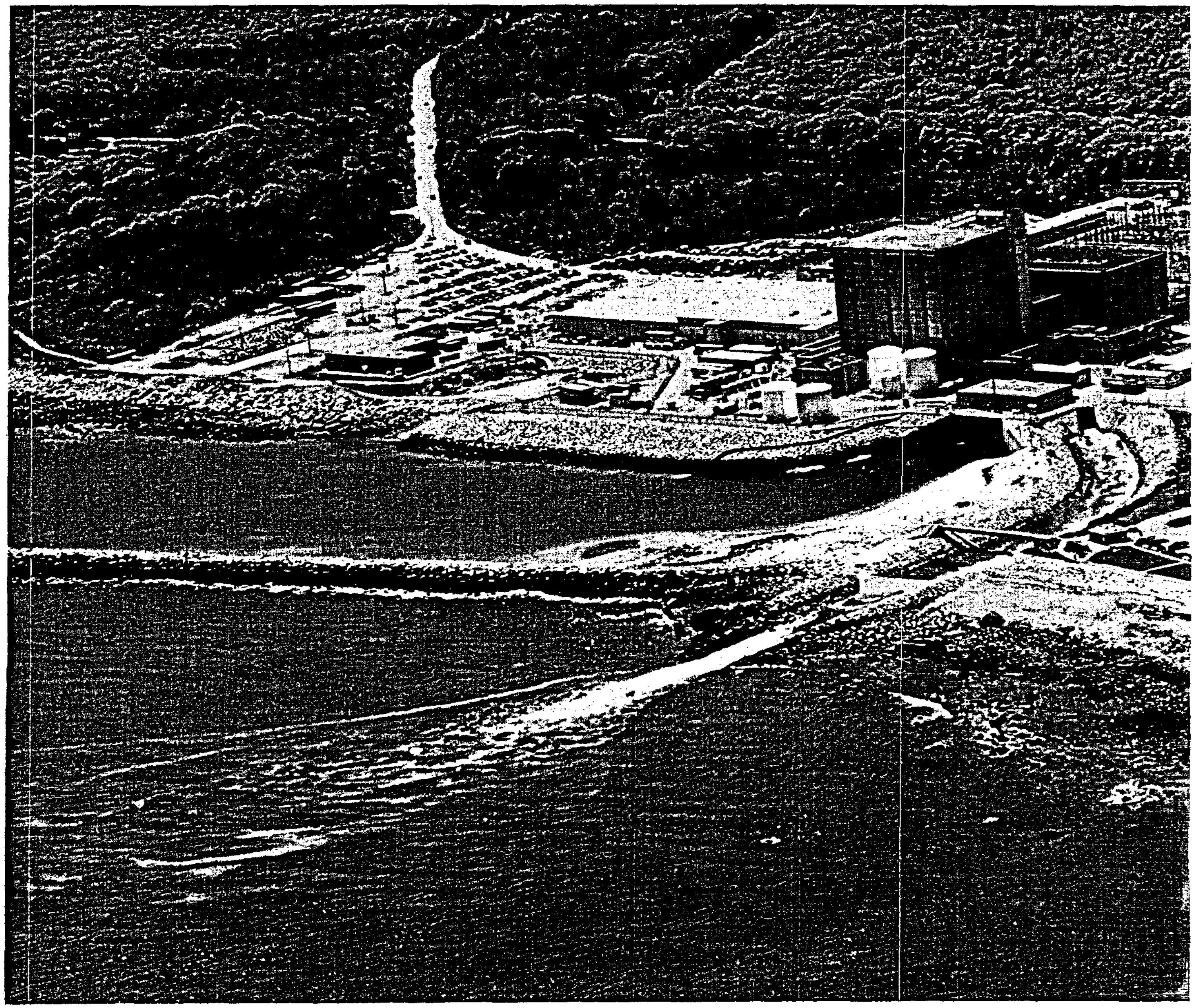
FINAL REPORT

PILGRIM NUCLEAR POWER STATION COOLING WATER DISCHARGE BOTTOM TEMPERATURE STUDY



EG&G GEOS
GLOBAL ENVIRONMENTAL & OCEAN SERVICES

FINAL REPORT

PILGRIM NUCLEAR POWER STATION

COOLING WATER DISCHARGE

BOTTOM TEMPERATURE STUDY

AUGUST, 1994

Technical Report to:

Boston Edison Company
Licensing Division
Pilgrim Nuclear Power Station
600 Rocky Hill Road
Plymouth, MA 02360

By:

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EXECUTIVE SUMMARY

A study of sea-bottom temperature in the vicinity of the cooling water discharge of the Pilgrim Nuclear Power Station was conducted in August, 1994, to map the extent of elevated bottom temperatures associated with the discharge plume, and to characterize plume variability as a function of ambient weather, current, and tide conditions. Fifty-nine internally recording temperature sensors, each mounted in a protective concrete bottom platform, were deployed in an array offshore of the discharge canal. Each instrument recorded temperature at half-hourly intervals. Instruments were concentrated near the discharge, but some were placed farther away to determine the ambient bottom temperature. Supplementary data comprising wind speed and direction, air temperature, plant thermal output and discharge temperature, tide height, and currents were collected.

The measurements were planned to extend over a 6-week period to observe maximum temperatures in late summer, as well as autumn cooling and storm conditions, while the PNPS was operating at full power. Deployment began on 17 August, and the full array was completed on 26 August 1994. Useful data ended on 29 August, after only 2.5 days (5 tidal cycles), when the PNPS unexpectedly shut down for a long period. Partial array data was obtained from 20-26 August. Approximately 75% of the instruments were recovered in late September, and all of them gave good data.

Weather during 26-29 August was warm, with low to moderate southwesterly winds, characteristic of Cape Cod Bay's stratified summer upwelling conditions. Elevated bottom temperatures were observed at each low tide interval, ranging up to 30 °C (86 °F) at instruments close to the discharge canal. Lesser temperature elevations were observed at other locations within 100 m offshore of the discharge, and 15 m to either side. Beyond about 110 m offshore, and ±30 m on either side of the centerline, there was no evidence of the plume.

Seafloor temperatures were mapped to estimate the area subjected to various temperature elevations above ambient for each of the 5 low-tide events. The maximum area covered by the lowest detectable temperature increment (+1 °C) is about 51,000 sq. ft., or 1.2 acres, under these environmental conditions. Significantly elevated temperatures (+9 °C) affect much smaller areas, typically less than 5,500 sq. ft., or about 0.12 acre. The shape and size of the +9 °C elevation contour compares well with the region of affected benthic organisms, as measured in Boston Edison's Benthic Monitoring surveys in June and October 1994. The following table summarizes PNPS operating conditions, peak temperatures, ambient temperature, and affected areas for the five low-tide events, designated events A-E:

Event	Date	Time	PNPS Power	Disch. Temp	Max Observed Bottom Temp		Ambient Temp	Area covered by temperatures elevations of:					
								+1 C (+1.8 F)		+5 C (+9.0 F)		+9 C (+16.2 F)	
		EST	%	deg F	deg C	deg F	deg C	sq. m.	sq. ft.	sq.m.	sq. ft.	sq. m.	sq. ft.
A	08/26/94	21:00	100	90.8	29.5	85.1	15.9	4,383	47,178	1,278	13,755	518	5,580
B	08/27/94	09:00	100	89.6	26.6	79.9	16.2	3,460	37,243	938	10,095	274	2,954
C	08/27/94	22:00	95	92.6	30.0	86.0	17.3	4,717	50,769	1,516	16,318	481	5,180
D	08/28/94	10:30	47	81.6	26.6	79.9	17.3	4,355	46,872	622	6,699	0	0
E	08/28/94	23:00	100	89.2	25.0	77.0	16.4	2,488	26,785	722	7,771	467	5,029

Note: 1 acre = 43,560 sq. ft.

During high tide, when the water is deep and the exit velocity is low, the discharge plume separates from the sea bottom very close to the canal mouth. No discernable temperature elevations were observed at any bottom location, even at stations as close as 50 m from the mouth of the discharge canal. Time histories of bottom temperature show that the plume begins to attach to the seafloor at about mid-tide. Extremal temperatures are observed only for short periods around slack water at low tide.

During 22-23 August, when only a partial array of bottom temperature recorders was installed, winds were from the north and northeast at higher speeds, representative of a homogeneous, downwelling circulation regime with higher temperatures and southward currents. Elevated seafloor temperatures were observed during this period at several stations near the outer edge of the partially installed instrument array, at locations as far as 200 m from the discharge canal. The alongshore extent of this plume was also much greater than was observed during upwelling conditions. All evidence of the discharge plume at these offshore locations disappeared when the onshore wind ceased, demonstrating the strong dependence of plume dynamics on the ambient circulation regime.

Although the abbreviated measurement interval of this study precludes detailed description of bottom temperatures under conditions other than summer upwelling, the results suggest that the worst-case condition would consist of downwelling-favorable winds in conjunction with spring tides, following a sustained period of unusually warm weather. Under these conditions, peak bottom temperatures could be higher, and the plume's bottom extent could also be significantly larger, than those observed in this study. However, such extremal conditions would occur only rarely, and would be unlikely to persist for more than a few hours, limiting their effect on benthic organisms.

PREFACE AND ACKNOWLEDGMENTS

This study of sea floor temperatures in the vicinity of the Pilgrim Nuclear Power Station's cooling water discharge was carried out under Boston Edison Company Purchase Order No. LSP000994. Mr. Robert D. Anderson, Principal Marine Biologist, was Boston Edison's technical monitor.

The study was performed by EG&G Global Environmental and Ocean Services (GEOS), a business element of EG&G Marine Instruments, Inc. of Burlington, Massachusetts. This report was prepared by Dr. Bruce A. Magnell, GEOS Project Manager. Mr. J. Bruce Andrews of ApDevInt Research, Inc., performed most of the data analysis. GEOS also gratefully acknowledges the efforts of Mr. Darren D. Moss, EG&G field engineer, the vessel operator, TG&B Marine Services, Inc. (Mr. Mark Avakian, Mr. Alan Davison), and the dive team (Mr. Scott Story and Mr. John Ryther).

EG&G GEOS would also like to acknowledge the members of the Benthic Subcommittee of the Pilgrim Administrative-Technical Committee for their guidance and review. Thanks are especially due to the subcommittee chair, Dr. Don C. Miller of the U.S. Environmental Protection Agency, Environmental Research Laboratory, Narragansett, Rhode Island.

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1. INTRODUCTION

Sea-bottom temperature in the vicinity of the cooling water discharge from Boston Edison Company's Pilgrim Nuclear Power Station, Plymouth, Massachusetts, was studied in August and September 1994. The study was sponsored by Boston Edison Company to quantify the seafloor area affected by elevated temperatures.

1.1 BACKGROUND

Boston Edison Company's 670-megawatt (electrical) Pilgrim Nuclear Power Station (PNPS) has been in operation since late 1972. The PNPS is located on the coast at Rocky Point, Plymouth, Massachusetts, on the western side of Cape Cod Bay (Figure 1), and uses seawater for once-through cooling. In accordance with its NPDES Permit (U.S. Environmental Protection Agency and Massachusetts Division of Environmental Protection), Boston Edison has conducted an extensive environmental measurement program in the coastal environment, beginning in the late 1960's during the design/construction phase, and continuing to the present. The study program has monitored biological impacts of the cooling water discharge, including benthic studies to determine the discharge plume's effect on bottom-dwelling organisms. In 1994, Boston Edison sponsored this physical oceanography study of the bottom temperature characteristics of the cooling water plume, to complement and assess the benthic monitoring program, particularly with regard to the direction of any future studies in this area.

1.1.1 The Ocean Environment at the PNPS

Geography - Cape Cod Bay, the southern portion of Massachusetts Bay, is about 30 km (20 n.mi.) wide at the latitude of the PNPS. The Bay is relatively shallow, with local water depths of typically 3 m (10 ft) close to shore and up to 10 m (35 ft) several kilometers offshore of the plant site (Figure 2). The sea floor in this part of Cape Cod Bay is generally sandy, but a shallow, rocky ledge extends seaward from Rocky Point, northwest of the plant. As a result, the southern half of the study region has a smooth, sandy bottom with a typical depth of 7 m (21 ft), while the northern half is shallower with rock ledges and boulders, typically 4 m (12 ft) deep.

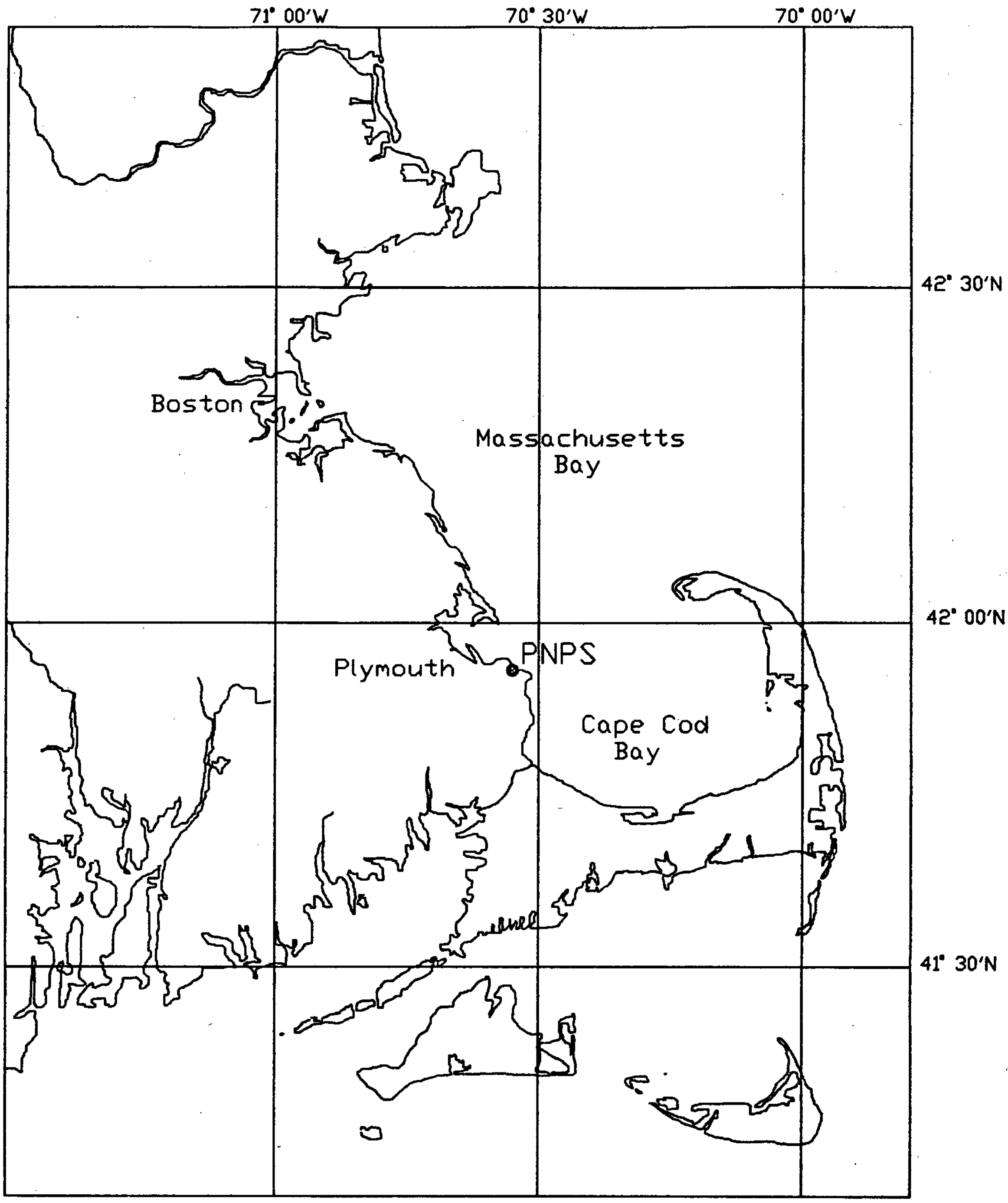


Figure 1. Map of Massachusetts Bay, showing location of Pilgrim Nuclear Power Station (PNPS) on the western side of Cape Cod Bay.

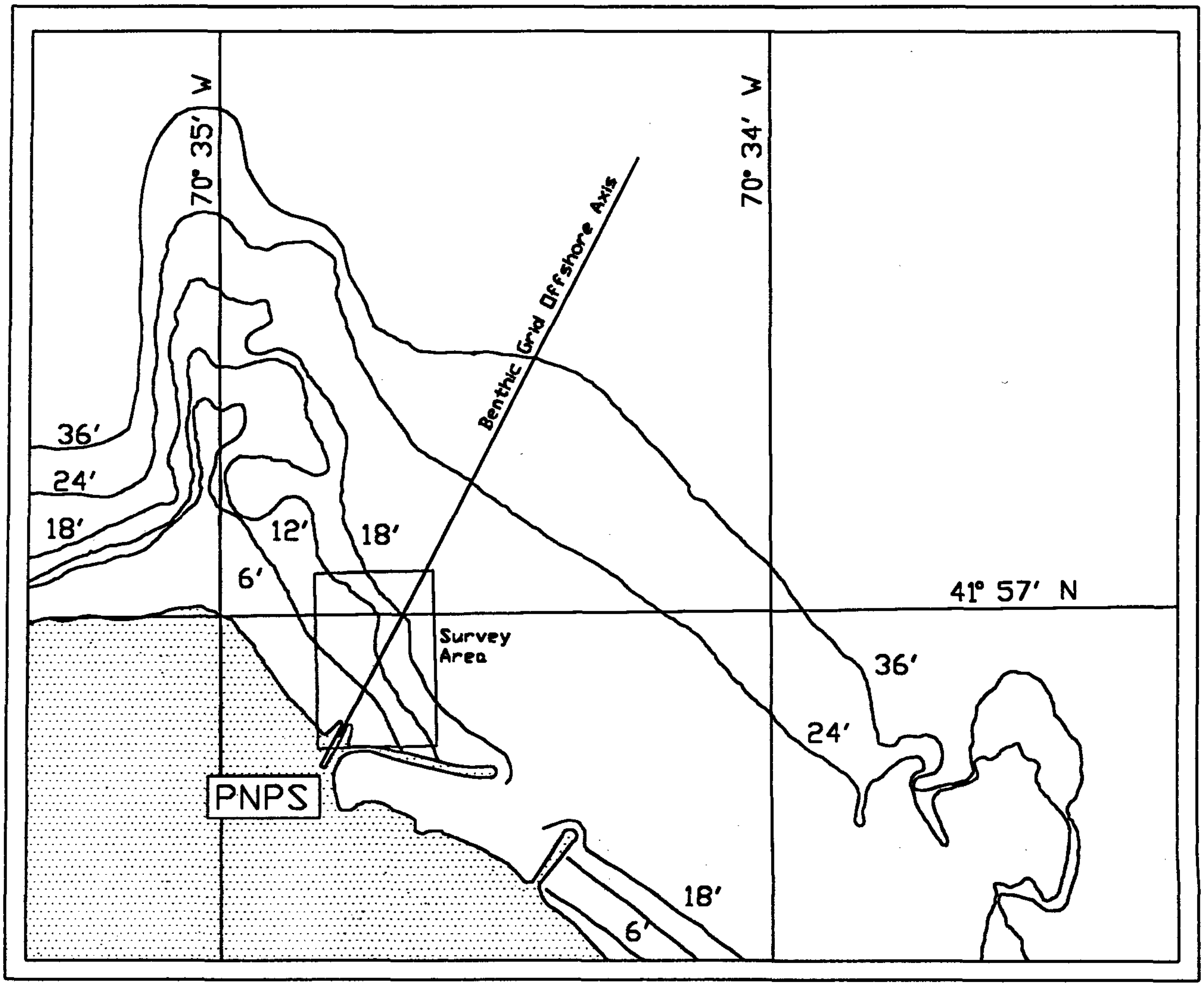


Figure 2. Chart of the study region, showing orientation of the shoreline and cooling water discharge canal, and approximate bathymetry (from U.S. Department of Commerce/NOAA navigation chart no. 13253; EG&G, 1991; and Doret, et al, 1973). Note the shallower waters to the left of the discharge channel, looking seaward.

Climate - Cape Cod Bay is partially enclosed by the mainland and Cape Cod, whose northern tip extends about 10 km north of the PNPS. The western shore of Cape Cod Bay is open to the ocean from the north and northeast. As a result, the ocean climate at the PNPS is generally benign for winds from the east, south, and west directions, while severe weather is associated with northerly and northeasterly storms in fall and winter. In summer, warm conditions are generally associated with southwesterly winds, which are directly off the land at the PNPS site. Due to this sheltering effect, warm water is often associated with calm conditions at the site.

Tides - Tide heights in Massachusetts Bay (Eldridge, 1995) are largely semi-diurnal (12.4 hr), with a typical range of over 3 m (9.5 ft). The maximum tide range at spring phase is 4.4 m (14.5 ft). Tide height and phase are essentially constant along the western side of Cape Cod Bay, from Boston to Barnstable (Eldridge, 1995). Tides at the PNPS location are therefore taken to be the same as Boston.

Currents - Ocean currents near the PNPS are generally southward on average (EG&G, 1976), part of the larger counterclockwise average circulation within Massachusetts Bay. Superimposed on the mean current are tidal currents, as well as wind-driven current fluctuations on time scales of a few days to a week or more. In summer, the characteristic southwesterly wind is associated with northward currents in the vicinity of the PNPS (EG&G, 1976). The tidal currents are primarily semi-diurnal (12.4 hour periodicity), with minor diurnal (24 hour) energy also present. Tidal current vectors tend to rotate clockwise, completing one revolution per tidal cycle.

1.1.2 PNPS Cooling Water Discharge Characteristics

Cooling water enters the plant from an intake embayment, separated from the open waters of the Bay, and from the discharge region, by breakwaters (Figure 2). After passing through the condensers, the cooling water returns to the ocean through a discharge canal oriented approximately at right angles to the coastline, located approximately 100 m (300 ft) northwest of the intake. The coastline in the immediate vicinity of the PNPS is oriented northwest-southeast.

Discharge Velocity - The discharge canal is 10 m (30 ft) wide at the bottom, with 30-degree sloping sides (Pagenkopf, et al, 1974). The bottom of the canal has an elevation of 0 feet relative to Mean Low Water (MLW). At low tide, therefore, the water level in the canal remains several feet higher than sea level, and the velocity in the canal increases markedly, in order to accomodate the flow. The discharge velocity is nearly independent of the sea surface elevation at this stage of the tide (Pagenkopf, et al, 1974), and the discharge occurs as a rapid, turbulent overflow, spilling down the sloping sea bottom at the mouth of the discharge canal. At high tide, the discharge velocity is much lower, due to the additional height of water and the trapezoidal cross-section of the canal, which provides much larger cross-section area. There are no actual observations of discharge velocity at the canal mouth, but an estimate can be derived as follows.

The nominal volume flow rate of cooling water, with the two main condenser pumps and the usual service water pumps operating, is approximately 700 cfs (R. Anderson/Boston Edison, personal communication, 1994). Table 1 illustrates the variation of discharge volume as a function of tide height, based on data supplied by Boston Edison Co. (1974). The flow volume varies somewhat with tide height, with the lowest volume flow rate occurring at low tide due to the increased head required to drive the flow out the discharge at low tide.

