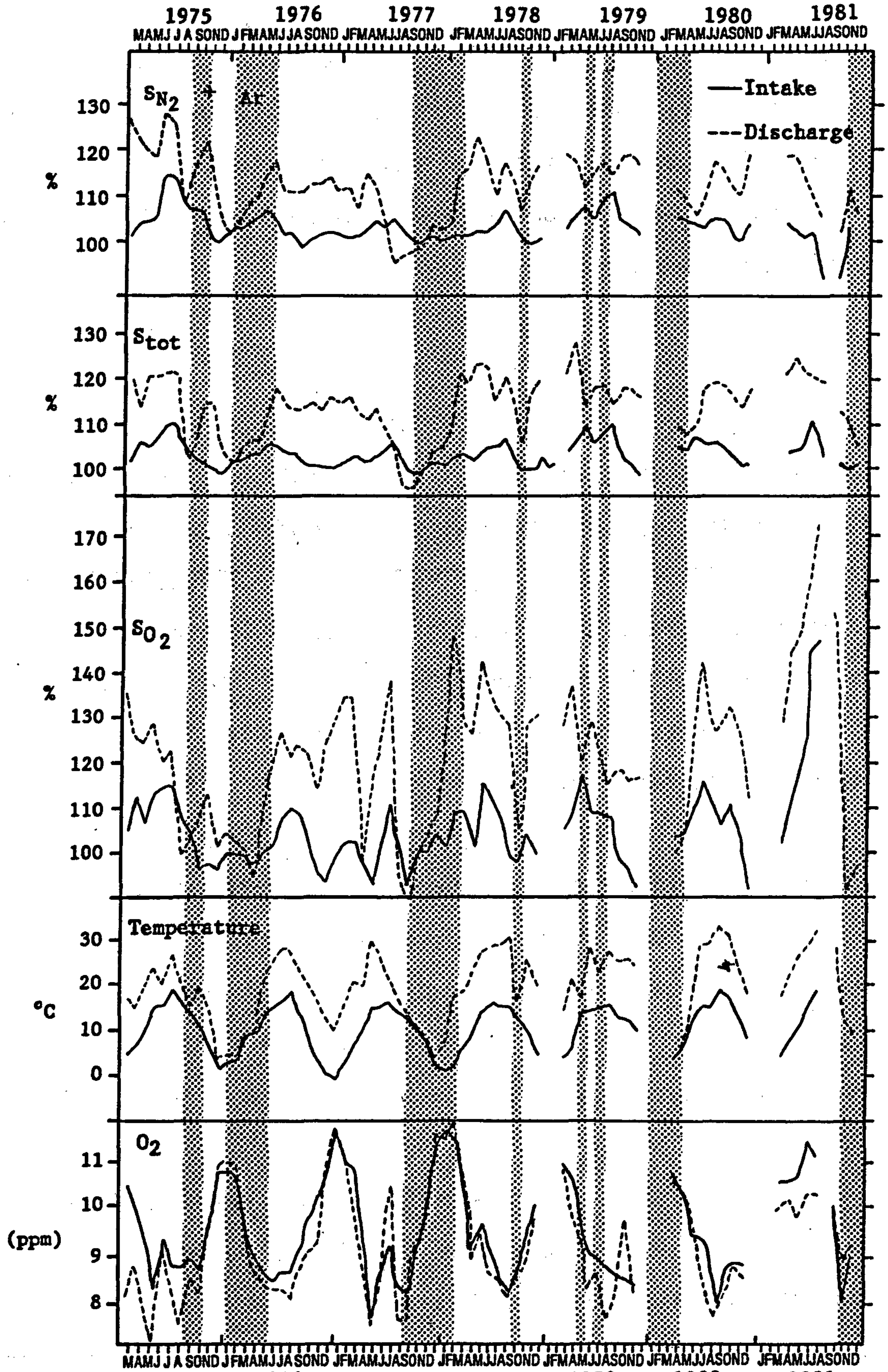

Figure 2. Monthly means of percent saturation of dissolved nitrogen plus argon (S_{N_2} + Ar), total dissolved gas (S_{tot}), and dissolved oxygen (S_{O_2}), and corresponding mean water temperatures (C) and dissolved oxygen (O_2) concentrations within the intake and discharge waters of Pilgrim Nuclear Power Station, 1975-1981. (Stippled areas indicate plant outages or reduced power production.)

lack of water circulation. The highest concentration of dissolved oxygen (13.1 ppm) was measured in the intake embayment. The lowest reading (5.2 ppm) occurred in the discharge canal in September 1975 during a plant outage.

Gas saturations are influenced by water temperature. All saturation levels of total dissolved gas, nitrogen plus argon, and oxygen (Table 1) were highest during periods of elevating ambient water temperatures (spring and summer). Under ambient conditions, total gas saturation and that of nitrogen plus argon were most often at equilibrium ($\simeq$100% saturation) during autumn and winter but supersaturated (> 100%) otherwise. Ambient levels of dissolved oxygen were variable but generally saturated throughout the year. Annual fluctuations in saturation levels of oxygen were greater than for total gas or for nitrogen plus argon (Fig. 2). Nebreker et al. (1976) reported that since nitrogen is inert, concentrations of this gas vary less than oxygen, which is influenced by biological activity.