Exit velocity can be calculated assuming that the canal cross-section area is constant all the way out to the point at which the discharge water level is equal to sea level. The canal cross-section area, A, is given by the expression:

$$A = 30\ h_o + 2h_o^2 \quad \text{(in units of ft}^2\text{, where } h_o \text{ is in ft) or,}$$

$$A = 10\ h_o + 2h_o^2 \quad \text{(in units of m}^2\text{, where } h_o \text{ is in m)}$$

where h_o is the water height relative to the canal bottom. The problem is to determine the relation between this height and sea level. Pagenkopf, et al (1974) report that the water depth in the canal at the pedestrian bridge, located about 75 m (250 ft) upstream from the mouth of the discharge canal, reached a minimum of +0.76 m (2.5 ft) with respect to MLW at low tide; there is no information as to whether this was at spring or neap tide. Obviously, this canal superelevation decreases to nearly zero at high water. For the purpose of estimating exit velocity, it is reasonable to assume that the superelevation of 0.76 m is appropriate for the Mean Low Water Springs (MLWS) condition. Since tide height is reported relative to Mean Sea Level (MSL), and Mean Low Water Springs (MLWS) is 5.6 ft below MSL (Boston Edison, 1974), the depth of water in the canal may be taken as:

$$h_o = (h_{tide} + 5.6) + (2.5)(1 - (h_{tide} + 5.6)/10.6) \text{ (in units of ft)}$$

$$h_o = (h_{tide} + 1.7) + (0.76)(1 - (h_{tide} + 1.7)/3.2) \text{ (in units of m)}$$

This formula assumes a linear variation of canal superelevation with tide height, and gives h_o = 0.76 (2.5 ft) at a tide height of -0.76 m (-5.6 ft) (i.e., MLWS), and h_o = +3.2 m (10.6 ft) at a tide height of +1.5 m (+5.0 ft) (MHWS). This approximation is valid for the as-built canal geometry, and does not account for flow obstructions such as boulders that may have fallen in. Exit velocity, calculated as volume / area, is given in Table 1.

Table 1. Discharge volume, temperature elevation, and exit velocity as a function of tide height at Pilgrim Nuclear Power Station (from: Boston Edison Company, 1974). Flow rate includes both Unit 1 main condenser pumps plus service water flow of approximately 23 cfs. Exit velcoity is calculated as described in the text. Note that the bottom of the discharge canal is at an elevation of 0 ft relative to MLW.

Tide Stage	Tide Height (m)	(ft)	Flow Rate (cms)	(cfs)	Delta T (°C)	(°F)	h_o (ft)	A (ft^2)	Exit Vel. (m/s)	(ft/s)
MHWS	+1.5	+5.0	21.8	773	15.6	28.0	10.6	543	0.4	1.4
MHW	+1.3	+4.3	21.8	773	15.6	28.0	10.1	506	0.5	1.5
MSL	0.0	0.0	21.3	753	15.8	28.5	6.8	260	0.9	3.0
MLW	- 1.5	- 4.8	20.1	713	16.7	30.0	3.1	113	1.9	6.3
MLWS	- 1.7	- 5.6	19.9	703	16.9	30.5	2.5	64	2.5	8.1

MHWS = Mean High Water Springs
MHW = Mean High Water
MSL = Mean Sea Level
MLW = Mean Low Water
MLWS = Mean Low Water Springs

cms = m^3/s
cfs = ft^3/s

Discharge Temperatures - As Table 1 shows, the temperature of the cooling water is elevated by about 16 to 17 °C (degrees Celsius) or 28 to 30 °F (degrees Fahrenheit) while passing through the plant's condensers. In summer, when the near-shore waters of Cape Cod Bay reach ambient temperatures of 18 to 21 °C (65 to 70 °F), the discharge temperature can exceed 38 °C (95 °F), a temperature that is potentially injurious to biological organisms.

At low tide, the turbulent discharge plume is initially well mixed vertically after leaving the canal, and remains in close contact with the ocean bottom for up to several hundred meters offshore. This is partially a consequence of the significant downward momentum imparted to the discharge water as it spills out of the mouth of the canal (Doret, el al, 1973). At the surface, the plume spreads by entraining and mixing with the surrounding ocean waters, while at the bottom, the plume's core temperature drops and its width shrinks with distance offshore. Elevated temperatures are therefore present at low tide over a limited region of the sea floor near the discharge canal. These episodic high temperatures are believed partially responsible for the observed effects on benthic organisms in this region. The high velocity of the discharge, which is strong enough to scour the seafloor in the vicinity of the discharge canal, is also believed to affect the biota.

At high tide, the water in the canal is deeper and the discharge is much slower, and has no downward momentum. Under these conditions, the discharge plume separates from the sea bottom almost immediately upon leaving the canal, and has virtually no effect on benthic organisms.

Due to the almost-constant volume flow rate through the condenser pumps (Table 1), the temperature elevation of the cooling water is relatively constant for a given plant thermal load factor. As a result, the discharge water temperature varies mainly as a function of intake water temperature. The intake temperature is averaged over about 8 m depths (25 ft) due to the structure of the intake embayment. The discharge shows little tidal modulation of temperature. Consequently, the observed fluctuations in ocean bottom temperature must be caused by dynamical properties of the plume, not by changes in the discharge temperature.

Backwashing - In normal operation, the cooling water discharge volume flow remains essentially constant, except during backwash operations. Thermal backwashing is designed to remove fouling on the intake structure surfaces and from the condenser tubes and tubesheets by heating the water and forcing it back out the intake. During thermal backwashing, plant thermal output is typically reduced to 50%, one of the two circulating water pumps is not run, and the cooling water is recirculated to the intake rather than being discharged through the canal. The objective is to raise water temperature in the cooling water pump bays to more than 105 °F for 1/2 hour. In the process, temperatures can reach over 110 °F, and significant warming of the intake lagoon may occur as well. Backwashing is preferably performed at high tide only, and the operation takes about 6 hours. When backwashing is complete, the normal discharge flow resumes, and the plant's thermal output is gradually returned to full power. The warmer water that has accumulated in the intake lagoon is released through the discharge canal, compensating for the reduced power output of the plant itself, thereby producing relatively high temperatures on the following low tide.

One thermal backwashing operation was conducted while the temperature recorders were deployed. This occurred on 28 August, shortly before a generator problem caused a 3-month shutdown of the PNPS.

1.1.3 PNPS Environmental Studies

Benthic Monitoring - Since the PNPS commenced operation in late 1972, Boston Edison Company has conducted an Environmental Surveillance and Monitoring Program to determine whether the operation of the plant results in measurable effects on the marine ecology, and to evaluate the significance of these effects, if any. As part of this program, the Benthic Algal Monitoring Study has carried out periodic (approximately seasonal) surveys of benthic algae (particularly *Chondrus crispus*, or Irish moss), which serves as an indicator for the nature and extent of habitat degradation due to the cooling water discharge.

The benthic studies reveal an area of the sea floor that is "denuded" of *Chondrus* and other common benthic organisms, and a larger area that is "stunted" but not denuded (Boston Edison, 1995). The size of the affected region varies seasonally, and responds slowly to long-period changes in the PNPS's thermal output (Figure 3). The total impacted area varies from near zero after prolonged plant shutdowns, to more than 2,000 m^2 (21,560 ft^2) following long periods of sustained plant operation. The denuded area is typically 50 to 60% of the total affected area. The seasonal variability is difficult to discern, but the affected area seems to be minimum in early spring and maximum in mid-summer, when the plant is operating, suggesting that discharge temperature may play an important role.

The maximum impacted area during the 12-year period from 1983 to 1994 was 2,243 m^2 (24,180 ft^2), which occurred in December 1993. Surveys in June and October 1994, which bracketed this bottom temperature study, revealed total affected areas of 1450 m^2 and 1800 m^2, and stunted areas of 1225 m^2 and 1200 m^2, respectively. These areas are representative of the average over the 12-year period, but are only about 2/3 of the maximum extent.

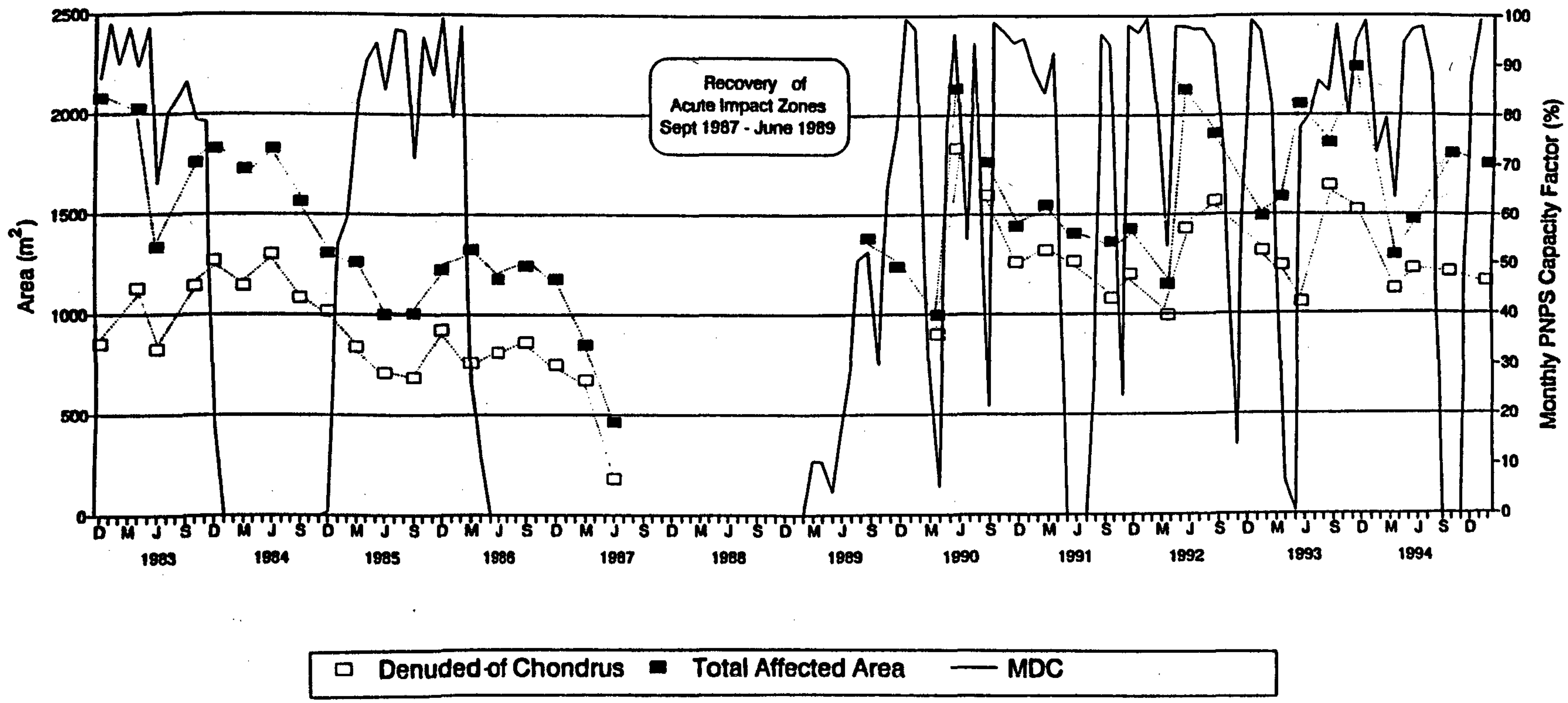


Figure 3. Time history of the denuded and total affected zones in the vicinity of the PNPS effluent canal, plotted with the monthly PNPS capacity factor (MDC) for the period 1983 - 1993 (from Boston Edison, 1994).

Local Coordinate System - To facilitate comparison of the physical oceanographic data with the biological studies, a similar, but not identical, local coordinate system was used for the bottom temperature study (Figure 2 and Figure 7). The y-axis of the temperature study coordinate system (purple grid on Figure 7)) is oriented at 30 degrees True (approximately parallel to the discharge canal axis), with its origin located just outside the mouth of the discharge canal. The benthic studies utilize a coordinate system oriented at 27 degrees True, with an origin located inside the mouth of the discharge canal. The map in Figure 2 also shows the limits of the study area.

1.2 STUDY OBJECTIVES

The goal of the cooling water discharge plume study was to provide a detailed physical characterization of the region affected by elevated temperatures. Specific objectives included:

a) <u>Characterize the area affected by elevated temperatures</u>

- Observe worst case bottom temperature - late summer
- Determine typical plume location
- Determine typical temperature gradients in the plume
- Estimate areas covered by various temperature elevations above ambient

b) <u>Characterize the variability of the elevated temperature region</u>

Variability may result from:

- Tide height
- Temperature and salinity stratification of ocean waters
- Currents, especially non-tidal currents associated with storms
- Winds, especially storm winds and calm conditions
- PNPS thermal power level
- Seasonal heating and cooling

The measurement program and its relationship to PNPS operations are described in Section 2. The observations are described and related to the physical environment in Section 3. Conclusions are given in Section 4.

2. THE MEASUREMENT PROGRAM

2.1 INSTRUMENTATION

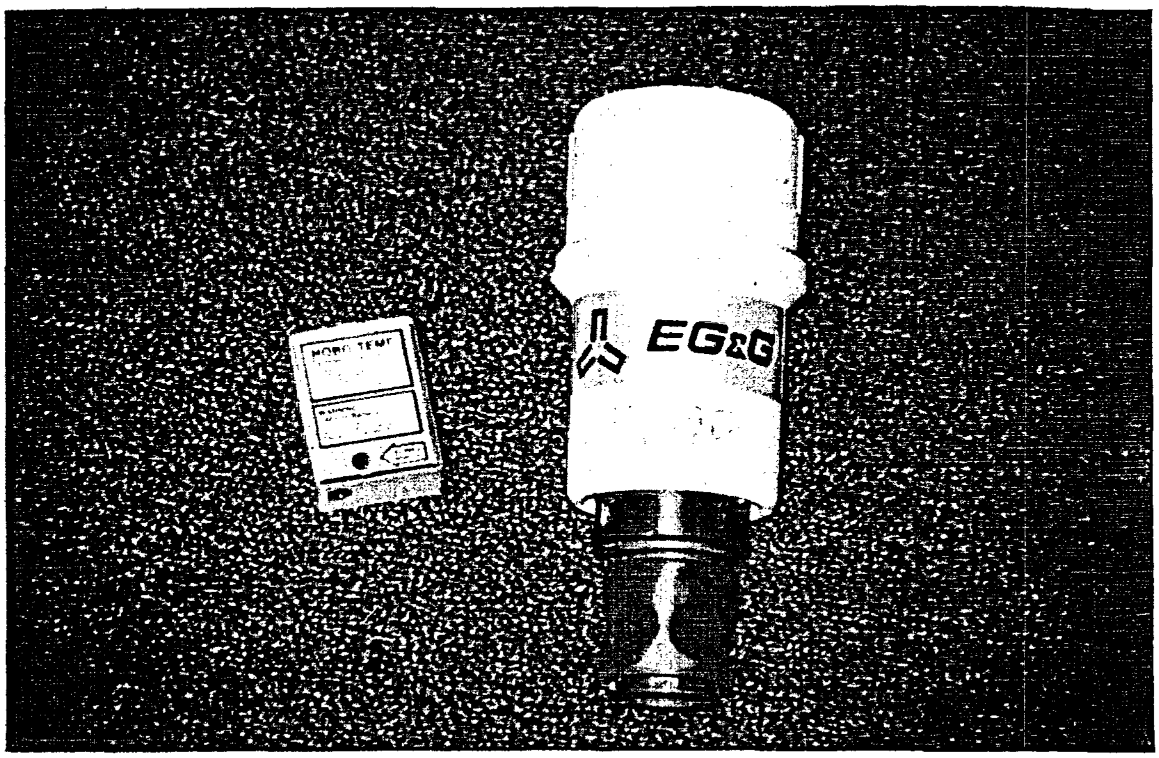
2.1.1 Temperature Recorders

Autonomous Measurement Systems - The program objectives required time-series measurements of bottom temperature at closely spaced locations in the plume area. The program was designed around the use of multiple independent temperature recorders, mounted in autonomous bottom platforms deployed in an array around the discharge canal. Approximately 60 inexpensive recorders were used, to provide maximum resolution of plume structure within the program budget.

Independent temperature recorders were chosen in preference to strings of temperature sensors connected to a single recorder, which was the only other alternative. Independent recorders avoided the possibility of catastrophic failure associated with a single recorder, while allowing optimum flexibility in the spacing of array elements. More importantly, the use of independent recorders was believed to offer the best chance of avoiding loss of sensors due to fishing activities. Temperature sensor strings would have required a network of wires across the sea floor, which posed a high risk of interference and loss due to the extensive lobster trapping and sport fishing activities in the area.

Temperature Recorder Specifications - A miniature, self-contained, low-cost, temperature recorder, the "HOBO-TEMP", was used for the study. The HOBO-TEMP, manufactured by Onset Computer Corporation of Wareham, Massachusetts, contains a thermistor temperature sensing element, a microprocessor data logger, a real-time clock, and a long-life lithium battery, in a package measuring 4.4 cm x 3.2 cm x 1.6 cm (1.75" x 1.25" x 0.625") (Figure 4a). In addition to the temperature data, the HOBO-TEMP records the turn-on time, the sampling interval, and unit serial number. Table 2 gives the HOBO-TEMP specifications and setup, as used for this study.

Since a key objective was to measure the sea-floor area corresponding to small temperature elevations (only a few degrees C above ambient), an overall accuracy of a few tenths of a degree was required to provide good resolution of local temperature gradients. The HOBO-TEMP's worst-case accuracy of $\pm$0.36 °C (0.65 °F), taken as the sum of thermistor and digitization errors,



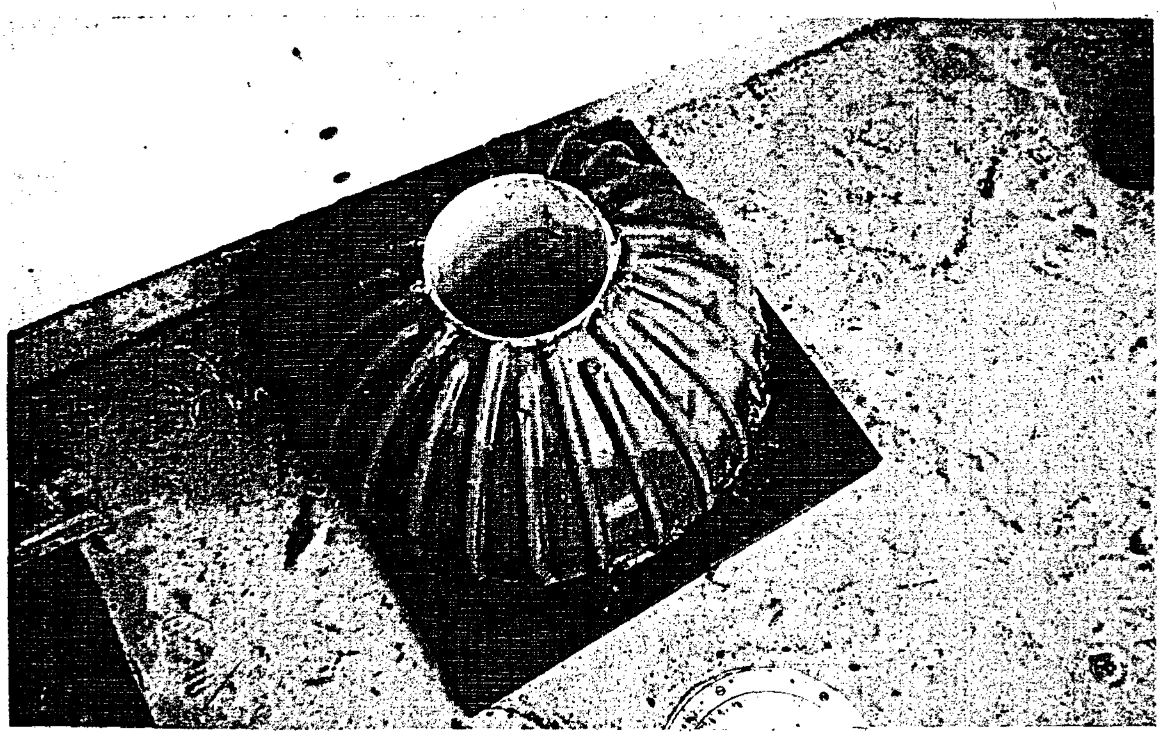


Figure 4. (Upper): HOBO-TEMP temperature recorder and waterproof canister; (lower): bottom platform (without HOBO-TEMP).

Table 2. HOBO-TEMP temperature recorder specifications and sampling parameters, as used for the PNPS cooling water discharge plume study.

Temperature range	-5 to +37 °C (22 to +100 °F)
Thermistor accuracy	±0.2 °C (0.36°F)
Digitizer accuracy/noise (LSB)	+0.16 °C (±0.3 °F)
Data capacity	1800 samples
Sample rate	36 minutes
Measurement duration	45 days

meets this requirement. The expected value of temperature measurement uncertainty, assuming that the thermistor and digitization errors are uncorrelated, would be about +0.26 °C (0.47 °F).

For use in the ocean, each HOBO-TEMP was equipped with a waterproof plastic canister, approximately 10 cm (4") in length and 5.7 cm (2.25") in diameter (also shown in Figure 4a). The HOBO's low price permitted the use of many units (60), and its small size also made possible an inexpensive design for the bottom platforms (section 2.1.2).

Pre-Deployment Calibration - The HOBO units were calibrated prior to the field measurement program using a precision temperature bath at EG&G Marine Instruments in Burlington, Massachusetts. This insulated, circulating water bath is controlled to within ±0.002 °C (±0.0036 °F) and is tracable to the National Bureau of Standards. All 60 HOBOs were calibrated simultaneously, in their waterproof canisters, using a frame to hold them in a regularly-spaced array and prevent them from floating to the surface of the bath. Vigorous water circulation ensured that all instruments were exposed to the same temperature. Calibration data were obtained at temperatures of 0.036 °C (32.1 °F), 20.05 °C (68.1 °F), and 30.00 °C (86.0 °F). The bath was held at each of these temperatures for at least several hours to ensure stable results, and the constancy of bath temperature was monitored using a precision digital thermometer. The HOBOs were set to sample at 96-second intervals over a period of 2 days. HOBO temperatures were compared with the absolute temperature of the bath and with each other to assess the accuracy of the sensors as a group. Average calibration results are given in Table 3, and Figure 5 shows the distribution of observed temperature values at each reference point.

Table 3. Pre-deployment calibration results for 60 HOBO-TEMP temperature recorders used in the PNPS cooling water discharge plume study.

	Reference Temperature		
	0.036 °C	20.05 °C	30.00 °C
No. of units averaged	59	60	60
Average recorded temp.	-0.003	19.97	29.86
Mean Error	-0.039	-0.08	-0.14

One HOBO-TEMP unit was found to differ significantly from the others at the 0.036 °C reference temperature, and was disqualified from the average at that temperature. This unit was not used in the field study, but it was later found that the erroneous temperature was caused by contact between the HOBO canister and an ice crystal on the bath's cooling coils.

In summary, the calibration tests showed that the 60 HOBO-TEMP recorders were all within $\pm$0.25 °C of the nominal bath temperature. This is within the manufacturers' combined thermistor and digitizer error specification. The HOBOs exhibited a negative bias on average, ranging from about -0.04 °C to -0.14 °C. At 20 °C (close to the typical ocean temperatures encountered in the study), only 7% of the units were outside the nominal manufacturer's digitization uncertainty of $\pm$0.16 °C. It was concluded that the HOBO units were accurate and consistent enough for the study without application of any further temperature error correction.

Response Time - The temperature of the bath could be changed more rapidly than the HOBO units could respond, allowing measurement of the effective time constant. The e-folding time constant (67% step response) with the canister was found to be about 20 minutes. This is well matched to the 36-minute sampling time selected for this study, and avoids significant aliasing. The response time is sufficiently rapid to observe the primary temperature variability of the discharge plume, which occurs on tidal time scales.