Dissolved gas measurements in the discharge canal were supersaturated during plant operation but were usually at equilibrium during plant outages. The cooling water becomes supersaturated with oxygen in proportion to the temperature rise across the condensers. Discharge oxygen saturation levels typically ranged from 120%-140% at full power station operation. Atypically, effluent oxygen saturations in June and July of 1981 were considerably higher (x = 163%) than during the same time period for previous years (1975-1980; x = 128%). This was attributable to higher dissolved oxygen concentrations (ambient and discharge) in June and July of 1981, as compared to previous years, averaging 10.9 ppm and 8.7 ppm, respectively.

Dissolved nitrogen plus argon reached a maximum saturation of 126.7% in the discharge canal during March 1979. The annual mean discharge saturation of nitrogen plus argon was < 115% for all years except 1975 and 1979 (Table

Table 1. Pooled monthly mean water temperatures (C), dissolved oxygen concentrations (ppm), and dissolved gas saturations (%) for total dissolved gas (tot), nitrogen plus argon (N_2+Ar), and oxygen (O_2) measured in the intake and discharge waters at Pilgrim Nuclear Power Station, 1975-1981.

	Intake					Discharge				
Month	Temp.	O_2 Conc.	S_{tot}	S_{N_2+Ar}	S_{O_2}	Temp.	O_2 Conc.	S_{tot}	S_{N_2+Ar}	S_{O_2}
January	0.6	11.0	99.3	99.5	98.8	8.0	10.9	103.5	103.5	104.1
February	1.3	11.4	101.2	101.7	99.4	7.0	11.5	104.1	101.9	112.7
March	4.3	11.0	102.1	101.9	103.1	12.0	11.0	116.8	114.2	127.5
April	6.7	10.6	106.9	100.1	107.8	14.0	10.2	115.8	112.2	125.3
May	10.7	9.3	104.1	103.5	105.1	17.0	9.1	115.3	114.7	117.3
June	14.3	8.6	104.8	103.2	110.7	23.7	8.3	117.5	113.8	131.4
July	15.0	8.8	105.2	104.2	109.1	23.7	8.6	116.0	113.4	125.5
August	17.0	8.9	105.8	105.1	108.3	25.0	9.1	114.3	111.1	126.2
September	16.0	8.6	101.5	95.9	108.7	21.3	7.7	109.5	106.5	120.8
October	13.0	8.8	99.7	99.8	98.9	17.3	8.2	107.8	107.6	108.9
November	9.7	9.3	99.5	100.1	97.0	16.7	9.0	110.9	110.5	112.2
December	5.7	9.9	99.8	100.3	97.6	13.0	9.6	112.6	111.9	115.4
Grand Mean 1975-1981	9.5	9.7	102.5	101.3	103.7	16.0	9.4	112.0	110.1	118.9

2). Within any given year of the study, discharge levels were never below ambient except during plant outages (Fig. 2), and exceeded 115% about 34% of the time (Fig. 3).

Reports from earlier studies attributed GBD to excess nitrogen, oxygen, or carbon dioxide (Marsh and Gorham 1905; Woodbury 1941). Subsequently, some investigators (Nitrogen Workshop 1972; Weitkamp and Katz 1973) contended that dissolved nitrogen is of primary importance. The U.S. Environmental Protection Agency recommended that 110% nitrogen saturation be considered the maximum tolerable level by fish, specifically salmonids (Newcomb 1974). Marcello et al. (1975) suggested that the threshold tolerance level of nitrogen saturation for Atlantic menhaden is approximately 115% at the surface. This recommended level was based on work conducted by Clay et al. (1976) of the New England Aquarium, who determined the 96 hr LD_{50} tolerance level for menhaden was 112% at 22C (72 F). Krabach and Marcello (1978) observed that menhaden in the discharge canal at PNPS were generally 0.3 to 0.6 m below the water surface. They reported that with increased water depth, the resulting hydrostatic pressure reduced a surface nitrogen saturation level of 115% to 112% at only 0.3 m of depth. It was therefore concluded that a surface nitrogen saturation of 115% would provide adequate protection from GBD-induced mortality at PNPS.

2) Saturated Dissolved Gas Plume Mapping

A 1983 survey to map gas saturations in the thermal plume revealed that during low tide, nitrogen plus argon saturations exceeding 115% are unlikely to occur in effluent surface waters beyond the mouth of the discharge canal. This is probably due to the shallow water and concomitant turbulence which is increased by the numerous boulders at the discharge mouth during ebb tide. These conditions are known to reduce gas supersaturation in streams and rivers

Table 2. Percent distribution of saturation levels by year of total dissolved gas (S_{tot}), nitrogen plus argon (S_{N_2+Ar}), and oxygen (S_{O_2}) at Pilgrim Nuclear Power Station.