Post-Deployment Calibration - The originally planned post-deployment calibration of the HOBO units was judged to be unnecessary, based on the behavior of the units observed during the deployment at times when the water column was well mixed. Well-mixed conditions prevailed most of the time after early September, as seasonal cooling and overturning proceeded. Because

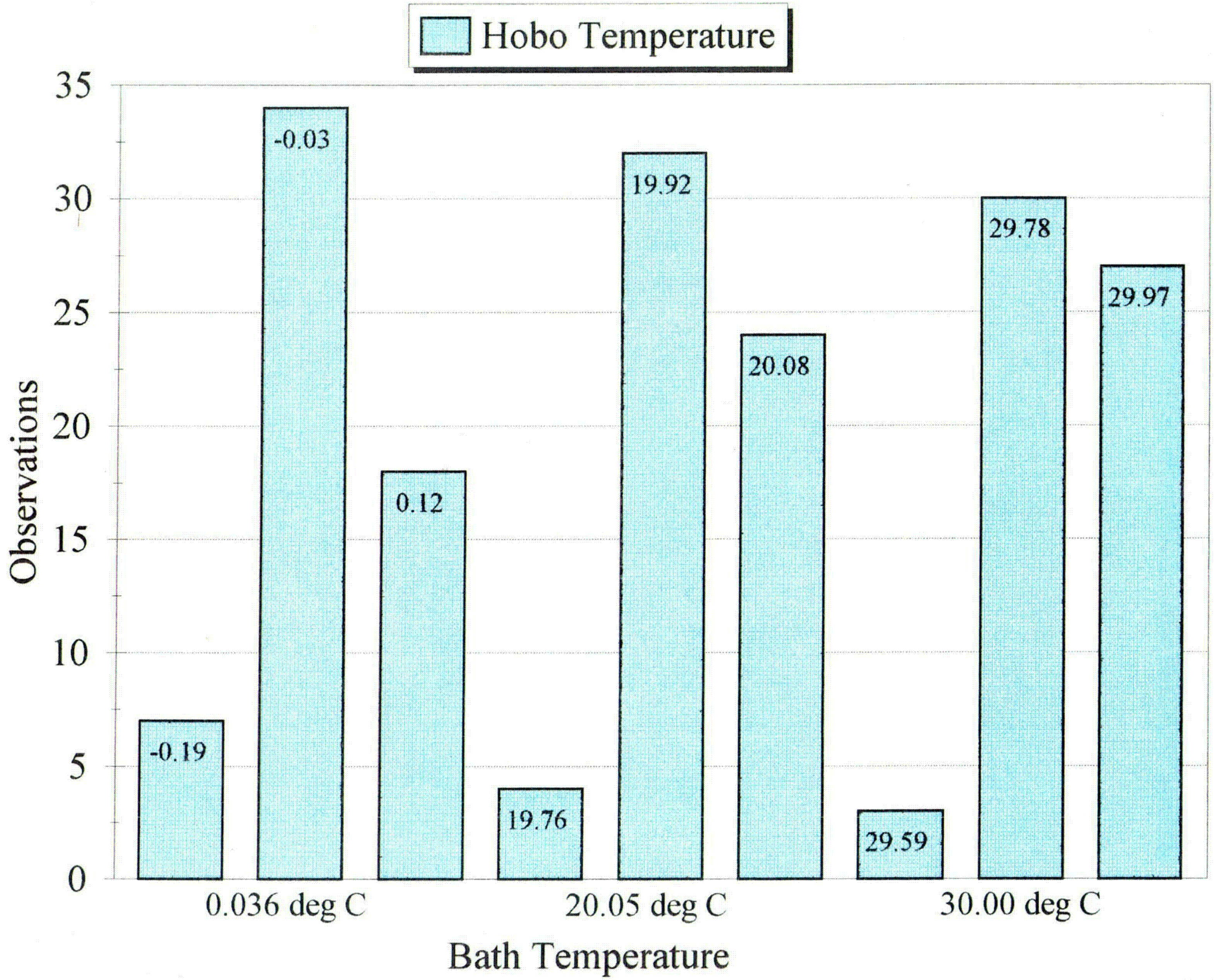


Figure 5. Distribution of observed HOBO-TEMP calibration temperature values at three reference temperatures during pre-deployment calibration. One observation at the 0.036 °C reference temperature was excluded from this distribution due to direct contact with the bath cooling coils.

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the recorders tracked within ± 0.2 °C during well-mixed periods, it was concluded that none of the units had drifted or shifted its calibration.

2.1.2 Bottom Platforms

Snag-resistant bottom platforms were built to hold the temperature recorders. The bottom platforms were designed to protect the HOBO-TEMP recorders, minimize the risk of snagging on lobster trap lines, fishing lines and nets, or vessel anchors; and maintain location in the presence of wave currents and possible sediment movement. At the same time, the bottom platforms were designed to avoid burial in the sand, which could have significantly slowed the thermal response time constant of the recorders and made the units difficult to recover.

Platform Design - The platform consists of a hemispherical concrete dome, 17 inches in diameter and 9 inches high (Figure 4b and Figure 6). A 6-inch dia PVC pipe cast through the center provides a recess for the HOBO temperature recorder, and provides access to the seafloor anchoring device. Cast into the bottom of the concrete base is a steel bar with a hole through it, and a lifting ring. The bottom platforms are designed to have no exterior protrusions, so that lobster pot lines and anchor warps will slide over rather than foul them. In the absence of additional ballast, the platforms are only slightly more dense than the sand that makes up most of the sea floor in the study area.

Sea Floor Attachment - Because the platforms were relatively small and light, and wave forces in these shallow waters can be high, the method of securing the platforms to the seafloor was critical. In sandy areas, where migration of the seafloor due to storm wave action was thought likely, it was desired to anchor the platforms without using excessive weight, as it was feared that the platforms would settle deeply into the sand if they were too heavy. Therefore, the method employed in sandy areas utilized stakes, jetted into the seafloor by divers, to anchor the concrete bases. The stakes were intended to provide resistance to overturning or sidewards movement of the anchor bases. Vertical lifting of the anchor bases was not believed to be a problem, since the bases were designed to prevent lobster trap lines and anchor lines from getting underneath. The original stake design consisted of iron pipes, 3/4" dia x 3 ft long. However, at many instrument sites, a hard layer of gravel was found to underlie the sand, and at these locations, shorter stakes with flanged bottom ends were used. A total of 29 platforms were deployed with jetted stakes of various lengths.

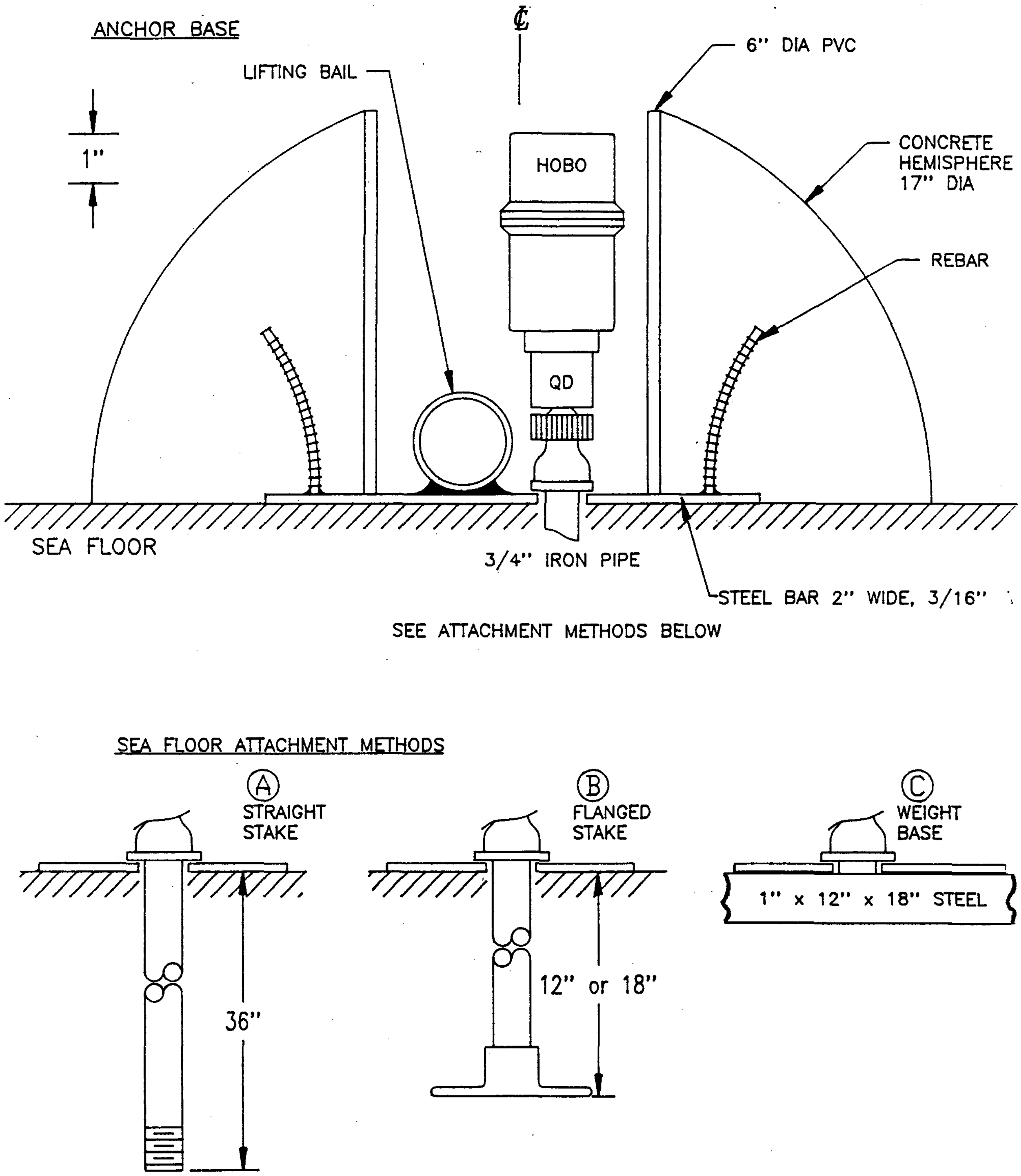

Figure 6. Cross-section drawing of the bottom platform, showing HOBO-TEMP mounting and methods of securing platform to seafloor.

Jetting, although very efficient, requires a quick-disconnect system for each pipe. To avoid corrosion and minimize the expense of such fittings, it was decided to use plastic garden-type quick disconnect (QD) fittings. Tests showed that the 3-foot pipe could be jetted into a sandy sea bottom in only a few seconds. The jetted pipe passes through the hole in the bottom of the anchor base and pins it to the sea floor (Figure 6 illustrates the stake method of attachment). The QD fitting on the end of the pipe is also used to attach the HOBO-TEMP recorder (see below).

At rocky locations, or where the sand layer was absent or very thin, heavy weights were used to anchor the concrete platforms to the sea floor. The weights consisted of steel plates, approximately 1" x 12" x 18" and weighing about 60 lb in water, secured to the underside of the concrete platforms with a short length of pipe (Figure 6). Settlement of the anchor bases was not thought to be a problem in these hard-bottom areas. A total of 30 platforms were equipped with this method of bottom attachment.

In practice, the jetted-stake method of attachment proved inferior to the weighted base, but neither method was fully satisfactory due to significant sand movement. Severe wave conditions associated with a major storm caused up to 2 feet of sand erosion in the deeper, sandy-bottom regions. In these areas, the concrete platforms tended to settle with the eroding sand surface, while the long jetted stakes were undisturbed. As a result, the stakes emerged from the platforms, making the HOBO-TEMPs attached to them vulnerable to snagging. The shorter stakes were eroded completely out of the sand, and proved unable to prevent the wave currents from moving the platforms.

The same storm conditions resulted in deposition and re-working of sand deposits in the shallow, rocky areas. As a result, most of the heavy weighted anchor bases were found to be sanded in or completely buried after the storm, and a few could not be located at all. However, none of these platforms was moved from its original location, and the recovery rate of these platforms was much higher than for the jetted stake design (see Section 2.3.5).

HOBO-TEMP Attachment - The HOBO-TEMP waterproof canister is supplied by the manufacturer with a small D-ring for attachment. However, this fitting (visible in Figure 5a) does not permit rigid attachment. With a loose method of attachment, the canister is liable to move continuously in the wave currents and might be subject to shock damage or breakage of the D-ring mount. Also, since the canister is buoyant, it tends to float up, making it awkward to attach and detach the unit inside the recess in the anchor base using the D-ring.

For these reasons, a rigid mounting system was designed, based on the same quick-disconnect fitting used for the jetting operation. A PVC adapter was fabricated and glued to the bottom of each canister, with a plastic quick-disconnect fitting screwed into the adapter. In use, the diver simply stabbed the HOBO-TEMP unit onto the QD fitting on the top of the jetted-in pipe. With this method, the HOBO canister remained upright and was approximately centered in the recess, to promote good circulation of water around it. The quick-disconnect fitting also permitted rapid recovery of HOBO canisters by a diver without having to recover the bottom platform itself. This was a key design feature, intended to minimize the cost of an emergency recovery operation (which, however, turned out not to be necessary).

In practice, this HOBO-TEMP attachment method was not entirely satisfactory. The QD fitting attached to the seafloor pipe/anchor base proved to be weak, and several are known to have broken off. Also, attaching the HOBO-TEMP to the pipe, rather than to the concrete base, proved unsatisfactory because the HOBO unit would become exposed if the sand eroded away and the base settled down around the pipe. This caused the loss of several units in the sandy parts of the study area. Finally, the QD device tended to fill up with fine sand and could not be easily released.

2.2 ARRAY DESIGN

2.2.1 Planned Instrument Locations

Spatial Resolution Requirements - The planned array of temperature recorder locations was based on previous measurements of the discharge plume (i.e., Pagenkopf, et al, 1974), as well as the results of the Benthic Monitoring Study (Boston Edison Co., 1994). In view of the objective of this study -- quantifying the areal extent of elevated temperatures -- the instrument array was designed to have maximum resolution at the expected edges of the plume. Because the plume is narrow, the array was designed with closer instrument spacing in the alongshore coordinate direction (15 m spacing) than in the on-offshore direction (30 m spacing). The minumum alongshore instrument spacing of 15 m was chosen based on the number of instruments available as well as the expected accuracy of the positioning system on the boat used to deploy the bottom platforms. The original plan called for a rectangular grid with 15 x 30 m spacing near the discharge canal outlet, and 30 x 50 m spacing farther away. Some instruments were located far outside the expected plume area, in order to determine the ambient temperature, that is, the background against which the elevated temperatures of the plume would be measured.

Pre-deployment CTD survey - Based on the results of a pre-deployment temperature and conductivity survey conducted on 8-9 August 1994, the original plan was altered to locate more instruments in the far field to resolve the ambient temperature structure. This was done because the CTD survey (not presented in this report) showed a significant on-offshore bottom temperature gradient, making it more difficult to define a single "ambient" temperature. The modifications resulted in fewer instruments in the immediate vicinity of the discharge canal, sacrificing resolution there. High spatial resolution in the core of the plume near the discharge was deemed less necessary, because these measurements would not contribute to measurement of the plume's areal extent.

Nominal Array - Figure 7 shows the planned array (purple lines) of temperature recorders, as modified prior to deployment. The array included a total of 59 instrumented bottom platforms (one of the 60 HOBO-TEMP recorders was held as a spare). The nominal array was symmetrical around a central line, denoted "line C0", which extends seaward approximately along the discharge canal axis. Station locations are named according to their alongshore/offshore position in the grid. Stations along the centerline are named "C0-XXX" where XXX refers to distance offshore from an arbitrary point at the mouth of the discharge canal (note: this point is <u>not</u> the origin of the Boston Edison local benthic survey coordinate system). Stations to the right and left of the center line (looking seaward) have names beginning with "R" or "L" and the alongshore distance from the centerline (i.e, R60-80 refers to a station 60 m to the right of center and 80 m offshore of the reference point).

2.2.2 Planned Deployment Schedule

The study was scheduled for the period 15 August - 30 September 1994. This period was chosen because the highest ambient water temperature typically occurs in late August, while cooling, overturning, and storms characterize the late September period. Therefore, this 6-week period offered the best chance of observing both maximum temperatures and a wide range of ocean variability.

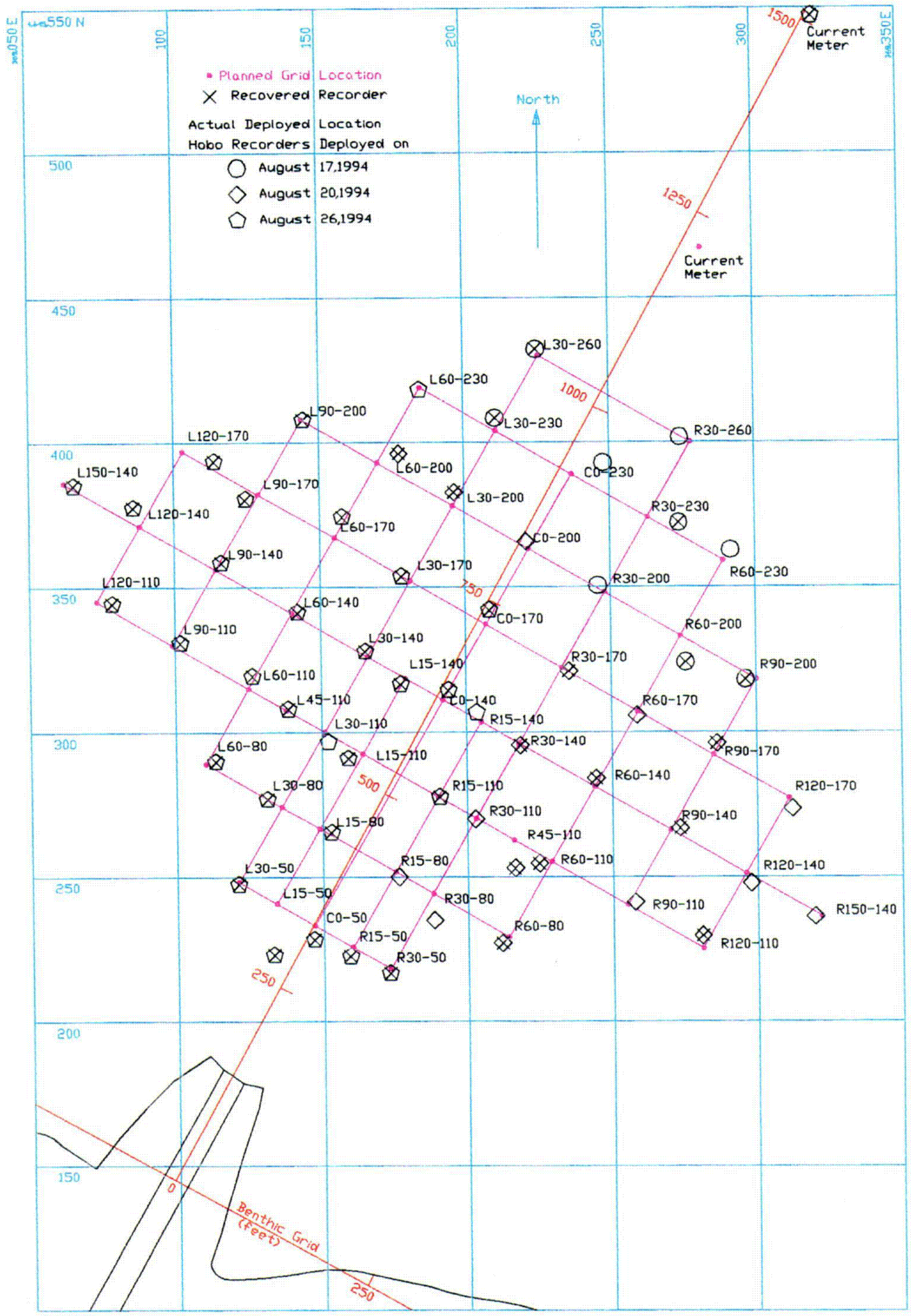

Figure 7. Plan view of bottom temperature array deployed in August 1994 for the PNPS Cooling Water Discharge Plume Study. The labeled grid (purple) shows the nominal array design. Actual deployment locations, as measured with differential GPS, are indicated by date-keyed symbols. Recovered instruments are shown by a cross inside the symbol. Axes of the PNPS benthic monitoring survey coordinate system are shown in orange.

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2.3 FIELD OPERATIONS AND DATA COLLECTION

2.3.1 Deployment Procedures

An 8 m (25-ft) survey vessel and divers were used to deploy the bottom platforms. The deployment team comprised the vessel operator, an EG&G engineer, and 2 divers. Deployment consisted of four steps: 1) anchoring the deployment vessel at the desired location; 2) lowering the bottom platform to the sea floor; 3) jetting in the anchoring stake through the hole in the bottom platform; and 4) snapping the temperature recorder canister onto the quick-disconnect (QD) fitting. Steps 3 and 4 were done by the divers. For units equipped with a heavy anchor plate instead of a jet stake, the plate was attached to the concrete base prior to deployment, and the entire assembly was lowered to the sea floor. The diver then snapped on the temperature recorder using the QD fitting. A small secondary vessel was used to ferry materials and personnel between the shore and the anchored deployment vessel.

2.3.2 Positioning

Positioning accuracy of only a few meters, or a fraction of the boat's length, was required. A mooring system was used to maintain the vessel's position, because active stationkeeping to this accuracy while subject to wind and tide would have been nearly impossible. Two or three anchors were put out with long scope, and the vessel was manuevered into position at each station by adjusting the lengths of the anchor lines.

The vessel's Magellan Differential Global Positioning System (DGPS) receiver was used to to determine position. The DGPS utilizes C/A code GPS satellite signals to determine approximate position. Reference signals broadcast by the U.S Coast Guard from fixed stations along the coast are used to provide real-time differental corrections, providing navigation accurate to ±3 m or better. Differential stations used in this study were located at Portland, Maine, and Montauk, New York. Each of these stations is approximately 150 km away from the PNPS site.

The absolute accuracy of the DGPS system is difficult to assess, as it depends on satellite constellation geometry and the distance to the reference stations. However, repeatability was observed to be better than ±3 m (12 ft, or about half the length of the vessel), judged by the ability to return to fixed objects (buoys, docks, etc.)

2.3.3 Deployment Schedule

Installation - Deployment operations were conducted on 17, 20, and 26 August 1994. Divers conducted a preliminary survey of the bottom on 17 August, and encountered difficulty in jetting in the stakes at many locations, due to inadequate sand depth. The divers reported that stations offshore and to the right of the discharge canal were mostly sand and could be jetted without difficulty. However, close to the canal and to the left of the discharge, the bottom was mostly rock. Although there were sandy patches between the rocks, the sand layer was found to be thin and penetration of the jet pipe to the desired 36" could not be achieved in most cases. A design change was implemented, utilizing shorter pipes (12" and 18") equipped with external flanges at the bottom end to obtain a better grip on the sea floor. A second design change, utilizing heavy steel plates as anchor bases for rocky areas, was also required for many stations.

Installation operations were very weather-dependent due to the positioning, anchoring, and diving operations. Winds from the northwest, north, or northeast caused unacceptable sea conditions as well as decreased visibility in the water, which hindered the divers. Due to northerly winds during the period 21-25 August, and the need to acquire additional materials to implement the design changes, the majority of the bottom platforms in the immediate vicinity of the discharge were not installed until 26 August.

PNPS Outage and Recovery Schedule Modification - During the spring and summer of 1994, the PNPS operated at near 100% capacity, and was expected to continue at that level throughout the study, until at least October. Unfortunately, on 29 August 1994 the plant suffered a major generator problem and was shut down until December. The shutdown terminated the useful measurement period, and prevented observation of any conditions other than the calm, warm, summer conditions that prevailed during 26 - 29 August. When the magnitude of the PNPS' problem became known, it was decided to recover the bottom temperature recorders as soon as weather and personnel schedules permitted.

2.3.4 Deployed Instrument Locations

Figure 7 also shows the actual deployment locations, determined with Differential GPS, and their deployment dates. The first group of 9 bottom platforms (indicated by circular symbols), was deployed on 17 August and consisted mainly of stations located at the outer edge of the array, where the 36" jetted stakes could be used. Twenty more platforms were installed on 20

August, mainly in the deeper, sandy-bottom area to the right of the center line (diamond-shaped symbols); both the long and short stakes were used at these locations. The remaining 30 platforms, which utilized the weighted plate method of bottom attachment (pentagon symbols), were installed on 26 August.

As seen in Figure 7, most of the stations were deployed fairly close to the nominal position, within ±3 m (±12 ft). A few were much farther off station, especially L15-50 which ended up much closer to the discharge canal than planned. The larger deviations from nominal position are believed to have been caused by momentary drop-outs of the differential GPS signals.

As a result of this phased deployment, there were insufficient temperature recorders in the immediate vicinity of the discharge canal to map closed contours around the discharge plume until 26 August. Beginning about 20 August, there were sufficient recorders offshore and to the right of the discharge to observe the outer limits of plume extent under certain weather conditions.

2.3.5 Recovery

Recovery Technique - Search operations were conducted at each instrument site by one or two divers, using a swing line around a marker float/anchor to ensure complete visual inspection of the sea floor. A hand-held metal detector was used if there was no visual indication. All hardware, including the concrete platforms and the jetted stakes, was recovered wherever possible.

Accurate positioning of the marker float at each deployment location, using the DGPS navigation system, was critical. Most of the recovered temperature recorders were found within a 5 m (16 ft) radius of the marker anchor, confirming that the original DGPS positioning was accurate to about ±3 m.

Recovery Schedule - A northeasterly storm occurred on 4-5 September, shortly after the PNPS shutdown, preventing immediate recovery of the bottom platforms. This storm and subsequent atmospheric cooling caused immediate and complete mixing of the coastal water, with isothermal conditions prevailing after the storm. The storm also caused substantial sand migration on the sea floor, resulting in movement, burial, or damage to a number of the bottom temperature platforms. Recovery operations were conducted 19 to 22 September, and again on 14 October.

Recovery Results - The recovered instrument array is shown in Figure 7 (indicated by crosses in the deployment symbols). Results are summarized below:

Sensors recovered:	44 (75%)
Sensors broken off, missing	9
Not found	6
Total deployed	59

Of the 30 steel-plate anchor bases, 28 (94%) were recovered. There was no damage to the HOBO-TEMP sensors on any of these platforms. The two platforms that could not be found are believed to be deeply buried by sand moved by the storm in early September.

Of the 29 jetted stake anchor bases, 14 (48%) were recovered in situ by the divers. Two HOBO-TEMP canisters from jetted stake platforms were found floating, and were returned by the U.S. Coast Guard. Data collected by these units indicated that they broke off during the storm on 5 September 1994, and floated around Cape Cod Bay for more than a week before being picked up.

A total of 11 units, including the 2 returned by the Coast Guard, are known to have broken off. All the broken units were on jetted-stake bases. The majority of the missing units (4) are also associated with this type of base. Several of the jetted-in stakes in the sandy areas were observed to be standing up out of the seafloor (by 6 to 18 inches) at the time of recovery, indicating that the sand had been eroded from beneath the platform. The concrete bottom platforms had settled down as the sand eroded, leaving the HOBO canister exposed at the end of the stake. It is concluded that some of the instrumentation losses, including the broken-off units, were due to wave action and fatigue of these exposed units during the storm, and/or entanglement with lobster trap lines.

A complete log of instrument recovery results is given in Appendix A.

2.3.6 Data Coverage and Quality

The study was cut short by the unexpected shutdown of the PNPS on 29 August. Useful bottom temperature data -- that is, when the array was fully installed and the plant was operating -- were obtained from approximately 1600 EST, 26 August, through 0600 EST, 29 August. This 2.5 day interval spanned only 5 low-tide events. The full-array measurement interval occurred during a calm, warm period of low winds, and is therefore not representative of storm conditions or seasonal cooling events.

The incomplete recovery of bottom platforms resulted in holes in the spatial coverage. The most significant hole was caused by the loss of instruments at adjacent stations R15-80, R30-80, R30-110, and R45-110. These were located slightly offshore and to the right of the array center. The absence of these data degraded the resolution of plume extent on the right side.

Partial array data were obtained from 17 August until installation of the complete array on 26 August. Although the partial array data are not adequate for determination of plume area, they provide insight into plume behavior under different weather conditions.

All of the recovered HOBO-TEMP recorders worked well and gave good-quality data.

2.4 SUPPORTING DATA

2.4.1 PNPS Thermal Output Data

Hourly time series data of cooling water temperature and plant thermal power level were supplied by Boston Edison. Cooling water temperature is measured at the condenser outlet, located at the head of the discharge canal. There are no direct measurements of the cooling water temperature at the mouth of the canal, where the discharge enters the ocean. However, given the fact that the transit time in the canal is less than 2 minutes at low tide, it is reasonable to infer that the actual discharge temperature must be close to the measured condenser outlet value at times when the plume is present on the bottom.

2.4.2 Current Measurements

Ambient ocean currents were measured with internal recording current meters on a taut-wire subsurface mooring. The mooring was located about 300 m (1000 ft) offshore from the discharge canal outlet (Figure 7), in a water depth of about 12 m (38 ft) at low tide. This location was chosen because the water depth was adequate to accomodate a 2-current meter mooring, and was far enough from the discharge not to be affected by the plume velocity or local topographic steering effects. One current meter was located about 2 m (6 ft) above the bottom, while the other was at mid-depth. The bi-axial acoustic current meters were programmed to record 5-minute vector velocity averages every 30 minutes. They also recorded temperature. Only the near-bottom current meter gave good quality data.

2.4.3 Tide Height Data

Hourly tide data for Boston were obtained from the National Oceanic and Atmospheric Administration (NOAA), National Ocean Service, Tides and Water Levels Branch, Rockville, MD. As discussed in Section 1.1, the amplitude and phase of the tide at Boston and Plymouth are the same, within the uncertainty of the measurements.

2.4.4 Meteorological Measurements

Hourly values of wind speed and direction and air temperature were provided by Boston Edison Company from meteorological sensors located on two towers on the PNPS grounds. Data used in this study were from the lower-level sensor suite on the 160-ft PNPS backup meteorological tower, which is the one nearest to the water. This tower's base is about 4 m above Mean Sea Level, and is about 300 m (950 ft) southwest of the power plant itself. The sensors are at a height of 10 m (33 ft) above ground level. These sensors are fully exposed to winds off the water, but are somewhat sheltered from westerly winds by the hills inland from the PNPS, and from northerly winds by the reactor building itself. The sheltering effect is evident in comparisons of wind data between the upper and lower levels at the 160-ft and 220-ft towers. The 220-ft tower is located about 400 m inland, in a wooded area on the top of a 50-ft hill. On balance, the lower level winds from the 160-ft tower were felt to be most representative of winds affecting the ocean near the discharge canal.

2.5 DATA EDITING AND QUALITY ASSURANCE INSPECTION

2.5.1 Bottom Temperature Data

After recovery of the temperature recorders, the data were transferred to a PC computer system. The data were recorded as counts (0-255), and were converted to temperature during playback. A separate time-series plot of each HOBO-TEMP record was made and inspected for data errors and time base inconsistencies (none were found).

Each 36-minute sampled time series was then interpolated to a common 30-minute time base using a cubic spline method. This was necessary because the HOBO-TEMP sampling times were not synchronized, and joint analysis of the data would have been difficult without the common time base. The 30-minute time series were overlaid with the original 36-minute time series to verify that the interpolation did not introduce any additional variance. All 44 adjusted time series were then combined into a single matrix of temperature values.

2.5.2 Other Data

Meteorological and plant operating data were received in tabular form, and were manually digitized; the results were checked against the original for accuracy. Tide height data were received from NOAA in digital form, and were archived. Current meter data were processed using the manufacturer's software, which extracts the vector averaged water velocity and temperature data.

3. ANALYSIS AND INTERPRETATION

3.1 BACKGROUND AND GENERAL CONDITIONS

Raw Data Plots - Time series plots of all data over the entire deployment interval, including bottom temperatures, meteorological, tide, current and plant operating data, are given in Appendix B (Figures B-1 through B-8). These eight plots show the bottom temperature data grouped by deployment date. Temperatures within each group are over-plotted to facilitate comparison. Data are shown only when the instruments were actually deployed on the bottom at their intended locations. These long time series plots serve as a further QA check, and as an introduction to the general environmental conditions before, during, and after the full-array measurement period. Elevated temperatures at measurement stations close to the discharge canal are clearly evident (for example, Figure B-4).

General Conditions During 26-29 August - The Appendix B plots provide insight into the representativeness of the brief full-array data collection period from 26 to 29 August when both the measurement array and the PNPS were operating. During the full-array measurement period, and for a few days after the PNPS shutdown, approximately 26 August through 1 September, the winds were generally from the southwest at speeds up to 6 m/s (11.5 kt), interspersed with calm intervals lasting a day or so. The weather was clear and sunny, leading to a strong diurnal air temperature variation. These conditions are representative of the fair-weather, southwesterly wind regime that is common on Cape Cod in summer.

This wind regime tends to promote an upwelling circulation regime along the Massachusetts mainland coast, including the Plymouth area. Specifically, the southwest wind opposes the general circulation pattern in Cape Cod Bay, which is southward along the west side of the Bay (EG&G, 1976). This leads to the observed low-current environment, in which tidal currents dominate. The observed mean current was northward, although weak, during the full-array measurement period. Peak current speeds during 26 -29 August rarely exceeded 10 cm/sec (0.2 kt).

This type of upwelling circulation would be expected to enhance offshore movement of the discharge plume at the surface, while retarding offshore movement of the plume at the bottom. Upwelling also tends to enhance the local stratification by bringing cold subsurface water from offshore locations into the shallow coastal region on the bottom, while the sunshine and warm winds off the land tend to heat the surface layer.

Consistent with this background, Figures B-1 through B-8 show that the period from 26 August through 1 September was a period of strong stratification, as evidenced by tidal-period temperature fluctuations over the range of 13 to 16 °C at all bottom measurement locations. The lowest bottom temperatures occurred generally at high tide, following a period of onshore-directed near-bottom current, which brought colder water from greater depths offshore. The temperature changes at each bottom recorder resulted from the vertical movement of the thermocline in response to these tidal currents and changing water levels. Superimposed on the ambient tidal temperature fluctuations are large temperature increases at inshore stations caused by the discharge plume (for example, Figure B-4). Temperatures reached 30 °C (85 °F) at stations closest to the discharge at low tide. At most stations, the tidal temperature signal was basically the same before and after the plant shutdown on 29 August. This permits comparison of high and low tide periods with and without the heated water discharge.

The full-array measurement period, 26 - 29 August, is also somewhat anomalous: prior to it, and immediately afterward, the ocean was vertically homogeneous at the site, as evidenced by identical bottom temperatures at all locations. All of the HOBO-TEMP recorders tracked perfectly (within the instrumental accuracy) during the well-mixed intervals, both before and after the full-array measurement period. The vertical mixing at the site before 26 August, and after 1 September, was associated with strong northwesterly winds and cooler temperatures. These conditions favor a downwelling circulation

In summary, the full-array bottom temperature data from 26 to 29 August corresponds to a warm, late-summer, stratified, upwelling-favorable period, which was sandwiched between two well-mixed, downwelling-favorable intervals. As the figures in Appendix B also demonstrate, the full-array measurement period occurred during an average tidal stage, that is, neither spring nor neap. Unfortunately, the power plant was not operating during the Labor Day storm, 4-5 September, when wind and current speeds increased dramatically.

Other Conditions - There is evidence of elevated temperatures at stations far offshore (L30-200, L60-200, R120-110, R30-140, R60-110, and R60-80) on 22 and 23 August, prior to the installation of the inner part of the array (Figures B-2 and B-3). This occurred during an unstratified period with a northerly wind, suggesting that the extent of plume attachment to the bottom may be sensitive to ambient wind and current conditions, as discussed further below (Section 3.2.4).

3.2 BOTTOM TEMPERATURE ELEVATIONS DUE TO COOLING WATER DISCHARGE

The foregoing general observations about the bottom temperature measurements are analyzed below in more detail, using expanded time series and spatial mapping to illustrate patterns of variability. Time histories of all data during the full-array measurement period, 26 - 29 August, are presented in Section 3.2.1. Section 3.2.2 focuses on the spatial patterns of temperature variability around the discharge canal over several low tide events, and the evolution of these patterns during a tidal cycle. Section 3.2.3 describes the spatial distribution of bottom temperature under different weather conditions during 22 - 23 August.

3.2.1 Discharge Effects During 26 - 29 August, 1994

The five low-tide events during 26 - 29 August, when the full measurement array was installed and the PNPS was operating, are displayed in more detail in Figures 8 through 20. These figures show expanded time histories of bottom temperature at various on-offshore and along-shore locations, together with wind, air temperature, current, discharge velocity and temperature, and tide height. Figures 8 through 10 show the time history of bottom temperature grouped along lines running offshore from the power plant, to illustrate the offshore extent of the plume. Temperatures along the center line (designated "C0") are shown in Figure 8, while lines 30 m to the left and right of center are shown in Figures 9 and 10, respectively. Instruments 15 m to the left and right of center are included in the centerline plot, Figure 8, to provide complete coverage. The closest instrument is 50 m offshore of the mouth of the discharge canal, and the farthest is 170 m. Figures 11 through 20 show the same data grouped into alongshore-oriented lines, at 50, 80, 110, 140, 170, and 200 m offshore of the discharge canal.

Low Tide Conditions - As the tide ebbs, the temperature at C0-50 begins to rise rapidly when the water level falls below Mean Sea Level (Figure 8). The plume detaches again from the bottom at C0-50 when the rising tide reaches Mean Sea Level or a bit higher. This plume separation at C0-50 corresponds roughly to exit velocities of about 0.9 m/sec (3.0 ft/sec).

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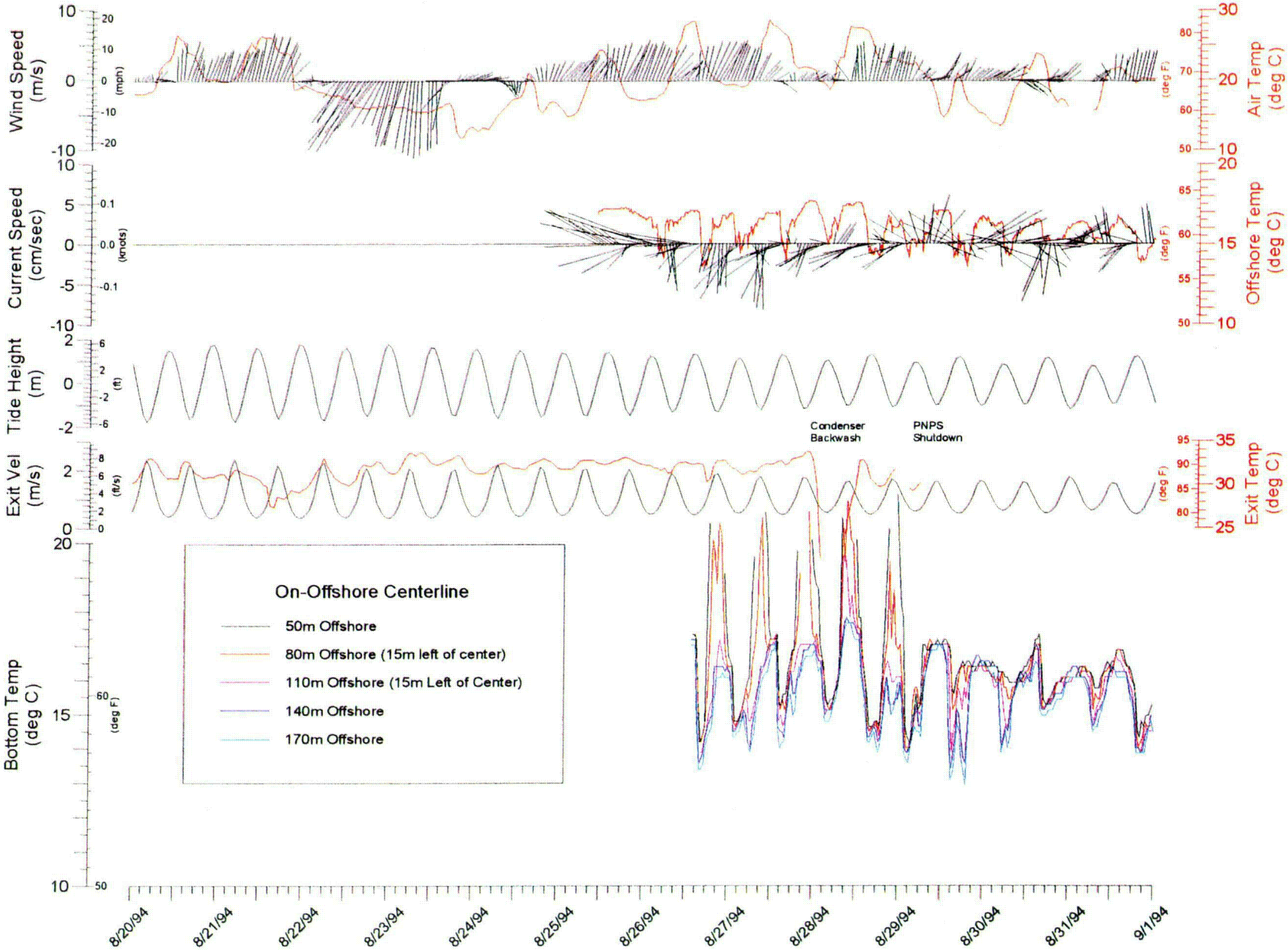

Figure 8. Bottom temperatures during the period 20 August - 1 September, 1994, measured on an on-offshore centerline passing through the discharge channel (line C0). Also shown are hourly wind vectors, air temperature, water current vectors and temperatures, tide height (Boston), cooling water discharge temperature, and calculated discharge exit velocity. All vectors originate on the graph axis, and their length and orientation shows the speed and direction tward which the flow was moving, relative to North (straight up on the page). Times are Eastern Standard.

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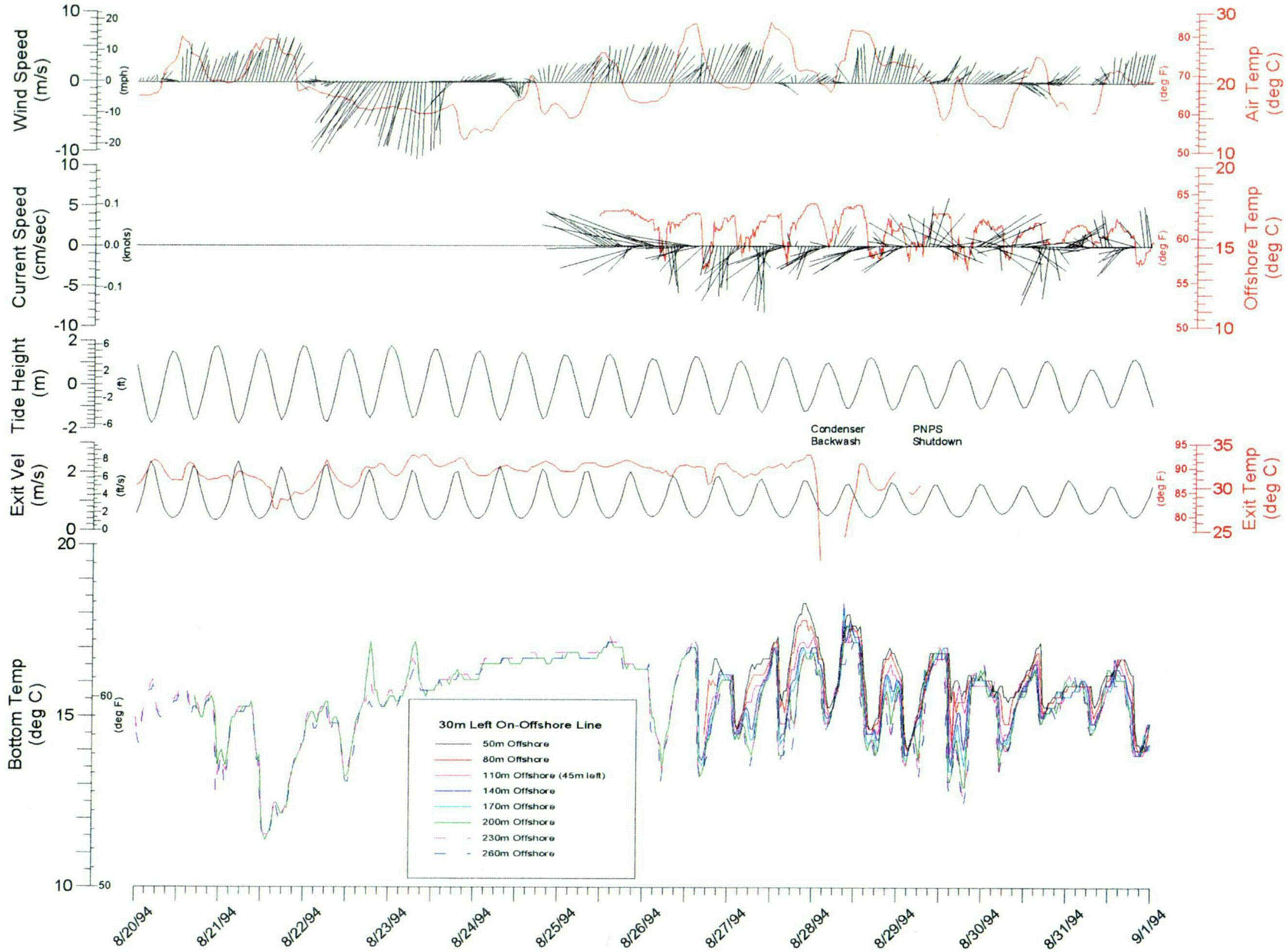

Figure 9. Time-history plot of bottom temperatures during the period 20 August - 1 September, 1994, measured along an on-offshore line 30 m left of the centerline. Other parameters plotted are as described in Figure 8.