Year	Saturation levels (%)	No. Samples	S_{tot} Intake	S_{tot} Discharge	S_{N_2+Ar} Intake	S_{N_2+Ar} Discharge	S_{O_2} Intake	S_{O_2} Discharge
1975	< 100		20.6	7.9	17.5	6.3	20.6	9.5
	100 - 105		47.6	9.5	60.3	11.1	25.4	4.8
	105 - 110	63	25.4	6.3	20.6	7.9	20.6	6.3
	110 - 115		6.3	14.3	1.6	15.9	15.6	15.9
	> 115		0.0	61.9	0.0	58.7	17.5	63.5
1976	< 100		24.5	6.1	21.3	4.2	51.0	18.4
	100 - 105		61.2	24.5	61.7	19.1	22.4	20.4
	105 - 110	49	14.3	14.3	14.9	31.9	10.2	10.2
	110 - 115		0.0	36.7	2.1	29.8	12.2	12.2
	> 115		0.0	18.4	0.0	14.9	4.1	38.8
1977	< 100		41.2	27.4	31.4	33.3	60.8	29.4
	100 - 105		52.9	11.8	62.7	9.8	17.6	5.9
	105 - 110	51	5.9	9.8	5.9	29.4	9.8	11.8
	110 - 115		0.0	37.3	0.0	15.7	7.8	3.9
	> 115		0.0	13.7	0.0	11.8	3.9	49.0
1978	< 100		28.3	4.3	41.3	4.3	34.8	4.3
	100 - 105		58.7	8.7	47.8	10.9	23.9	4.3
	105 - 110	46	13.0	6.5	10.9	15.2	15.2	6.5
	110 - 115		0.0	17.4	0.0	26.1	13.0	2.2
	> 115		0.0	63.0	0.0	43.5	13.0	82.6
1979	< 100		12.8	2.6	5.1	2.5	35.9	2.6
	100 - 105		53.8	2.5	56.4	2.6	23.1	0.0
	105 - 110	39	23.1	7.7	30.8	10.3	20.5	15.4
	110 - 115		5.1	12.9	5.1	25.6	10.3	7.7
	> 115		5.1	74.4	2.6	59.0	10.3	74.4
1980	< 100		19.3	0.0	29.0	3.2	25.8	9.7
	100 - 105		58.1	12.9	58.1	9.7	22.6	6.4
	105 - 110	31	22.6	3.2	12.9	22.6	9.7	6.4
	110 - 115		0.0	29.0	0.0	41.9	25.8	3.2
	> 115		0.0	54.8	0.0	22.5	16.1	74.2
1981	< 100		37.9	13.8	44.8	10.3	27.6	20.7
	100 - 105		48.3	3.4	51.7	20.7	13.8	3.4
	105 - 110	29	10.3	10.3	3.4	20.7	13.8	6.9
	110 - 115		3.4	17.2	0.0	24.1	10.3	0.0
	> 115		0.0	55.2	0.0	24.1	34.5	69.0

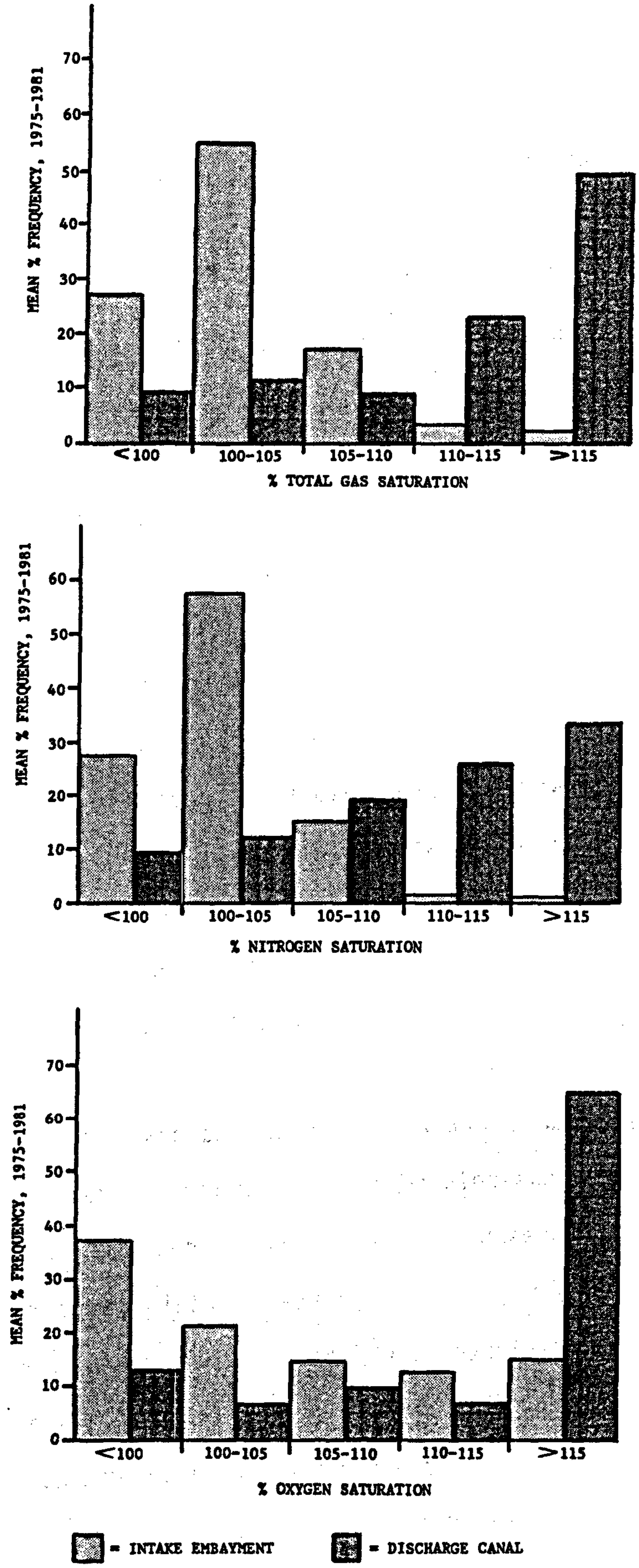

Figure 3. Frequency distribution of percent gas saturations in the marine waters around Pilgrim Station, for the study years 1975-1981 combined.

(Clark 1977). During flood tide, however, surface saturations exceeded 115% out to 100 m from the mouth of the discharge canal. Less turbulence is created by the rocks and boulders at high tide because they are submerged. In both spring and fall, saturations were higher during high water at all stations sampled (Figs. 4-7). At both high and low tide, saturations were highest near the mouth of the discharge canal and generally decreased seaward.

A review of the data showed that nitrogen plus argon gas saturations were high in April and late August through early September (Lawton et al. 1978). In 1983, nitrogen saturations were higher in April than in September, as expected, given past data and annual trends for the Gulf of Maine described by Stickney (1968). Stickney (op cit.) reported that oxygen concentration tends to be highest when water temperature is low, but percent saturation is highest during periods of rising temperature. Further, the rapid warming of saturated water or the mixing of warm and cold saturated water results in supersaturation. All of these conditions exist at PNPS during April.

Clay et al. (1976) determined that a probable threshold toxic effect of GBD for adult Atlantic menhaden exists between 115 and 120% nitrogen saturation at 22 C (72 F). To reiterate, although our plume mapping indicates that 115% nitrogen saturations do not occur beyond the mouth of the discharge canal at low tide, this level does occur in surface waters out to 100 m at high water. The potential for gas-related disease, which exists at PNPS, is likely reduced, in part, by the presence of the barrier net near the mouth of the discharge canal. The net may create greater turbulence which could reduce saturation levels and is designed and deployed to prevent large numbers of fish from moving into the upper two-thirds of the canal where they would be continuously exposed to high levels of supersaturated gases. However, the extended distance of supersaturated water out from the barrier net may pose a problem to menhaden remaining in the area for prolonged periods.

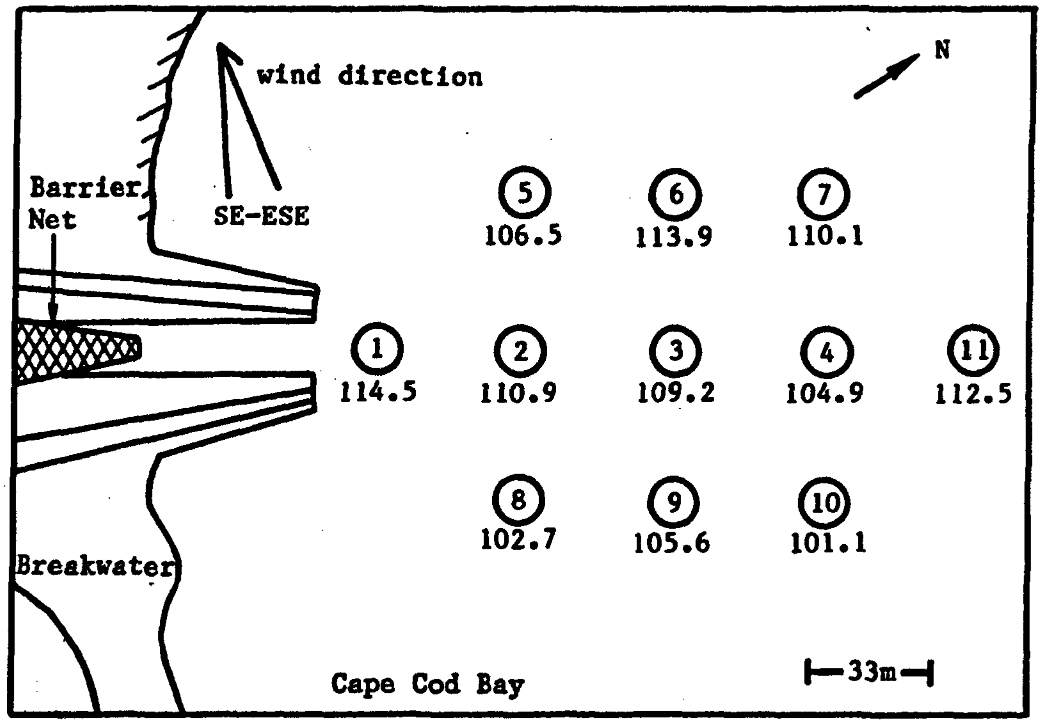

Figure 4. Nitrogen + Argon percent gas saturations at 11 stations in PNPS discharge plume, 7 April, 1983 - low tide.