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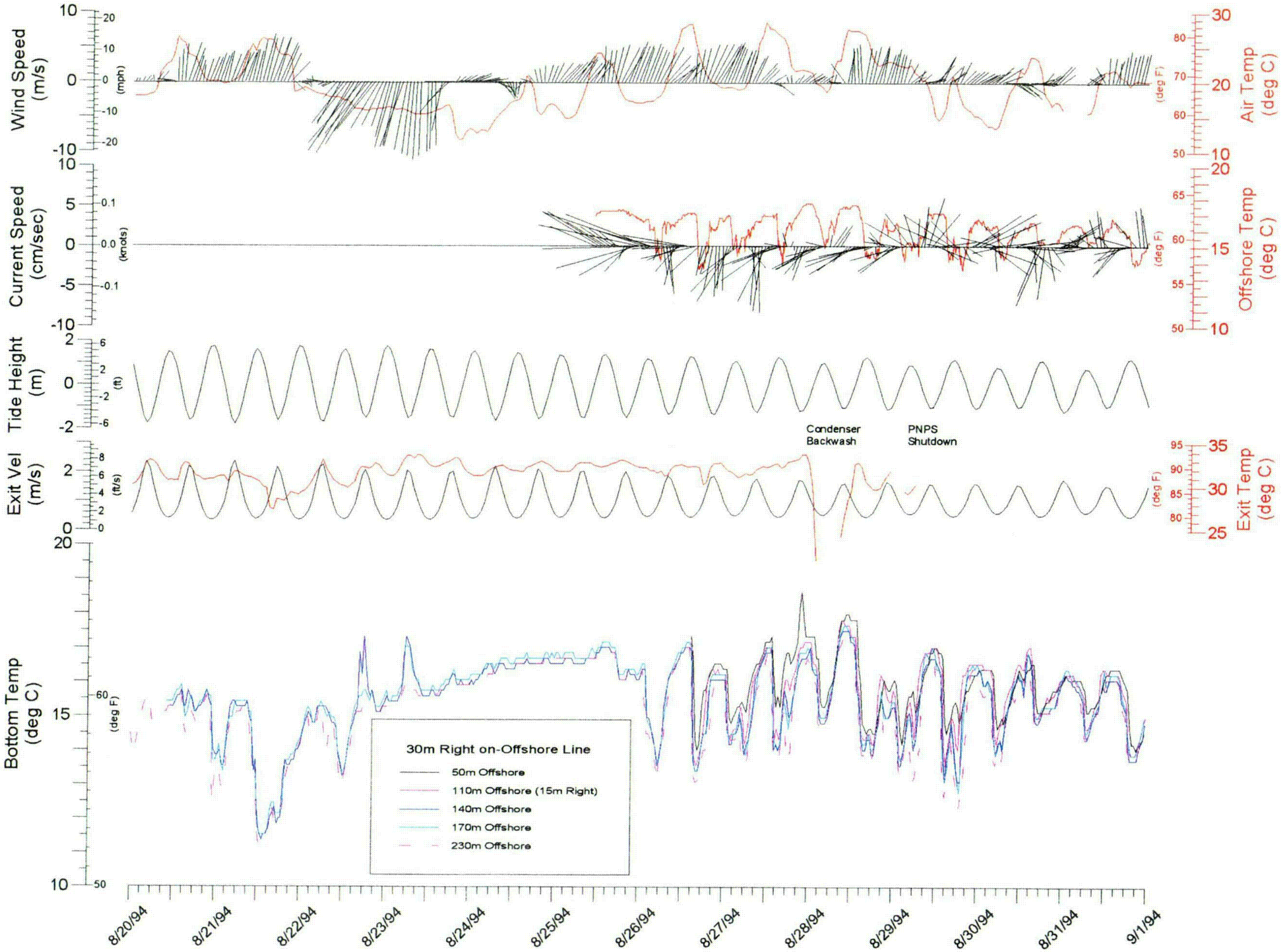

Figure 10. Time-history plot of bottom temperatures during the period 20 August - 1 September, 1994, measured along an on-offshore line 30 m right of the centerline. Other parameters plotted are as described in Figure 8.

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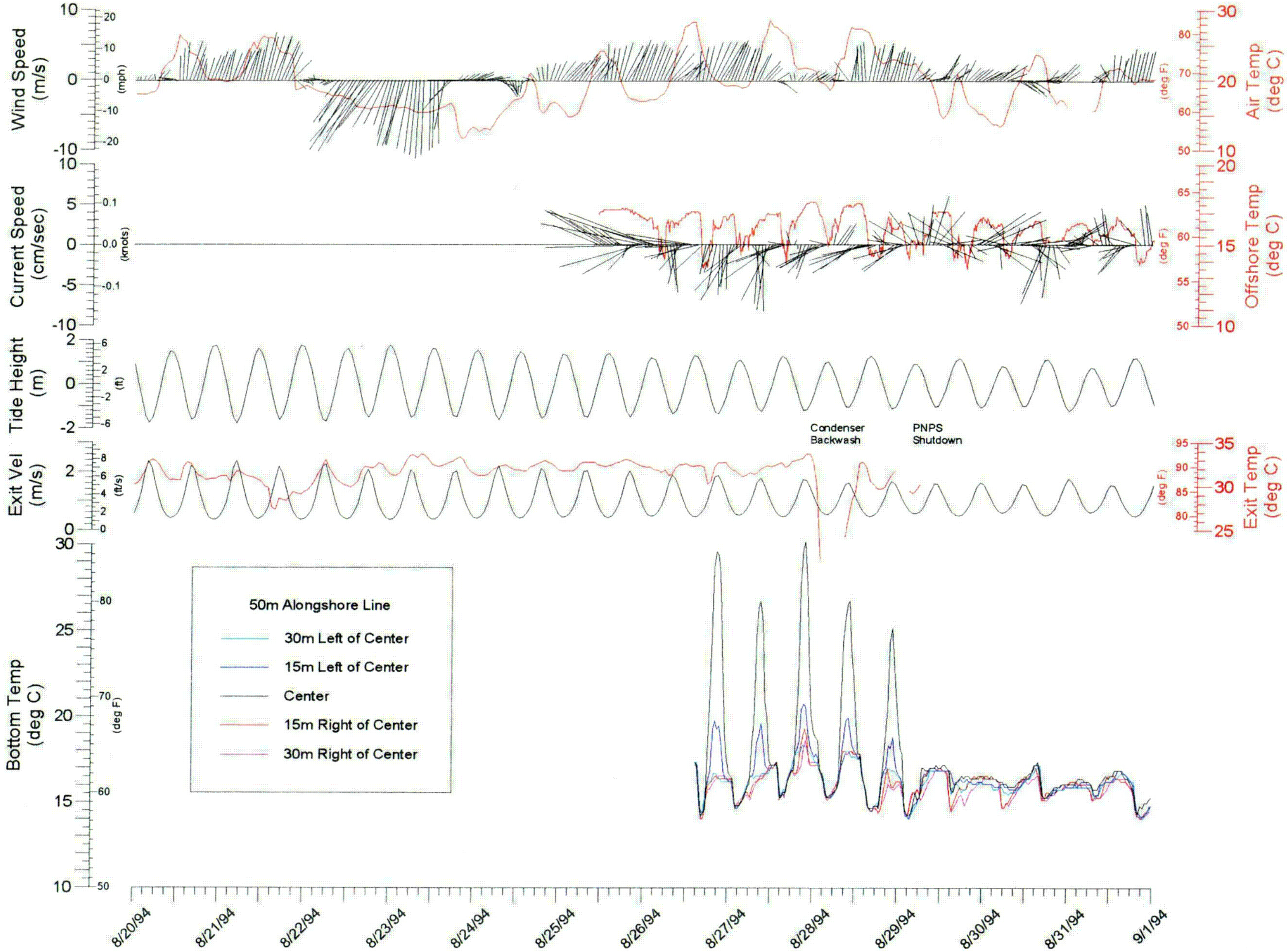

Figure 11. Time-history of bottom temperatures during the period 20 August - 1 September, 1994, measured on a shore-parallel line 50 m offshore of the mouth of the discharge channel. Other parameters plotted are as described in Figure 8, except that a larger temperature scale (10 - 30 deg C) is used to show peak temperatures near the discharge.

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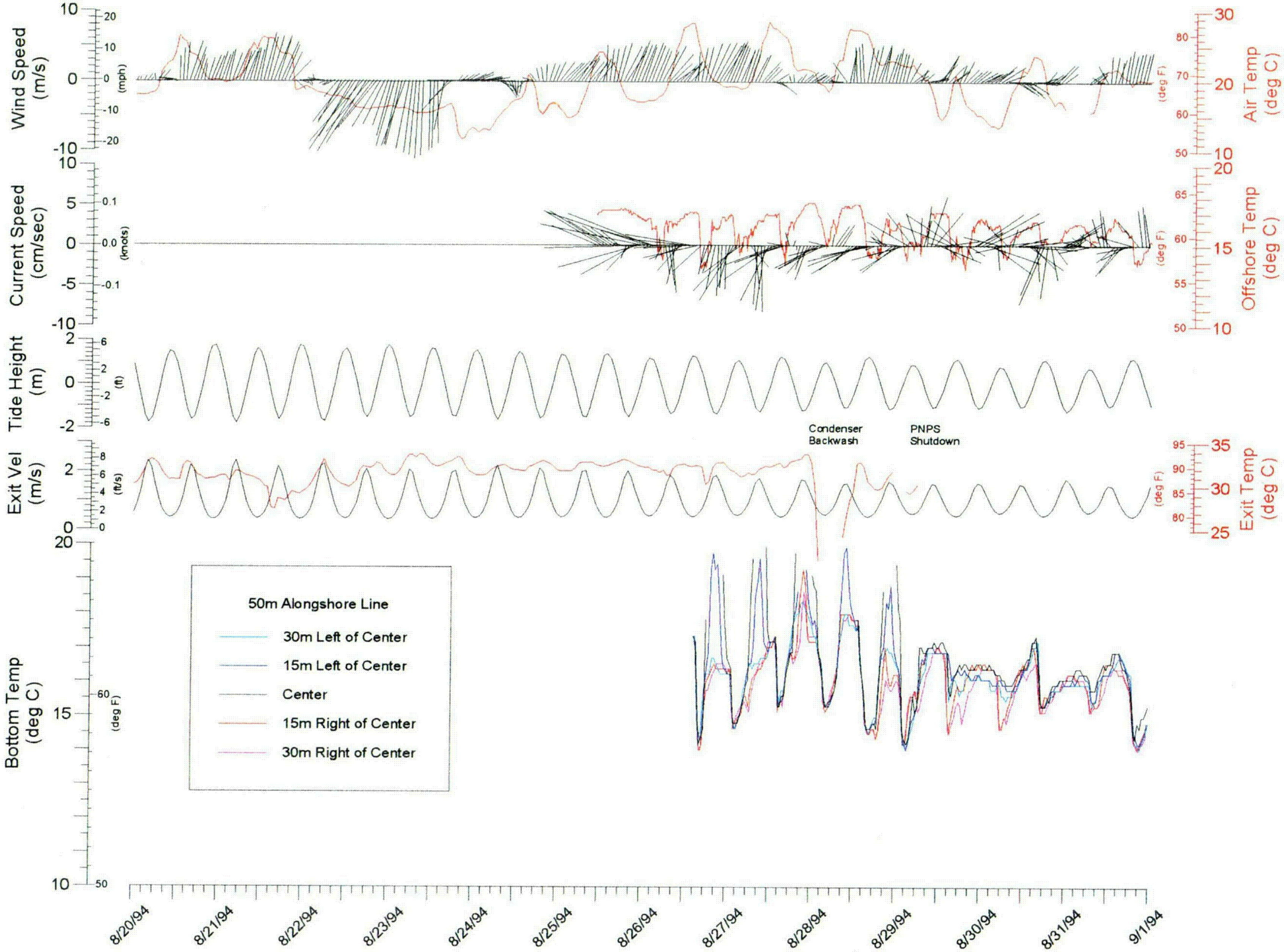

Figure 12. Time-history of bottom temperatures during the period 20 August - 1 September, 1994, measured on a shore-parallel line 50 m offshore of the mouth of the discharge channel. Other parameters plotted are as described in Figure 8.

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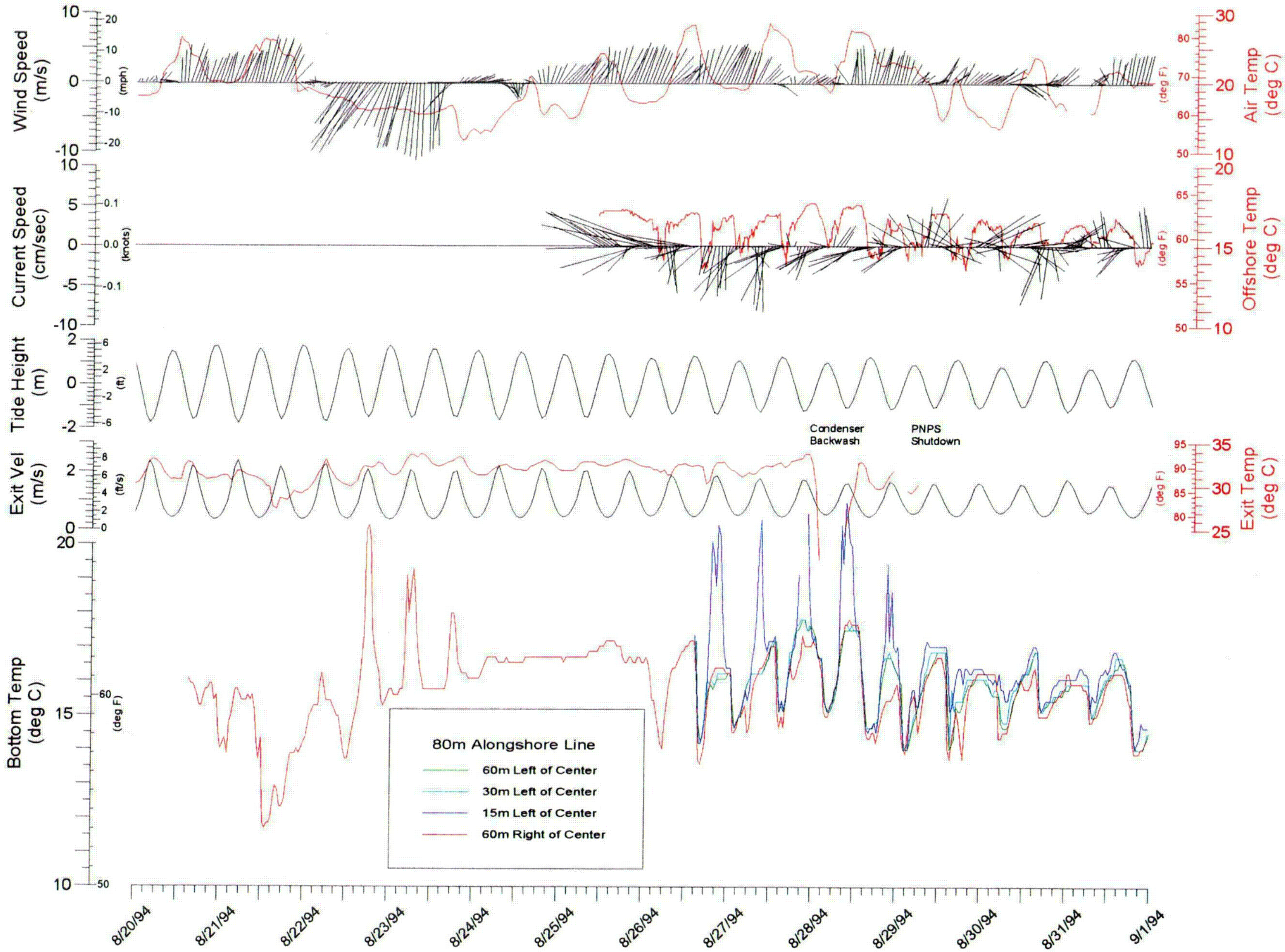

Figure 13. Time-history of bottom temperatures during the period 20 August - 1 September, 1994, measured on a shore-parallel line 80 m offshore of the mouth of the discharge channel. Other parameters plotted are as described in Figure 8.

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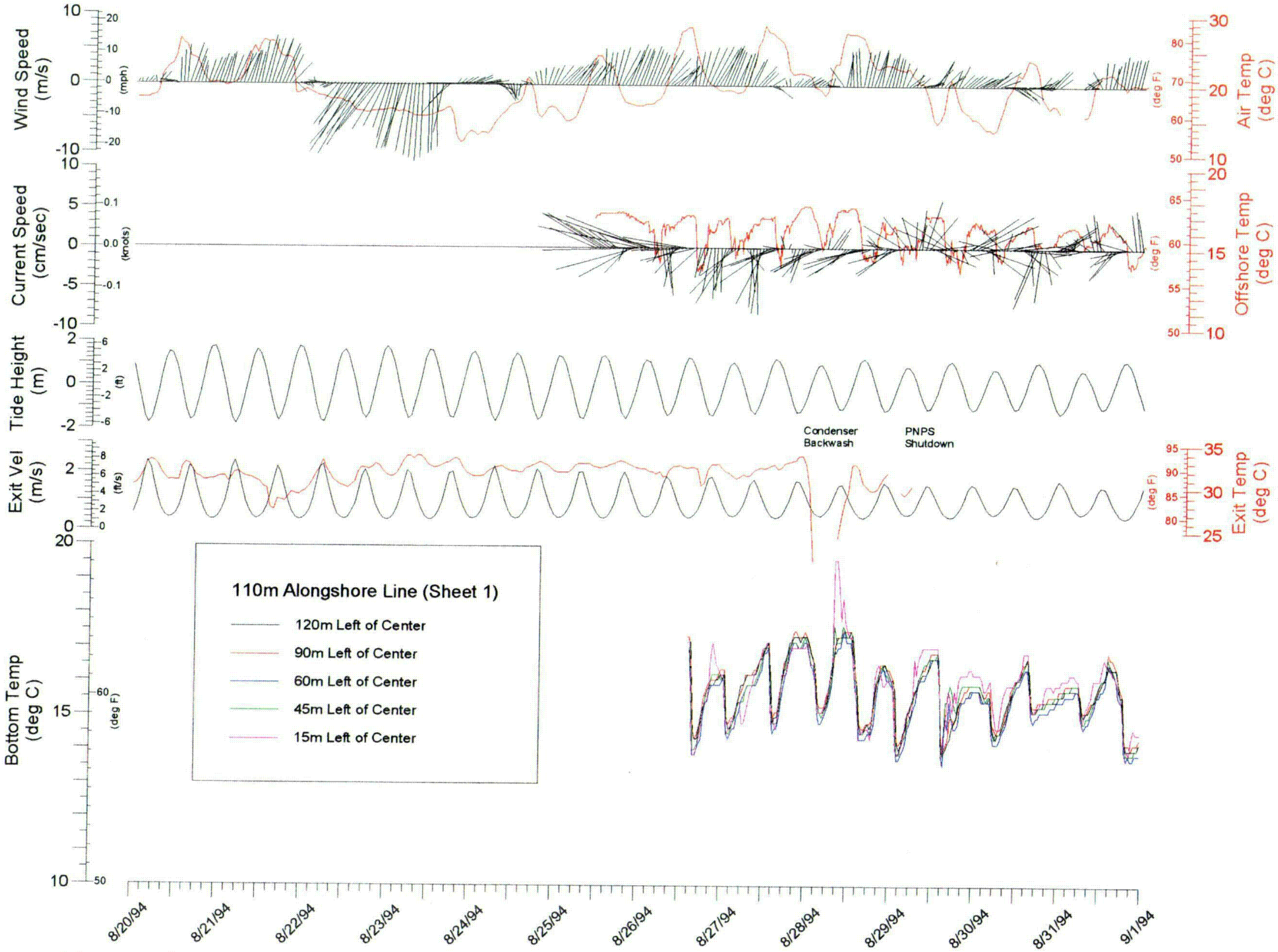

Figure 14. Time-history of bottom temperatures during the period 20 August - 1 September, 1994, measured on a shore-parallel line 110 m offshore of the mouth of the discharge channel (Sheet 1 of 2). Other parameters plotted are as described in Figure 8.

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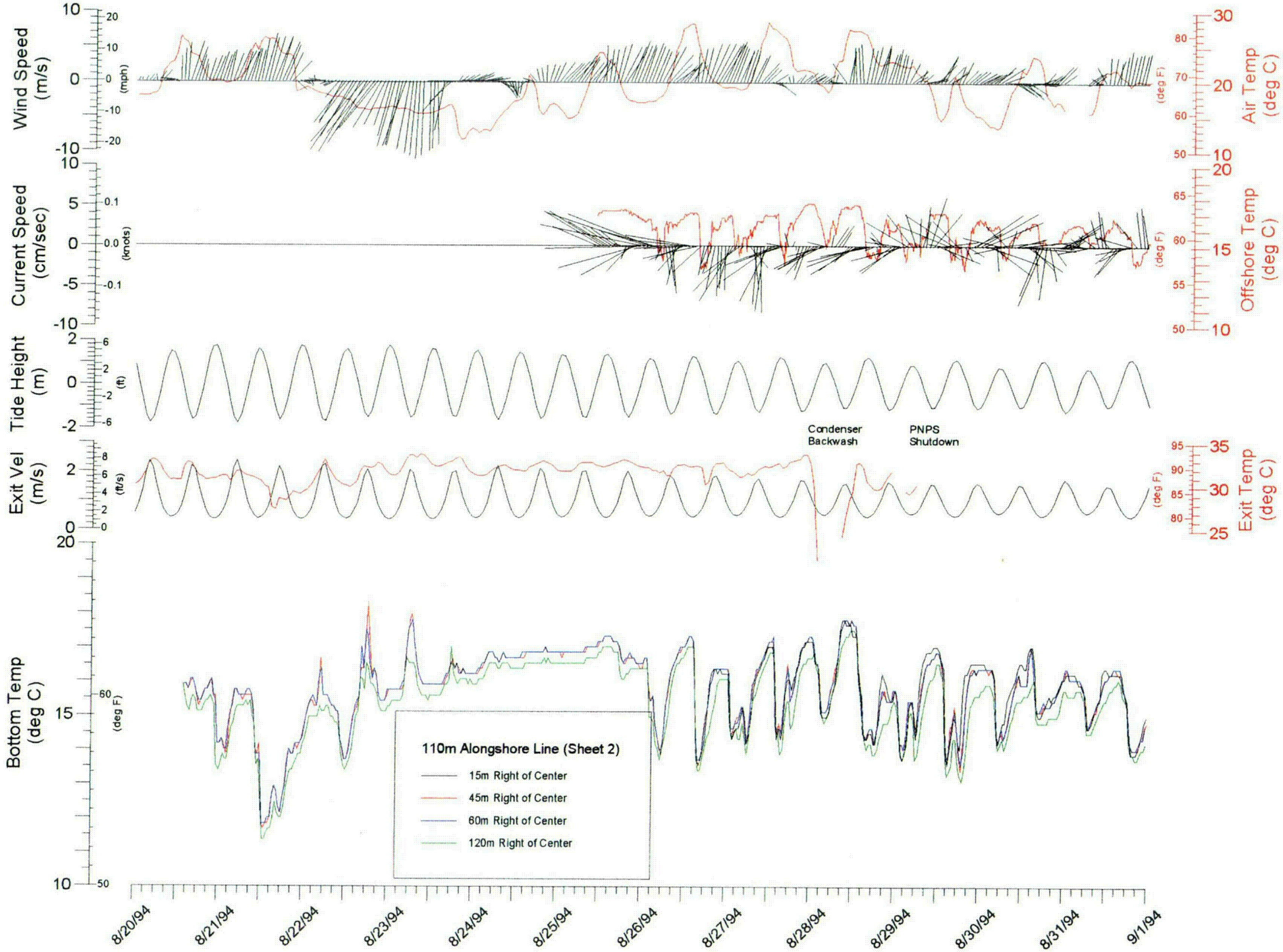

Figure 15. Time-history of bottom temperatures during the period 20 August - 1 September, 1994, measured on a shore-parallel line 110 m offshore of the mouth of the discharge channel (Sheet 2 of 2). Other parameters plotted are as described in Figure 8.