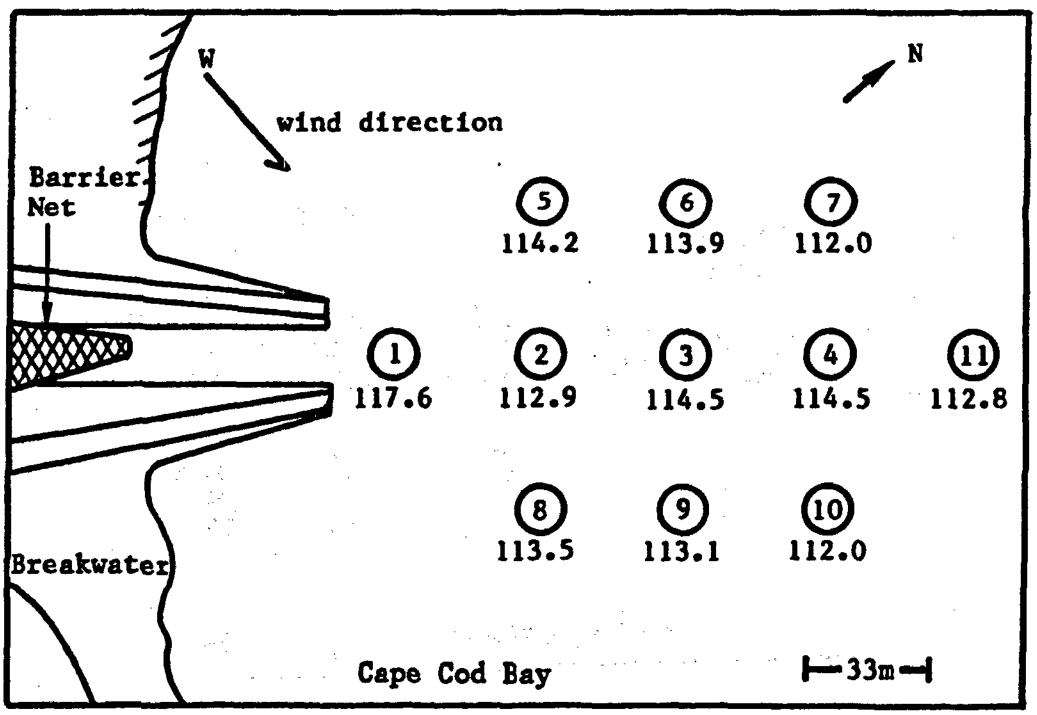

Figure 5. Nitrogen + Argon percent gas saturations at 11 stations in PNPS discharge plume, 26 April, 1983 - high tide.

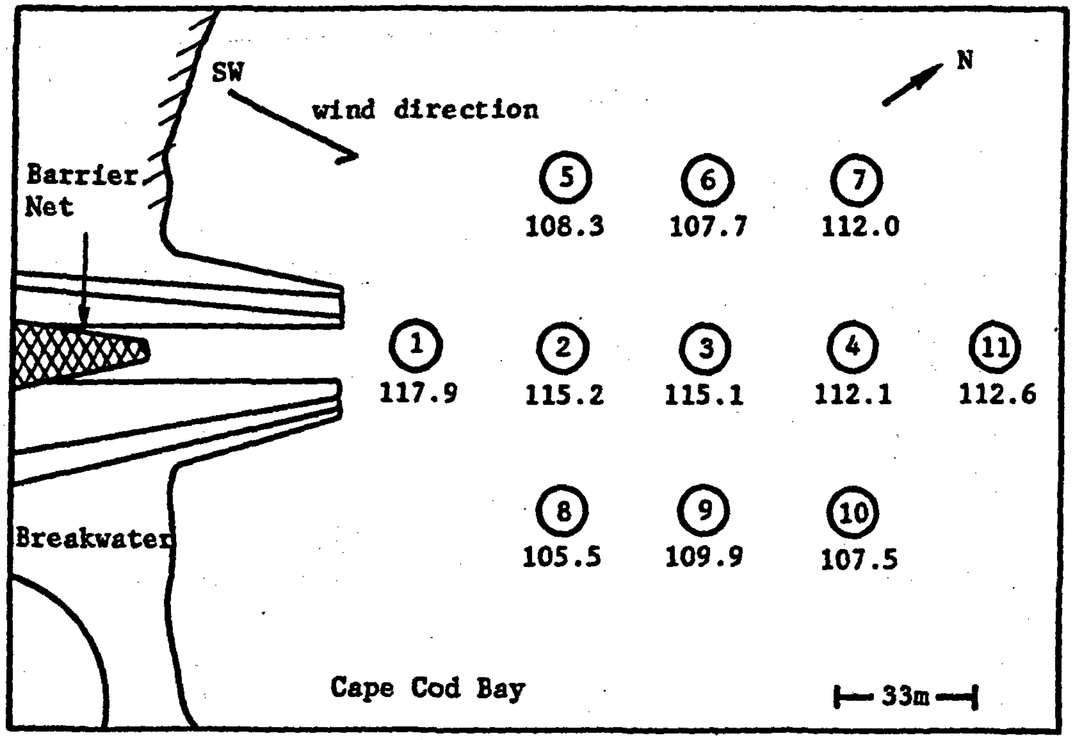

Figure 6. Nitrogen + Argon percent gas saturations at 11 stations in PNPS discharge plume, 6 September, 1983 - high tide.

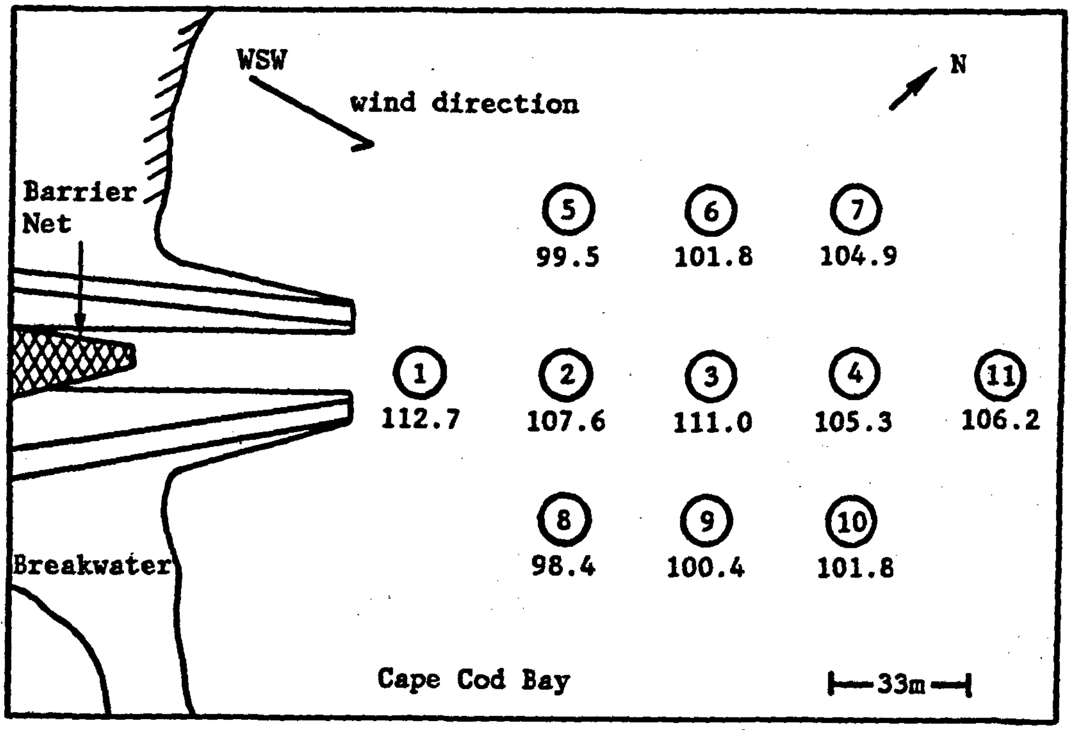

Figure 7. Nitrogen + Argon percent gas saturations at 11 stations in PNPS discharge plume, 26 September, 1983 - low tide.

3) Gas Bubble Disease Impact Incidents at Pilgrim Station

April 1973

An estimated 100,000 Atlantic menhaden, approximately 30-40 cm total length (TL) and averaging 500 g in weight, established residence in the discharge canal and thermal plume at PNPS in early April 1973 (Marcello and Fairbanks 1976). This incident occurred when migrating menhaden had arrived in the Plymouth area from their wintering grounds. At the time, the power plant was operating at or near maximum capacity, and ambient seawater and discharge temperatures were 5 C (41 F) and 21 C (70 F), respectively. With a preferred temperature range of 15-20 C (59-68 F) (Goode 1879), menhaden were evidently attracted to the warmer discharge water.

There was no observed avoidance response by these fish to the supersaturated discharge water in contrast to literature reports for chinook salmon (Oncorhynchus tshawytscha) and Atlantic herring (Clupea harengus harengus) in other areas (Stickney 1968; Meekin and Turner 1974; Dawley and Ebel 1975). Mortality was noted within 24 hours of the first observation of fish in the discharge canal. From 9-19 April, an estimated 43,000 menhaden died. At least 90% of the fish examined displayed one or more of the following symptoms: gross external lesions, gas emboli, pronounced exophthalmus (Plate 3), and loss of equilibrium. Frequently, individuals were observed in the thermal effluent to leap clear of the water and propel themselves on their sides at the surface. Prior to death, fish became disoriented and gyrated on or just below the water's surface. On the basis of external symptoms, aberrant behavior, and external/internal pathological examination (Wolke 1973), GBD was diagnosed as the causative agent (Marcello and Fairbanks 1976).

Water temperature, dissolved oxygen concentration, and oxygen saturation level averaged 20 C (68 F), 9.7 ppm, and 126%, respectively, during the observed mortality. Nitrogen levels were not determined. From 20-22 April,

Plate 3. Finfish specimen afflicated with gas bubble disease at Pilgrim Station. (Photo by Edgartown Research Laboratory, New England Aquarium, Boston, MA).