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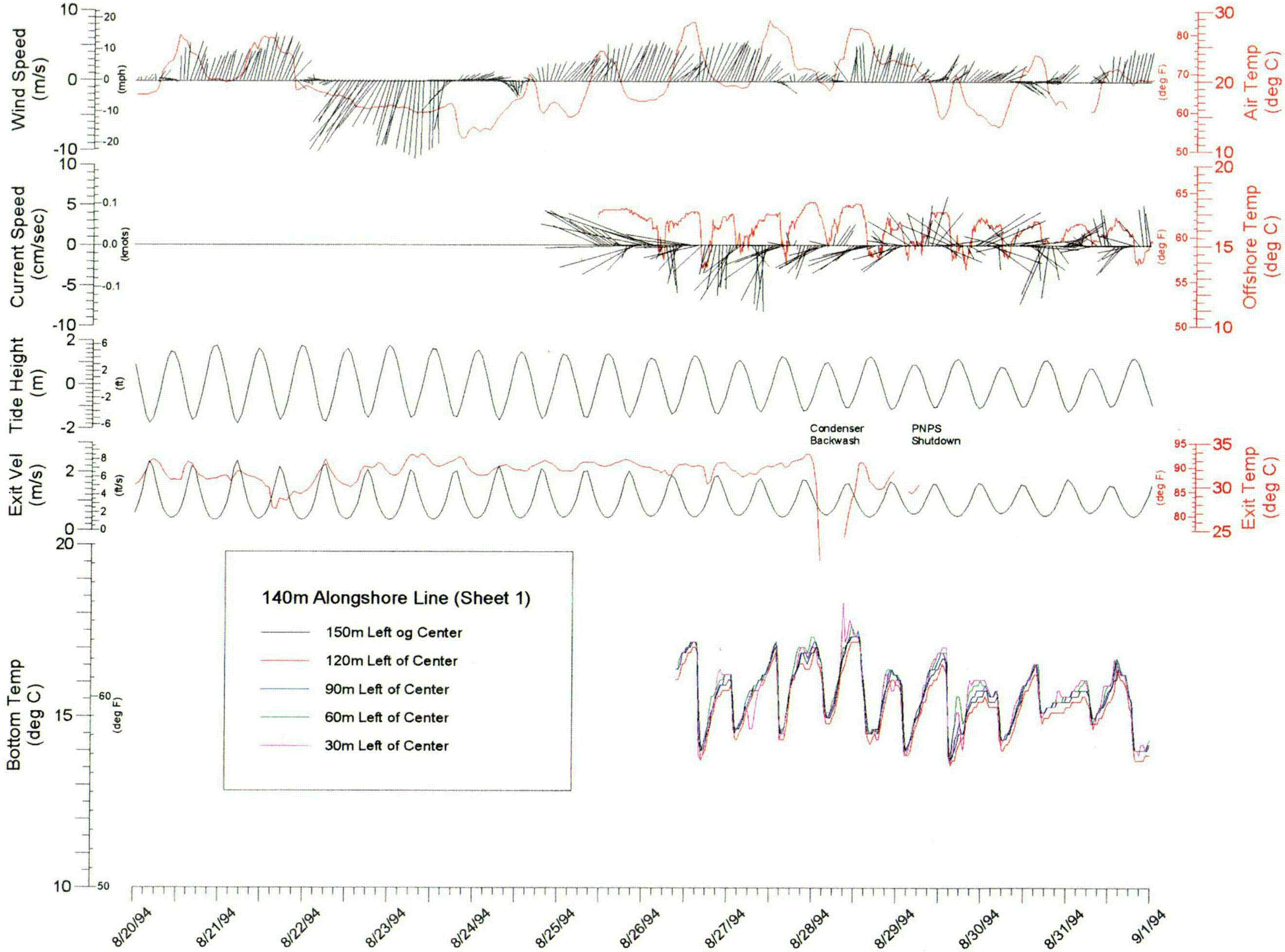

Figure 16. Time-history of bottom temperatures during the period 20 August - 1 September, 1994, measured on a shore-parallel line 140 m offshore of the mouth of the discharge channel (Sheet 1 of 2). Other parameters plotted are as described in Figure 8.

C11

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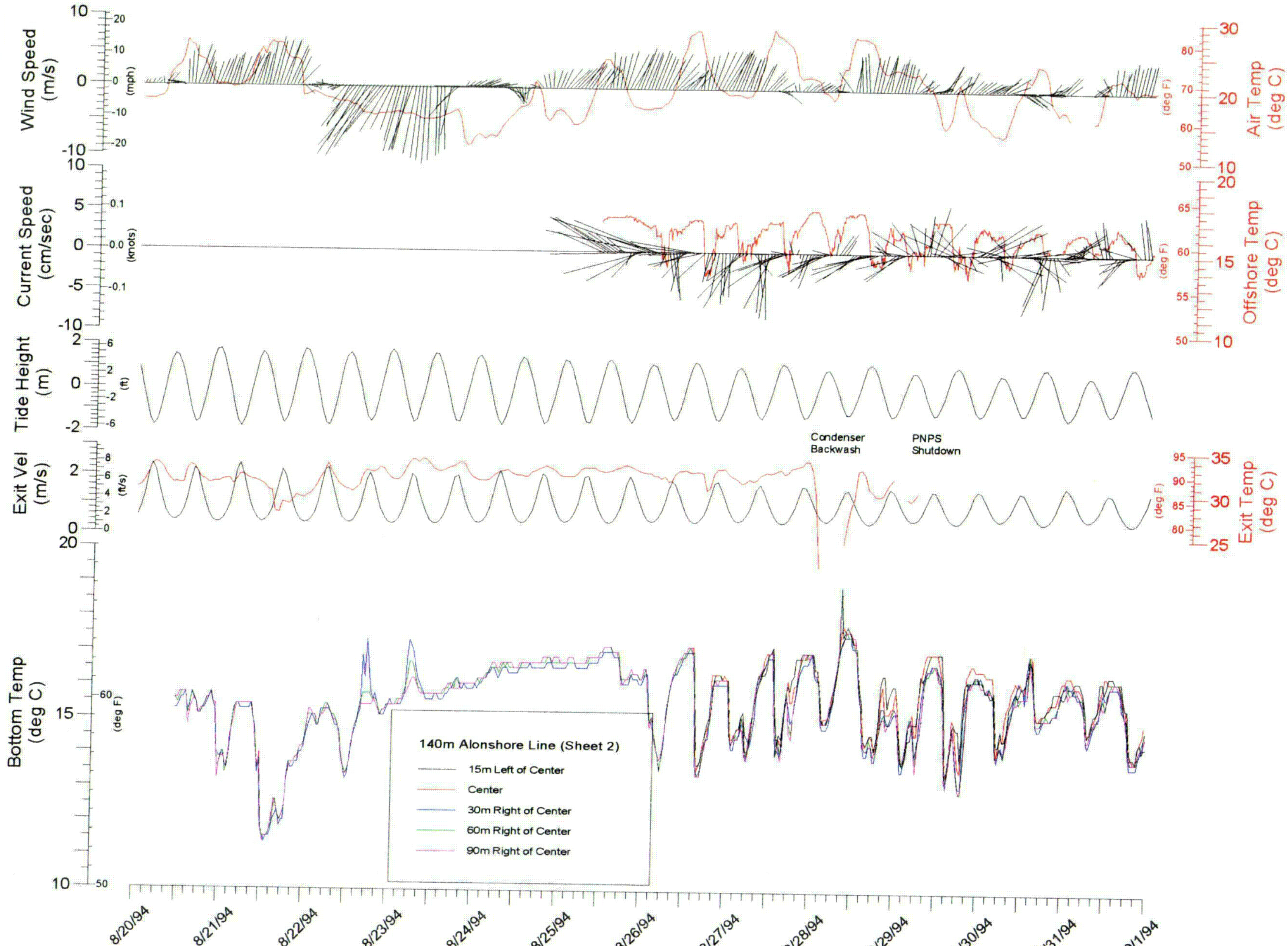

Figure 17. Time-history of bottom temperatures during the period 20 August - 1 September, 1994, measured on a shore-parallel line 140 m offshore of the mouth of the discharge channel (Sheet 2 of 2). Other parameters plotted are as described in Figure 8.

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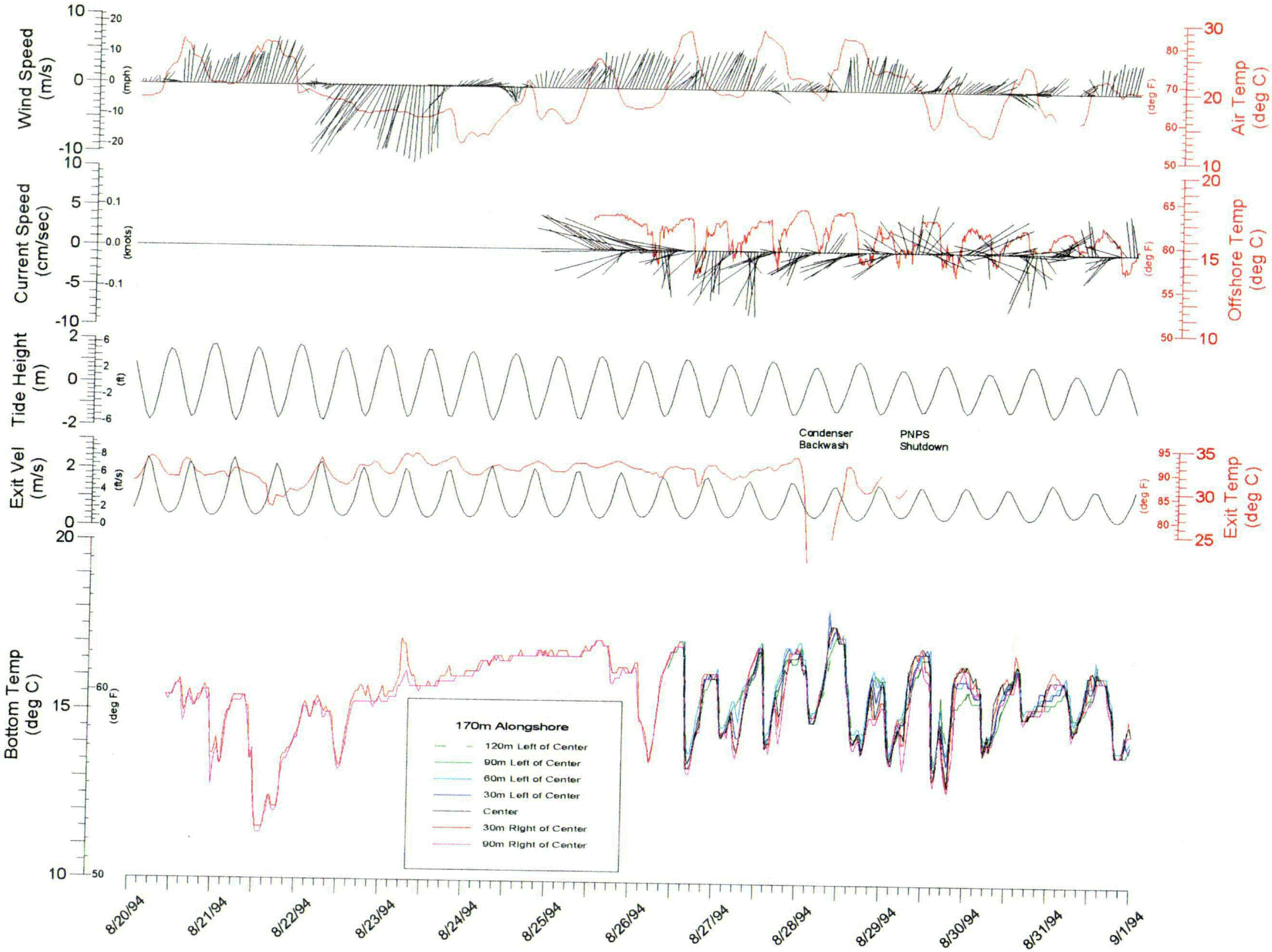

Figure 18. Time-history of bottom temperatures during the period 20 August - 1 September, 1994, measured on a shore-parallel line 170 m offshore of the mouth of the discharge channel. Other parameters plotted are as described in Figure 8.

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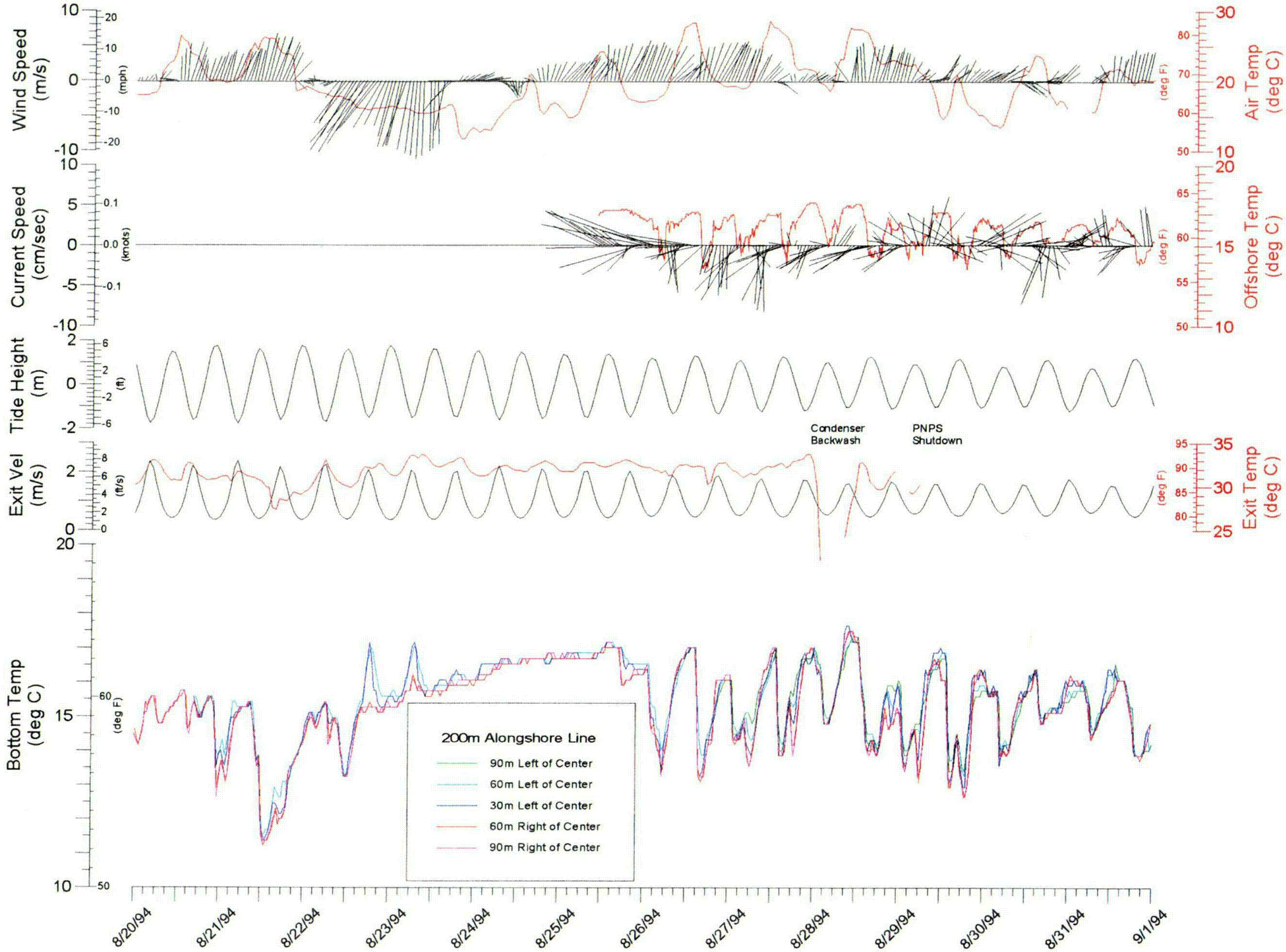

Figure 19. Time-history of bottom temperatures during the period 20 August - 1 September, 1994, measured on a shore-parallel line 200 m offshore of the mouth of the discharge channel. Other parameters plotted are as described in Figure 8.

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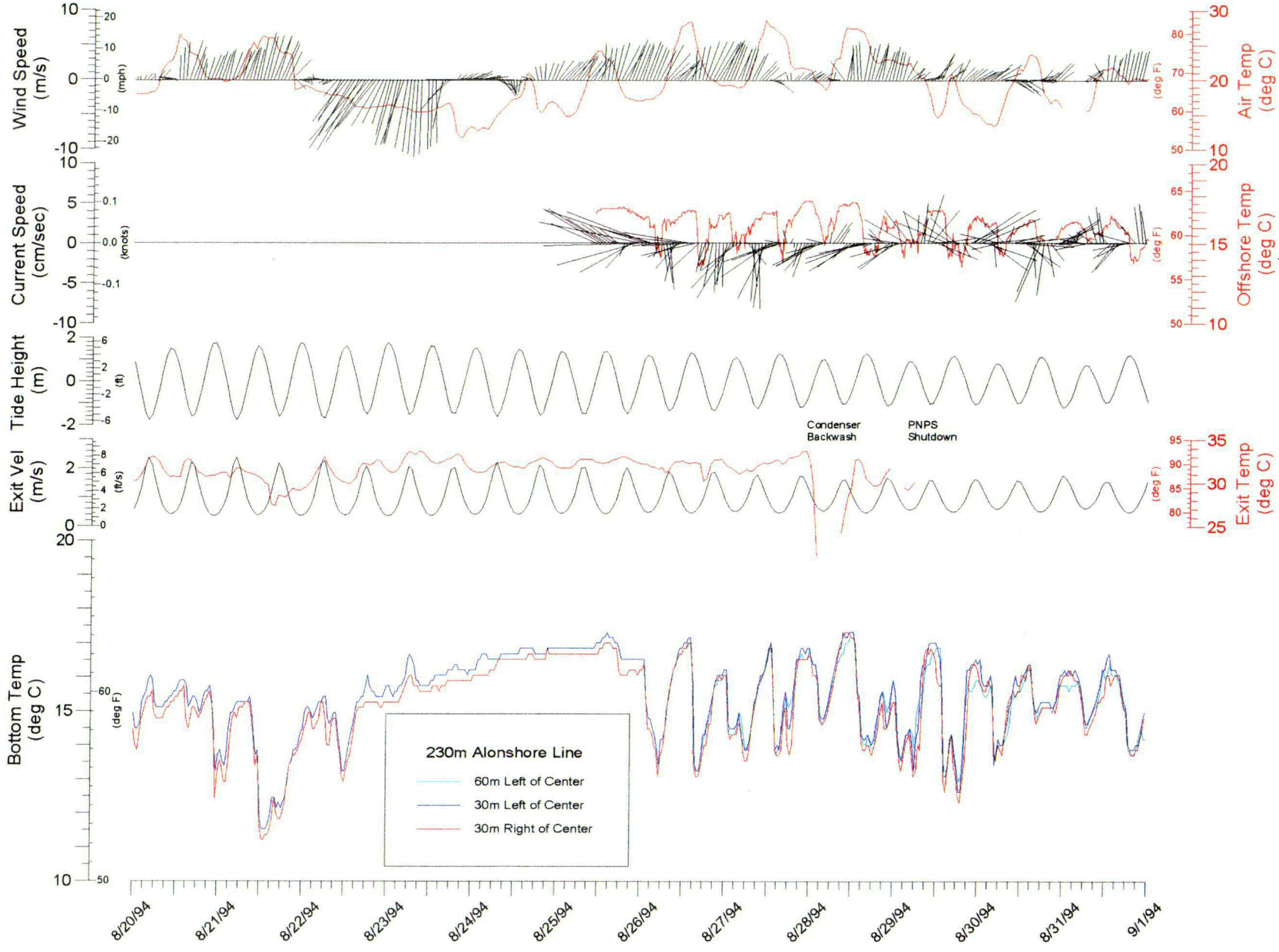

Figure 20. Time-history of bottom temperatures during the period 20 August - 1 September, 1994, measured on a shore-parallel line 230 m offshore of the mouth of the discharge channel. Other parameters plotted are as described in Figure 8.

C15

Cooling water discharge temperature ranges from 31 to 34 °C (88 - 92 °F) during the full-array measurement period, and shows little change over each tidal cycle. Maximum bottom temperatures are reached at the time of low tide. Peak bottom temperature at C0-50 reaches nearly 30 °C (86 °F), close to the actual condenser water discharge temperature. This high temperature suggests that the plume remains in contact with the bottom, with little dilution, as far out as this location. This is consistent with the high velocity and turbulence of the discharge during low water conditions (up to 2.5 m/s, or 8.1 ft/s). Farther offshore, elevated temperatures are also observed, although reduced in magnitude.

Along the centerline (Figure 8), temperatures become indistinguishable from ambient at a distance of about 100 to 140 m (330 to 460 ft). In the alongshore direction, there is much more variability. For example, Figure 11 shows that station R15-50, only a few meters to the right of the discharge canal, experiences no temperature elevation even when the nearby C0-50 station is at its peak temperature.

During low tide conditions, temperatures tend to be higher to the left of the discharge (compare Figures 9 and 10). This is probably a consequence of the shallower water depths there (4-5 m on the left vs 6-8 m on the right).

High Tide Conditions - During the high-water half of each tidal cycle, all stations show nearly identical temperatures, and there is no evidence of the discharge plume, even at the closest stations. At the deeper (outer) stations, temperatures are slightly lower than at stations near the discharge (by about 0.5 °C), due to the ambient stratification. The buoyant plume evidently separates from the bottom very close to the canal mouth during high tide conditions. This is consistent with the plume's low velocity (about 0.4 m/s, or 1.4 ft/s), and the absence of downward momentum and turbulence during high water conditions.

Post-Shutdown Conditions - After the power plant shut down on 29 August, tidal-period temperature fluctuations persisted at all locations for a few days. The only discernable difference was the absence of elevated temperatures close to the discharge canal during low tide conditions.

3.2.2 Bottom Temperature Patterns and Areas

Mapping and Contouring - Patterns of bottom temperatures at selected times, and the areas covered by various elevated temperatures are mapped and calculated using a comercial surface mapping software system (SURFER, by Golden Software, Inc.). SURFER accepts irregularly spaced geographic data at an instant of time, and interpolates and extrapolates the data over a dense grid of points within the domain. The program offers a variety of gridding options, including rectangular and triangular grids, and several methods of optimum interpolation, including non-isotropic Kriging and linear interpolation. For this study, a rectangular grid and the Kriging method was found to give the best results. Once gridded, the data are contoured and displayed. Smoothing is applied to the contours.

Additional data points ("pseudo-points") were added where necessary to control the placement of contour lines in regions of sparse data. This was necessary in order to produce physically meaningful results. Pseudo-points were arbitrarily assigned to have the same temperature as the ambient temperature, taken as L120-110. The rationale for pseudo-points, and the uncertainty in the area calculations, are described in Appendix C.

Figure 21 shows the mapping region around the PNPS, including the array of actual data points and pseudo-points, and the plume region (shaded blue) which is used for the area calculations in this report. Contours are displayed within the plume region, although the data are actually gridded over a larger region, indicated by the box in Figure 21.

The contoured bottom temperature field at 2200 EST, 27 August, plotted over the entire measurement area, is shown in Figure 22. The plume is seen to be restricted to an inner area within about 200 m of the discharge canal. Figure 23 shows the same data, but with the scale expanded to focus on the plume region. This low-tide event contained the highest bottom temperatures observed in this study: 30 °C (86 °F) at station C0-50. This event is discussed further below, and is compared with the benthic monitoring survey results in section 3.2.3.

Area Calculation Method - SURFER calculates the area enclosed by any specified temperature value. The program calculates area directly from the gridded values, independent of the contouring interval chosen for plotting. SURFER tends to maximize the area enclosed by contour lines. The analysis in Appendix C suggests that the accuracy of SURFER's calculated areas is: -5% to +1% for large, well-resolved temperature structures (i.e., regions of +1 °C temperature elevation); -14% to +35% for intermediate increments (+5 °C): and +43% to +84% for small, poorly resolved structures (i.e., +9 °C high temperature plume core regions).