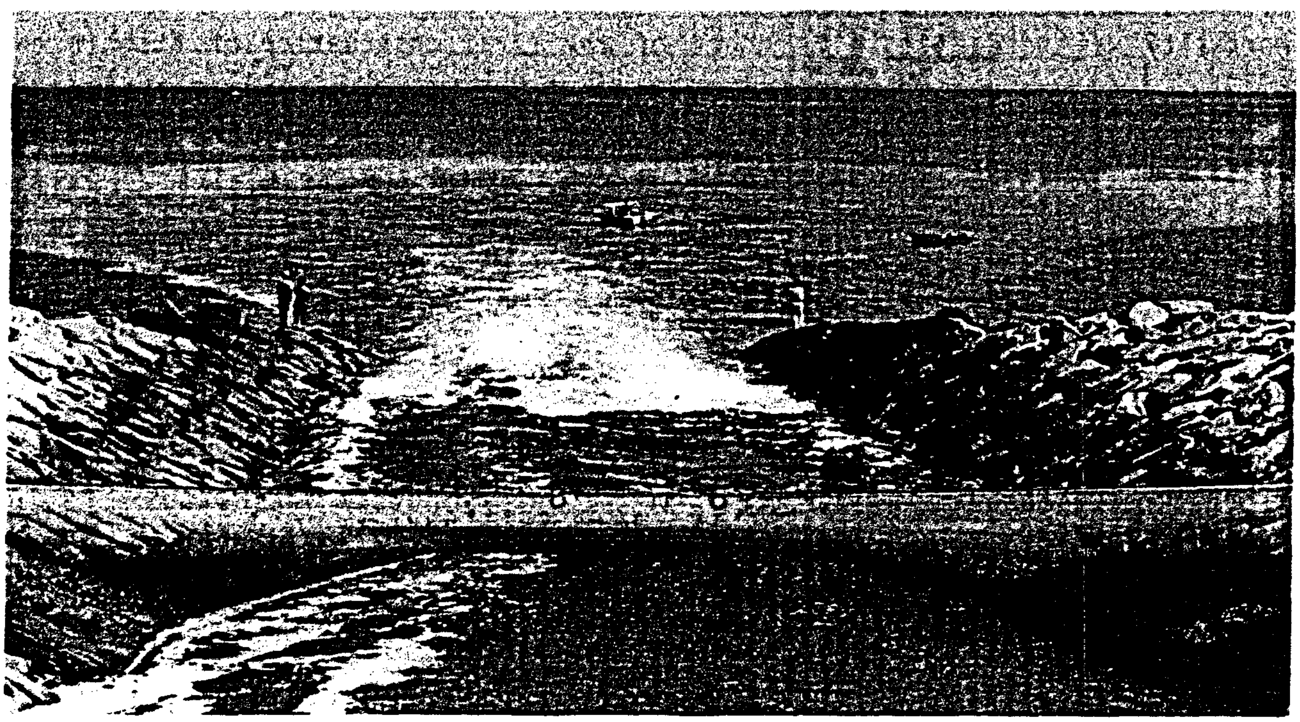

Plate 4. Modified barrier net in place at Pilgrim Station discharge canal (foreground); also pictured is thermal effluent discharging into Cape Cod Bay with associated turbulence at low tide.

PNPS gradually reduced power output which, in turn, decreased the discharge temperature to 14 C (57 F), and concomitantly dissolved oxygen saturation dropped to 119%. On 23 April, the power station resumed full power operation, and by 30 April the discharge water temperature had increased to 22 C (72 F), and the oxygen saturation to 124%. The school of menhaden left the discharge area unexpectedly on 30 April; ambient water temperature was 8 C (46 F) at the time. The reason for their departure is not known.

April 1975

GBD also caused a second but lesser mortality of approximately 5,000 menhaden (mean size = 30 cm TL) in the discharge canal and plume area of PNPS from 2-15 April, 1975. Ambient mean seawater temperature was 6 C (43 F), DO concentration 11.3 ppm, and saturation parameters near equilibrium in the intake embayment during the incident. Effluent water temperature was 16 C (61 F) when menhaden were first observed in the vicinity of the power plant. Water temperature averaged 18 C (64 F), and oxygen content, 10.8 ppm while fish were in the discharge area. Menhaden mortality apparently peaked on 15 April when the discharge temperature reached 19 C. Total dissolved gas saturation increased from 118% on 4 April to 128% on 15 April; oxygen and nitrogen plus argon saturations increased from 126% and 115% on 4 April to 149% and 123% on 15 April, respectively. Oxygen saturation levels were similar during both menhaden mortalities at Pilgrim Station. A planned reduction in plant operating capacity on the evening of 15 April decreased water temperature of the thermal discharge to near ambient, and with that gas saturation levels dropped concurrently. By the following morning, surviving menhaden left the plant locale, presumably because the reduction in discharge temperature nullified any thermotaxis.

November 1975

In late November 1975, a school of large striped mullet (Mugil cephalus), visually estimated at 500 fish (38-64 cm TL), moved into the discharge canal at PNPS, apparently attracted by the warm water (Fairbanks and Lawton 1977). This was an unusual occurrence, as striped mullet only stray from southern waters and usually as juveniles (Bigelow and Schroeder 1953). Ambient seawater and effluent temperatures were 10.0 C (50.0 F) and 19.8 C (67.6 F), respectively, upon arrival of the fish and declined to 2.0 C (36.5 F) and 11.0 C (51.8 F) by 5 January, when mullet departed from the discharge canal following an unscheduled plant outage. Seven of 11 specimens captured in mid-December exhibited gross external symptoms of GBD. Dissolved nitrogen and total gas saturations averaged 115.2 and 114.9%, respectively, while mullet were in the discharge canal. However, no mortality clearly ascribable to GBD was noted.

August 1985

On 31 July 1985, fish with symptoms of GBD were noted above the barrier net in the upper discharge canal at Pilgrim Station. The species affected were Atlantic silverside, river herring, and Atlantic menhaden (for the latter two species, only juveniles were involved). Dissolved gas saturations, in particular nitrogen plus argon, were measured for the next five days (1-5 August). Nitrogen plus argon saturations ranged from 112-119% in the discharge canal. Discharge Water temperatures ranged from 22.6-30.5 C (72.7-86.9F), and Station operational capacity was at a 100%. Tide was a factor, with saturation levels in the canal declining about 10% at the ebb.

Diving observations (1-3 August) revealed that of the 5000-7000 fish in the upper discharge canal about 20% exhibited behavioral characteristics and gross external symptoms (e.g., exophthalmus and hemorrhaging) of GBD.

However, no mortality was apparent in the canal although several individuals were severely stressed. No fish were observed below the barrier net to be afflicted. As the fish had departed from the canal within a week's time, there was determined to be no serious threat to local ecology, and no mitigative actions were requested by the regulatory agencies.

4) Mitigation of Gas Bubble Disease Impacts

There are studies that maintain that the component saturation levels of oxygen and nitrogen, and the resulting proportionate ratios are less important than total dissolved gas saturation (Rucker and Kangas 1974; Rucker 1975; Weitkamp and Katz 1975; and Nebreker et al. 1976). Fish mortalities will not occur unless total saturation exceeds 100% regardless of the saturation ratios of oxygen and nitrogen (Nebreker et al. 1976). Other factors which can affect the severity of GBD, depending upon species, include the level of physical activity of affected organisms (Marcello and Strawn 1972), depth of fish in the water column, size of fish, synergism of temperature to total gas pressure, avoidance reaction (Weitkamp and Katz 1973, 1975), and the expousre time. Colt (1983) reported that gas bubbles will exist in a liquid only if the total dissolved gas pressure exceeds the total pressure at that depth.

As a result of menhaden mortalities, a number of possibilities for minimizing or preventing future mortalities were evaluated for PNPS (Marcello et al. 1975; Doret et al. 1976; and Krabach and Marcello 1978). These considerations included: behavioral barriers, physical barriers, high current velocity barriers, offshore diffuser system, effluent degassification, dilution pumping, power reductions, and unit outage. It was concluded that a fish net barrier would be a cost-effective method for addressing the problem; thus in the fall of 1973, a preliminary physical barrier was installed at PNPS. This barrier consisted of a modified bottom trawl net that was positioned in the discharge canal at a location approximately 61 m from its downstream end

(Plate 4). Net placement was dictated by engineering considerations which included protection from storms. Deficient in preventing fish passage, the aforementioned net was found to lift off the bottom allowing fish to get under the footrope. In 1976, a more effective structural support system was incorporated into the barrier design, which included formed concrete side and bottom sills to which the net was anchored.

The barrier net (50.8 mm or 2-inch stretch mesh) was designed to preclude adult menhaden from entering the major portion of the discharge canal but does not occlude fish from the thermal plume as it emerges into Cape Cod Bay or the lower third of the canal and, therefore, may not prevent future mortalities in these areas, should similar conditions recur. In October 1985, we observed adult bluefish (Pomatomus saltatrix) in a feeding frenzy chase adult menhaden into the discharge canal as far as the barrier net, keeping them trapped for hours. Although there have been no documented mortalities of finfish attributable to GBD since 1975 at PNPS, it should be noted that this was the last year any number of large fish resided in the discharge canal for an extended period of time. Another limitation is that small fish can pass through the meshes of the net and be exposed to chronic gas supersaturation levels in the discharge canal as observed in the incident of August 1985 (previously discussed in this report).

In conjunction with the barrier net, a bubbler system (air diffuser) was recommended by Marcello et al. (1975), but was not implemented at PNPS. Stripping dissolved gases from the thermal effluent (degassification) would require costly structural modifications to the discharge canal and increase operational costs but, relative to cost-effectiveness, may be preferable, along with the barrier net, to load reduction or unit outage if the frequency of fish mortalities was to increase in the future.

V. CONCLUSIONS

From years of gas measurements in the surrounding waters of PNPS, the following findings are evident. The highest surface water temperatures (ambient and discharge) generally occur in August and the lowest in January or February. Inversely related to temperature, the concentration of dissolved oxygen in the water peaks in winter. However, dissolved gas saturations are highest during spring and into summer concomitant with increasing ambient water temperatures and lowered gas solubility. Of the principal dissolved gases, oxygen in the intake waters is saturated/supersaturated ($\geq$ 100%) an average of 63% of the time. In the thermal effluent, oxygen saturations > 115% predominate about 60% of the time. Discharge dissolved oxygen saturation levels can range from 120%-140% at full PNPS operation. Total gas saturations in the discharge canal often exceeded 115%. The intake water is $\geq$ 100% saturated with nitrogen plus argon about 75% of the time; levels are highest during the spring and summer seasons. At full power operation, discharge nitrogen saturations are correspondingly highest in spring and summer and can exceed 130%. Sixty percent of the discharge nitrogen measurements were $\geq$ 110% saturated; 34% exceeded the 115% saturation level.

Dissolved nitrogen gas saturations ($\geq$ 115%) potentially lethal to Atlantic menhaden via GBD occur in the thermal cooling water discharge of PNPS during the fish's stay inshore (March - November) in Cape Cod Bay. Migrating menhaden in the spring encounter ambient water temperatures in Cape Cod Bay below the 15 C lower limit of their preferred temperature range. However, during April and May, the thermal discharge is within the menhaden's optimum temperature regime which may signal a positive attraction to fish passing by. Although large numbers of menhaden could possibly be attracted to the warm discharge waters during autumn, this has not yet happened. This does not preclude other species from being attracted in the fall as ambient temperatures decline (e.g., the incident in late November-December, 1975 when an aggregation of large striped mullet took up temporary residence in the discharge canal). GBD problems with adult menhaden are less likely at PNPS in summer because as ambient water warms to an annual high, the corresponding temperature of the thermal discharge becomes a limiting factor exceeding the 20 C upper preferred temperature for menhaden. Thermal attraction is minimal during the warmest season of the year and unlikely during the coldest when most fish have moved into deeper water or migrated out of the Bay.

Tide is a factor influencing the level of effluent gas saturations at PNPS. Nitrogen/argon saturations exceeding 115% in the thermal effluent are unlikely to occur in surface waters beyond the mouth of the discharge canal at low tide. This is attributable, in part, to the shallow water and increased turbulence at the discharge mouth during ebbing water. During high tide, however, surface saturations can exceed 115% out to 100 m from the mouth of the discharge canal. The extended distance of supersaturated water from the discharge canal terminus during flood tide may pose a problem to menhaden or any other fish species (e.g., Atlantic silverside) remaining in the area of the thermal plume for prolonged periods. The potential for gas-related mortality, which exists at the power station, is likely reduced, in part, by the presence of the barrier net positioned near the mouth of the discharge canal. The net is designed and deployed to prevent large fish from entering the major portion of the canal where they would be continuously exposed to high levels of gas saturations.

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