Ambient Temperature - The data show noticable temperature gradients at low tide, with temperatures offshore and to the right of the discharge canal being lower by 0.5 to 1.0 °C, due

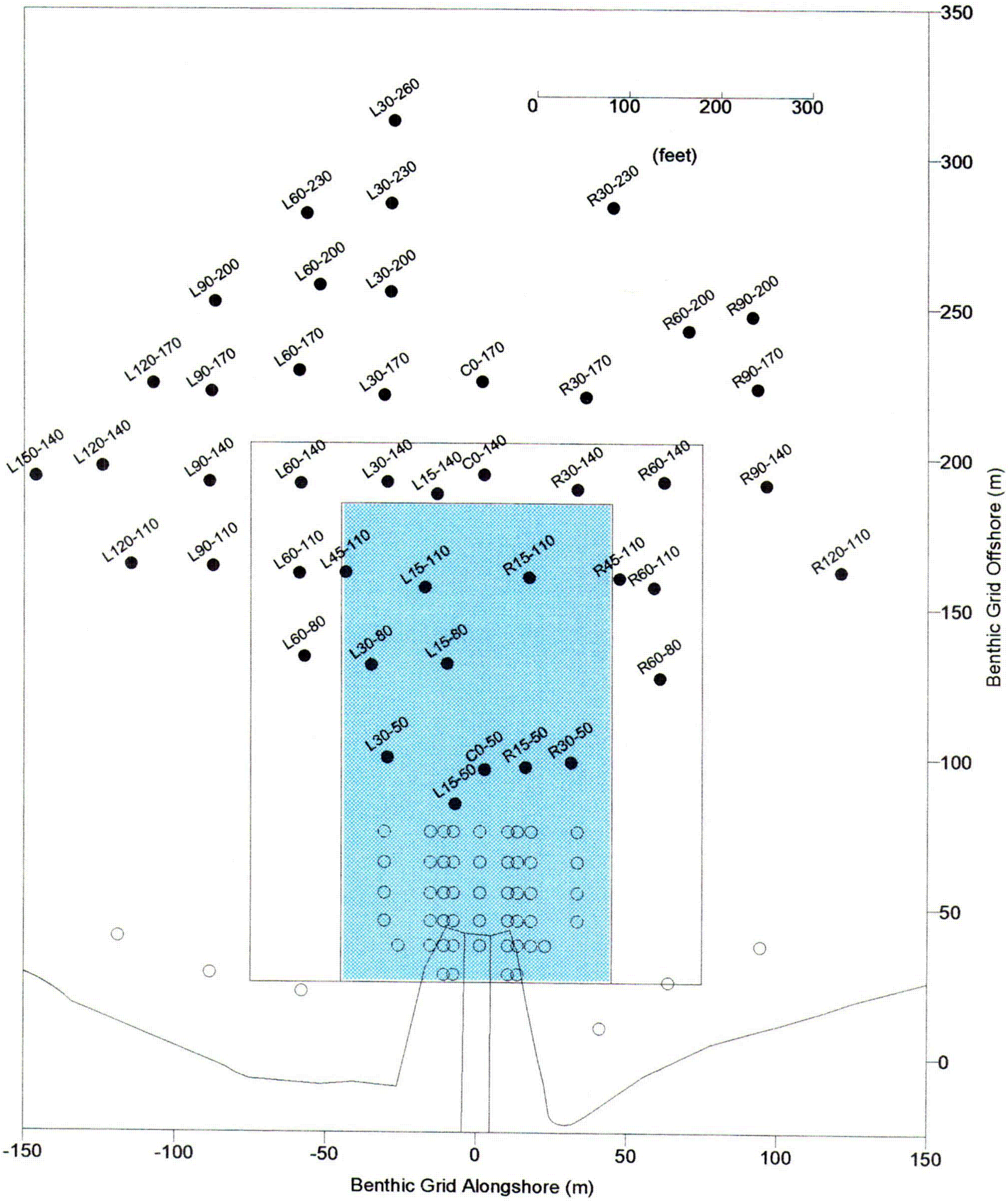

Figure 21. Map of measurement locations and contouring areas for PNPS cooling water discharge study. Solid circles represent actual measurement stations. Open circles represent "pseudo-points" used to control contouring in areas where data are lacking (see Appendix C). Inner shaded box shows the plume region, for which most detailed plots are made. Outer box indicates limits of data points used for gridding and contouring in the plume region.

C16

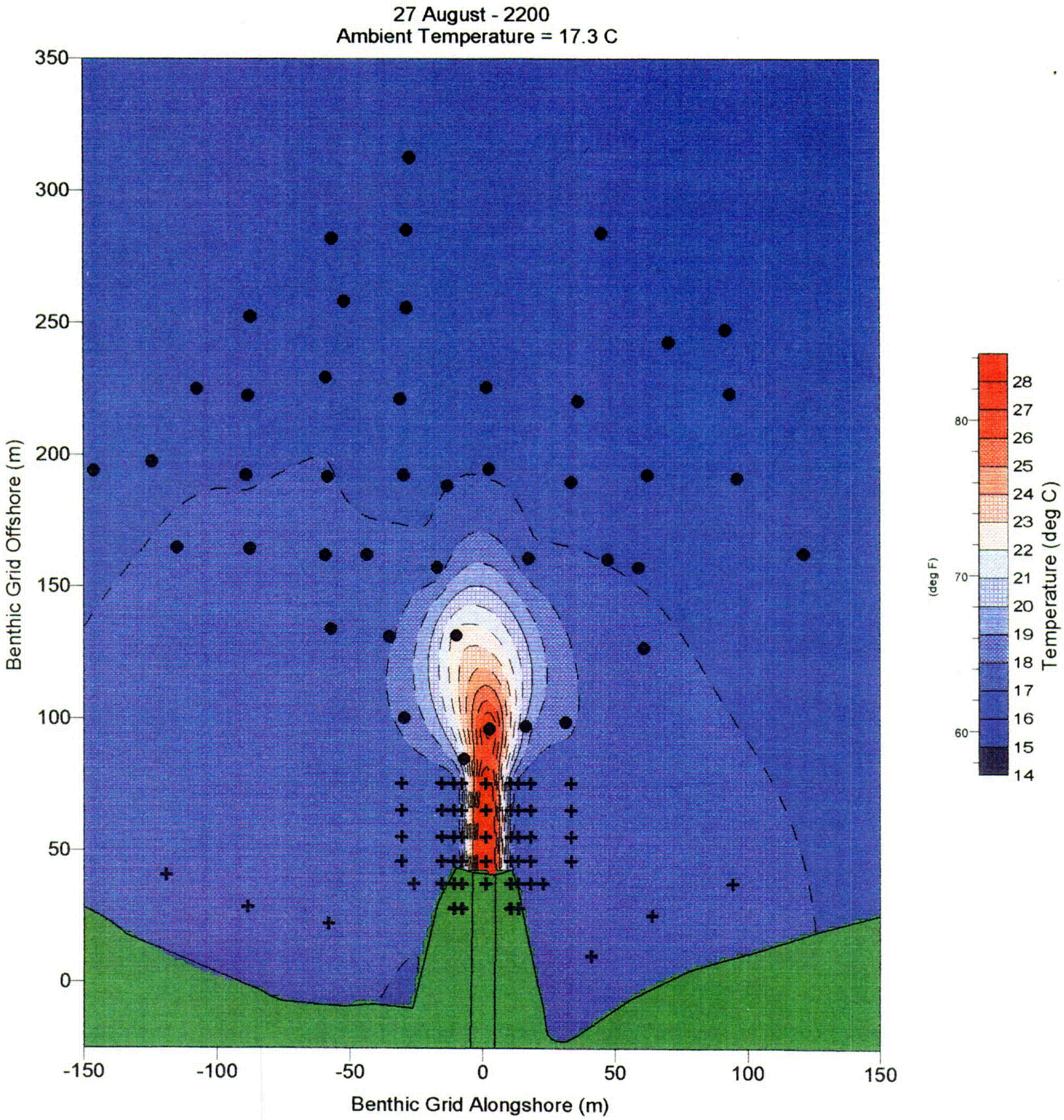

Figure 22. Color-shaded contours of bottom temperatures at 2200 EST, 27 August 1994, plotted over the entire measurement domain. All data points used in contouring are shown

C17

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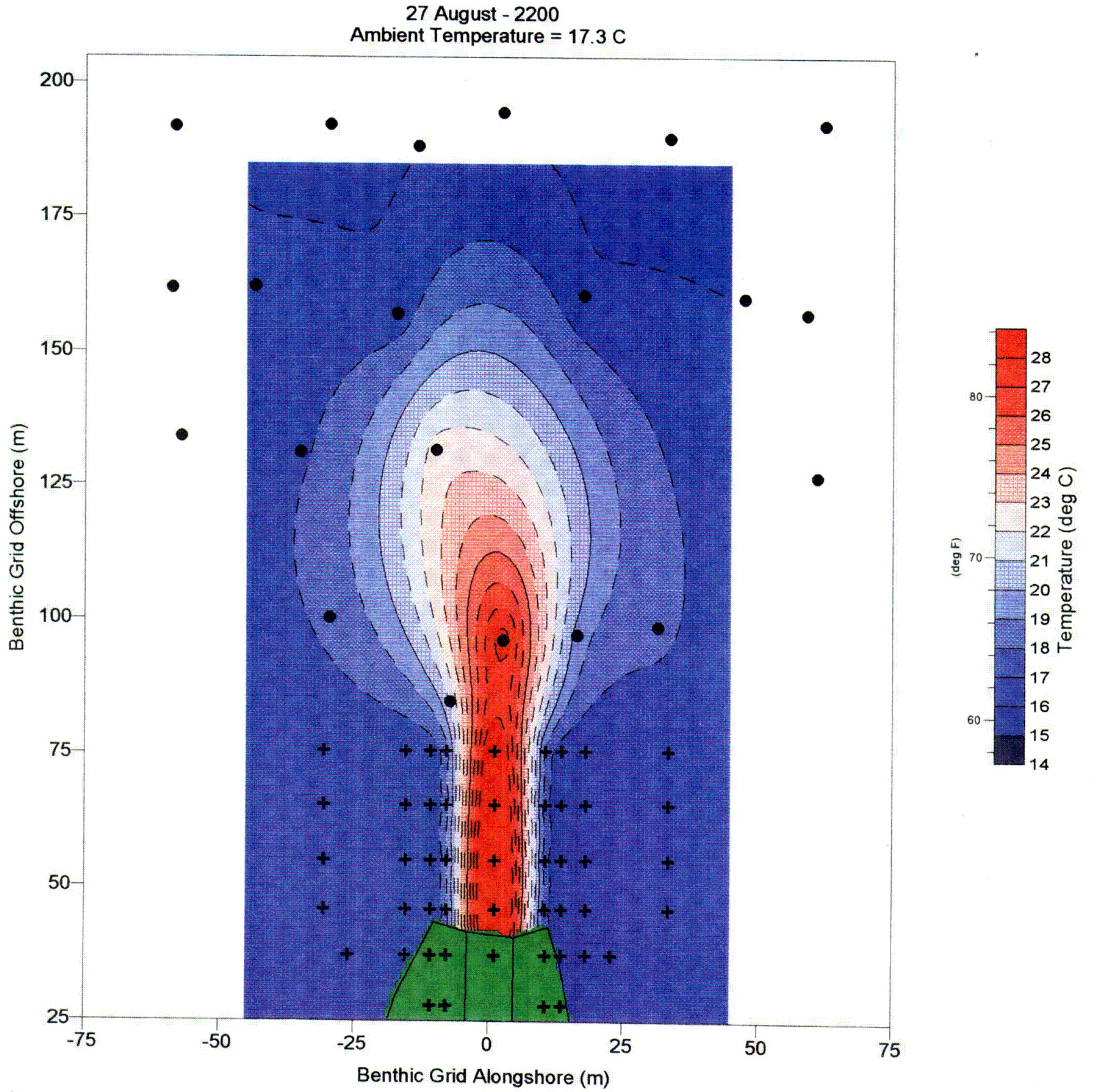

Figure 23. Color-shaded contours of bottom temperatures at 2200 EST, 27 August 1994, plotted over the plume region

C18

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to the deeper water there. Although these gradients make the selection of a single temperature to represent the entire ambient temperature field somewhat problematical, it was found that most far-field temperatures at moderate distances offshore were quite consistent. The recorded temperature at station L120-110 was therefore selected to represent the ambient value at each instant of time. Temperature elevations of as little as +1 °C above this arbitrary reference were found to yield meaningful closed contours defining the plume.

Peak Temperature Events and Areas Covered by Elevated Temperatures - Figure 24 is a composite time series showing all stations at which elevated temperatures were observed, as well as others representative of background conditions. The five low-tide events prior to plant shutdown (designated Events A - E) are evident, especially at station C0-50, which is closest to the discharge. Contour maps of bottom temperature for each of these low tide events, and for the four intervening high tide events, are shown in Figure 25. Areas enclosed by temperature increments of +1 °C (+1.8 °F), +5 °C (+9.0 °F), and +9 °C (+16.2 °F) above ambient are also shown on Figure 25.

Table 4 summarizes the peak temperatures observed at C0-50 during the five low-tide events, the corresponding areas covered by the three temperature elevations, and the plant operating parameters. The smallest temperature increment, +1 °C (1.8 °F) covers the largest area, ranging from 2,500 to 5,500 m^2 (about 27,000 to 51,000 ft^2, or 0.6 to 1.16 acre). The +5 °C (9.0 °F) increment encloses an intermediate size area. The highest temperature increment, +9 °C (+16.2 °F) covers a much smaller area, typically less than 500 m^2 (5,500 ft^2, or approximately 0.12 acre).

Table 4. Peak bottom temperatures at C0-50, and area covered by temperature elevations, for the five low tide events observed during 26 -29 August 1994.

Event	Date	Time	PNPS Power	Disch. Temp	Max Observed Bottom Temp		Ambient Temp	Area covered by temperatures elevations of:					
								+1 C (+1.8 F)		+5 C (+9.0 F)		+9 C (+16.2 F)	
		EST	%	deg F	deg C	deg F	deg C	sq. m.	sq. ft.	sq.m.	sq. ft.	sq. m.	sq. ft.
A	08/26/94	21:00	100	90.8	29.5	85.1	15.9	4,383	47,178	1,278	13,755	518	5,580
B	08/27/94	09:00	100	89.6	26.6	79.9	16.2	3,460	37,243	938	10,095	274	2,954
C	08/27/94	22:00	95	92.6	30.0	86.0	17.3	4,717	50,769	1,516	16,318	481	5,180
D	08/28/94	10:30	47	81.6	26.6	79.9	17.3	4,355	46,872	622	6,699	0	0
E	08/28/94	23:00	100	89.2	25.0	77.0	16.4	2,488	26,785	722	7,771	467	5,029

Note: 1 acre = 43,560 sq. ft.

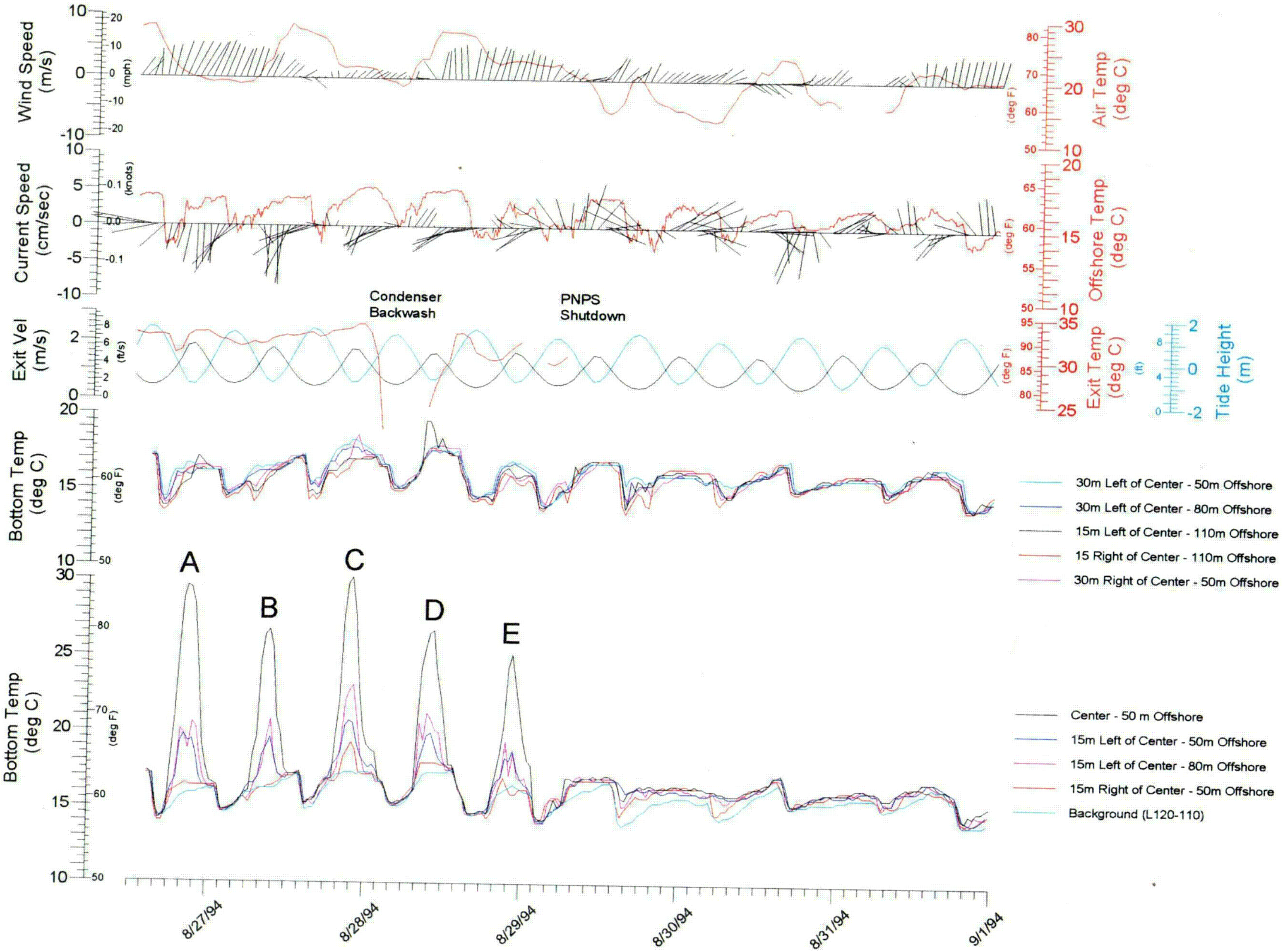

Figure 24. Composite time series of bottom temperature at selected stations in and out of discharge plume; also showing wind and current vectors, air and water temperature, tide height, exit velocity and temperature. Times are Eastern Standard.

C19

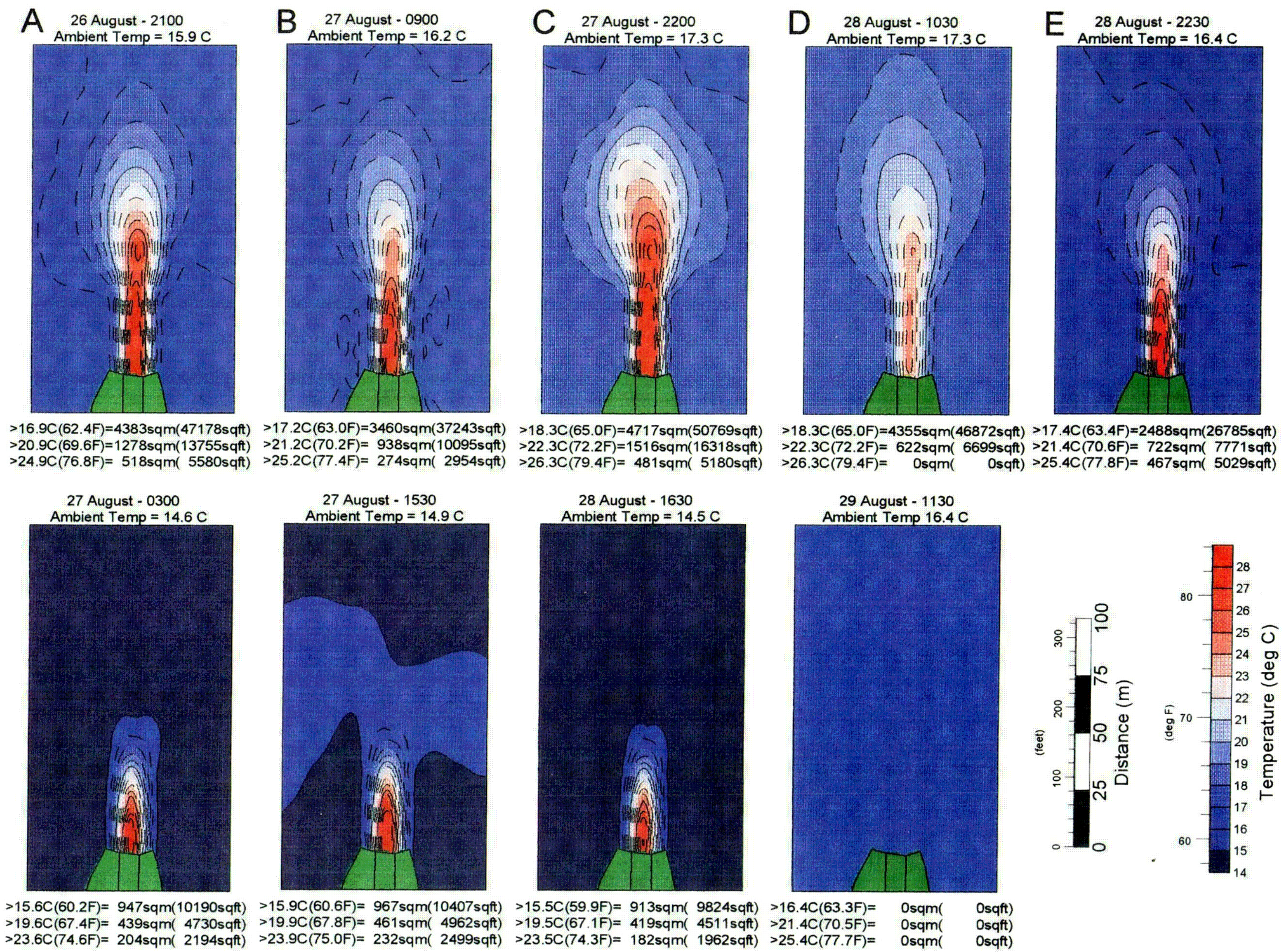

Figure 25. Color-shaded contour plots of bottom temperatures for 5 low-tide events and four high-tide periods. Areas enclosed by various temperature contours are shown below each figure

C20

As shown in Table 4, the observed peak temperatures ranged from 25.0 °C (77.0 °F) to 30.0 °C (86.0 °F). The area covered by the various temperature elevations varied more widely, by about a factor of two. The highest peak temperature corresponded to the largest plume area (Event C), but the correlation was poor for other events (for example, Event E). Although the reason for the high variability of areal extent is not known, it may be significant that the maximum observed temperature and area (Event C) occurred during a brief period of nearly calm conditions on 28 August. Winds were moderate from the southwest (Figure 24) during the other four events. This suggests that upwelling-favorable winds may reduce the bottom extent of the plume. Low discharge temperatures were associated with reduced plant thermal output, which had a very pronounced effect on the area covered by the highest temperature elevation.

Event C -- Event C is significant, as it represented the maximum bottom temperature observed in this study. The event occurred at 2200 EST on 27 August 1994, immediately prior to a backwashing operation, which was performed by Boston Edison on the following high tide; in fact, plant output was already being reduced. Ambient temperatures during Event C ranged from 16.5 °C (61.7 °F) offshore and to the right of the discharge, to 17.5°C (63.5 °F) on the left. The ambient value selected for the area calculations (station L120-110) is 17.3°C (63.1 °F). The alongshore gradient is probably due to the depth of water, which ranges from 6-8 m (20-26 ft) on the right, to 3-6 m (12-20 ft) on the left. The wind during this event was light (2 m/s) from the southwest. Near-bottom current at the time was flowing toward the west/southwest, that is, mostly onshore with an upcoast component (toward Boston). This current would tend to push the plume to the left, looking seaward. The +9°C isotherm encloses an area less than 10 m wide x 100 m offshore. On the other hand, the +1°C isotherm extends more than 160 m seaward and has a maximum width of 75 m.

The area of elevated temperature is slightly skewed to the left, where the water is shallower. This might suggest that the plume hugs the shallow, rocky area as it moves offshore, or that it is pushed onto the shallow area by the upcoast-directed ambient currents.. However, the same bottom temperature pattern could also be explained by a vertical temperature gradient within the plume, which would be manifested as higher bottom temperatures in shallower water.

Other Events - Event D, immediately after the backwashing operation, exhibited surprisingly high bottom temperature, given that the plant was operating at less than 50% power level. According to Boston Edison (R. Anderson, personal communication), this is probably due to the accumulation of warm water in the intake lagoon and condenser pump bays during the backwash cycle, when the discharge is stopped. When normal pumping resumes, this warm water contributes to elevated temperature at the discharge, temporarily adding to the heat produced by the plant itself. The agreement in maximum temperature between events B and D is apparently fortuitous.

Plume Evolution - The time history of plume evolution over a low-tide cycle for Event C is shown in Figure 26. The plume begins to extend outward along the bottom about 3 hours before low tide. By about 1 hour prior to low tide, the plume area has reached 75% of its maximum value. After slack water, the plume area declines rapidly, falling to less than 50% of maximum at 1 hour after low tide. Thus, elevated temperatures are felt on the sea floor for only limited periods of time on each tidal cycle, and only over limited areas. For example, the +9 °C (+16.2 °C) temperature elevation affects a maximum area of a few hundred square meters (about 0.1 acres), and even that limited area is only affected for a few hours per tidal cycle. This repeated, transient temperature cycling of the bottom may be the primary mechanism by which the cooling water discharge affects the nearshore benthic organisms.

3.2.3 Comparison with Benthic Survey Results

Figure 27 shows bottom temperature during Event C, at 2200 EST, 27 August 1994 (left) compared with the denuded and total affected areas determined by the benthic monitoring survey in June 1994 (right), plotted on the same scale for comparison. Benthic survey results for October 1994 (not shown) are similar. The denuded area resembles the region of +9 °C temperature elevation both in size and in shape, including the slight skewing to the left. This suggests that the observed biological impact of the discharge is not associated with small temperature increments.

The most striking result of this comparison is the small size of the region containing affected benthic organisms. Both the denuded and total affected areas extend no farther offshore than about 100 m (300 ft), similar to the maximum extent of the high-temperature core of the discharge plume. This core region is much smaller than the area covered by the minimum temperature elevation (+1 °C), which extends nearly 200 m offshore. The bottom temperature study does not resolve the structure of the core region. In fact, only one of the bottom temperature measurement stations (C0-50) is within the denuded area.

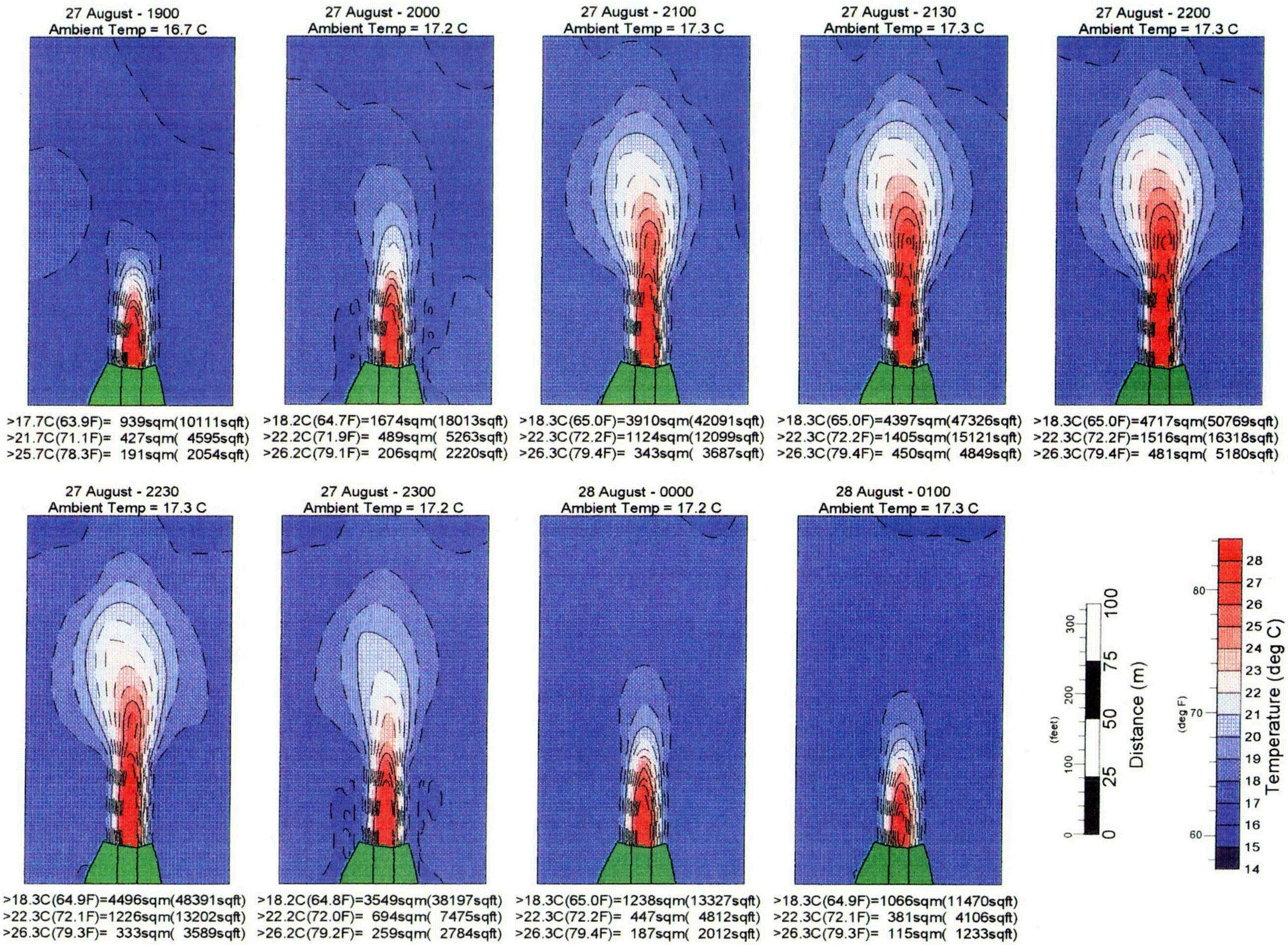

Figure 26. Color-shaded contour plots and areas at hourly and half-hourly intervals from 1900 EST 27 August to 0100 28 August, illustrating the evolution of the bottom temperature plume over a low tide cycle. Low water slack occurred at 2200 EST.

C21

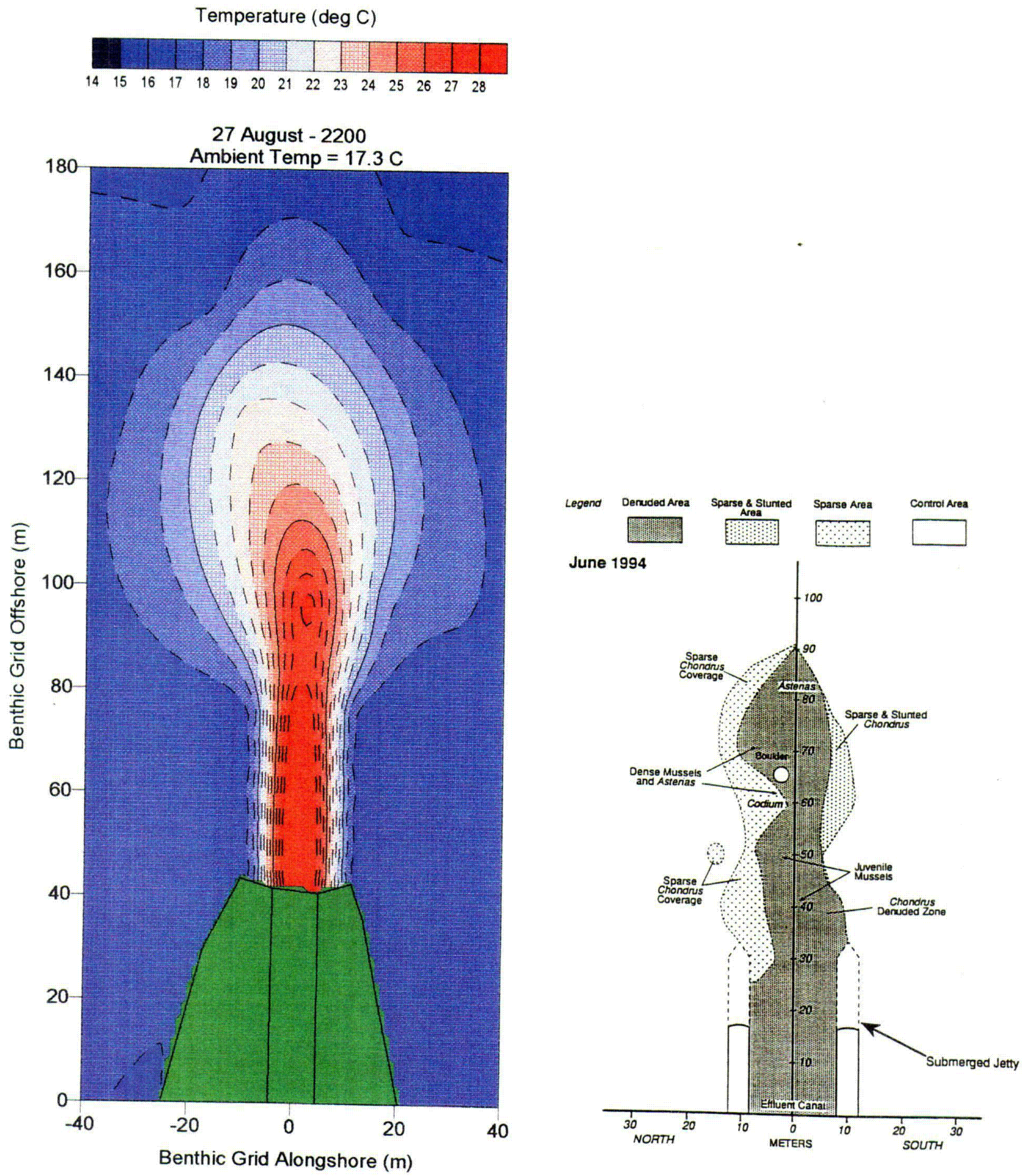

Figure 27. Comparison of bottom temperature at 2200 EST, 27 August 1994 (left) with results of the benthic monitoring survey of June 1994 (right) (from Boston Edison, 1995)

C22

Although the physical extent of the plume on the seafloor, measured in terms of significantly elevated temperatures at low tide, is roughly consistent with the area of biological impact, it would be incorrect to conclude that elevated temperature is solely responsible for the benthic impact. This is because significantly elevated temperatures in the plume core are also correlated with high water velocities, which can cause scouring of the sea floor. Therefore, at least a portion of the overall biological impact may be due to direct, mechanical impingement effects, especially near the mouth of the discharge canal.

3.2.4 Discharge Effects During 22 - 23 August

Prior to the deployment of the full measurement array, elevated temperatures were observed at several stations located at the outer edge of the array (Figure 28). Temperature recorders at these stations were installed on 17 and 20 August. Through 21 August, temperature fluctuations of tidal origin were observed, but there was no evidence of the discharge plume at any of these stations. On 22 August, strong winds from the northeast and north, combined with cooler air temperatures, caused a reversal of the circulation regime and overturning and mixing of the water column. Simultaneously, elevated temperatures due to the cooling water discharge became evident at low tide, especially at R60-80, and to a lesser extent, at R60-110 and R30-140.

Figure 29 is a partial contour map of the actual temperature at the measurement stations at 1800 EST, 22 August 1994. The temperature at R60-80 exceeded 20 °C (68 °F), against a background temperature of 16 °C (61 °F), at a time when the wind was strongest from the northeast. Lesser temperature elevations were observed during the subsequent low tide periods on 23 August, when the winds were more northerly. After 23 August, the winds became weak out of the southwest, and the elevated temperatures ceased to be evident at these stations. The strong dependence of bottom temperature on wind direction demonstrated by the 22 - 23 August data suggests that downwelling-favorable onshore winds influence the bottom extent of the cooling water discharge plume.

Although the current meter had not yet been installed when these temperature measurements were taken, it is reasonable to infer that winds from the north and northeast would cause the mean current to flow southward along the coast, and set up a downwelling circulation. The collapse of temperature stratification throughout the study area is certainly consistent with this

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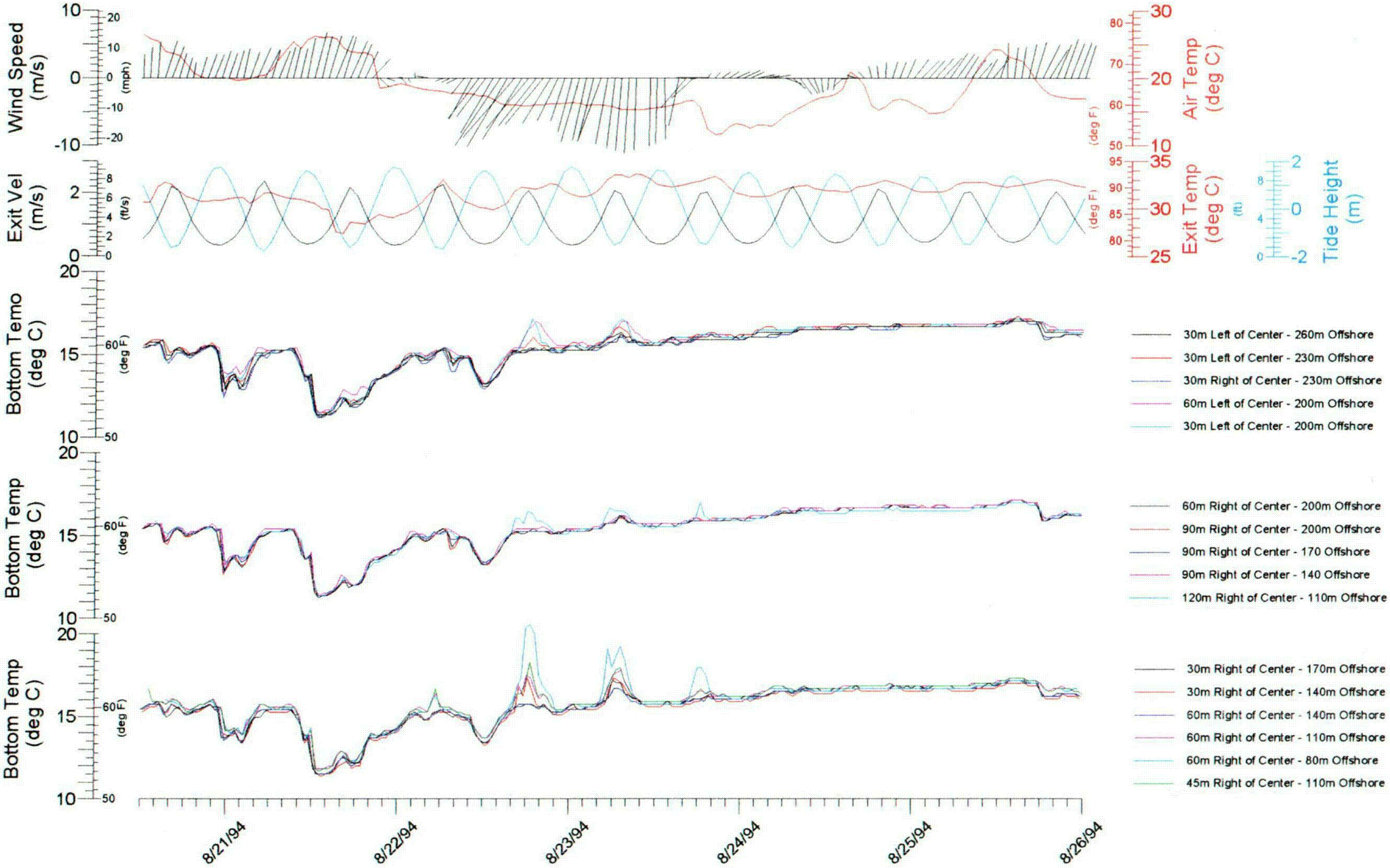

Figure 28. Time-history of bottom temperatures during the period 20 - 26 August 1994 (prior to deployment of the full array). Upper temperature panel: stations L30-260, L30-230, R30-230, L60-200, and L30-200; Middle temperature panel: R60-200, R90-200, R90-170, R-90-140, and R120-110; Lower temperature panel: R30-170, R30-140, R60-140, R60-110, and R60-80. Also shown are hourly wind vectors, air temperature, tide height (Boston), cooling water discharge temperature, and calculated discharge exit velocity. All vectors originate on the graph axis, and their length and orientation shows the speed and direction toward which the flow was moving, relative to North (straight up on the page). Times are Eastern Standard.

C23

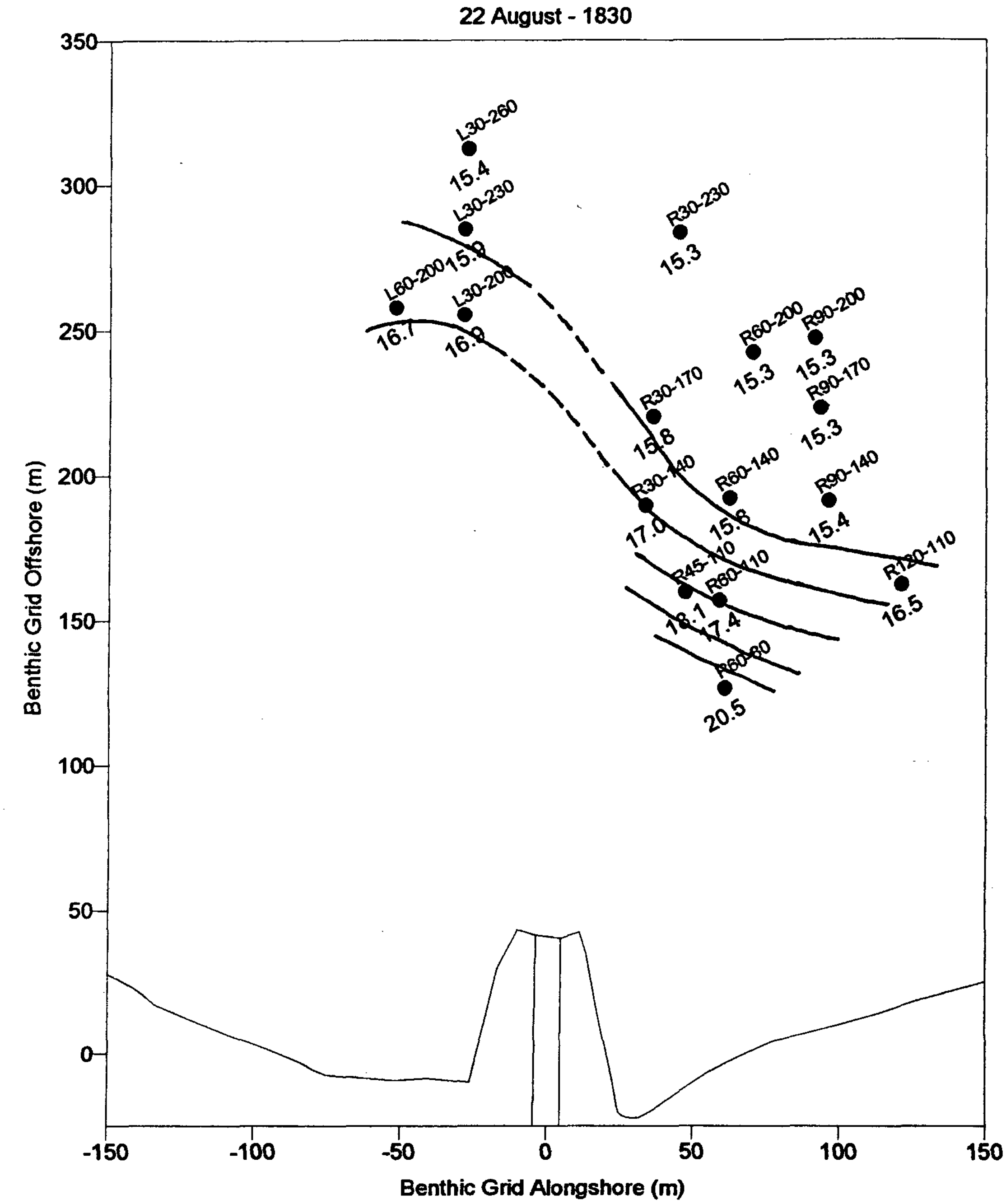

Figure 29. Partial contours of elevated temperature observed at 1800 EST, 22 August 1994, during northerly winds and downwelling conditions. Note the much greater area affected by elevated temperatures, compared to patterns of bottom temperature observed under upwelling conditions during 26-29 August.

inference, and a similar pattern was observed during the stronger northeasterly storm on September 4th and 5th. A downwelling circulation pattern would directly favor enhanced offshore transport of the heated effluent at the bottom. In addition, onshore winds may also trap the heated water near the coast at the surface, resulting in higher temperatures there, while restricting the normal offshore dispersion and mixing. This could further raise the bottom temperature of the plume.

The lack of temperature recorders near the discharge canal during this period precludes direct measurement of plume area under these downwelling conditions. The partial array data do, however, permit some speculation as to the maximum area covered under these dynamic conditions. The following table gives the approximate distances along and across the plume axis at which a temperature elevations of 2 °C above ambient was observed.

Date	Time	Maximum Extent of +2°C Elevation: Offshore	Cross-Plume
22 August	1800 EST	200 m (660 ft)	60 m (200 ft)
27 August	2200 EST	110 m (360 ft)	30 m (100 ft)

These data suggest that the offshore extent of the discharge plume at this low temperature elevation is greater by a factor of 1.8, while the width is greater by a factor of 2. Assuming that the measured horizontal extent is representative of plume width, and is not merely an artifice of a southward-directed current, this suggests that the bottom area covered by the +2°C elevation could be larger under downwelling conditions by a factor of 3.6, compared to the upwelling situation.

The 22 - 23 August data are not adequate to describe the plume shape or directly measure the area covered by higher temperatures. However, the limited data do show that the discharge spreads over a much wider bottom area under these conditions. In fact, Figure 29 suggests a shape more like a pool of warm water on the bottom than a plume. In particular, a temperature elevation of +5 °C was observed 60 m to the right of center on 22 August (Figures 28 and 29), compared with only 15 m left of centerline for the same elevation during 26 - 29 August. This factor-of-4 difference in lateral extent is even greater than the factor of 2 estimated from the +2 °C isotherm described above. Combined with the broad shape shown by the lower-temperature isotherms, these observations suggests that the core of the plume at the bottom is likely to be either larger or warmer, or both, under downwelling conditions. It is possible that the core region, near the discharge canal, may be significantly warmer due to the pooling of warm surface waters. The factor of 1.8 in length, combined with a factor of 4 in width, gives an area increase of a factor of 7.2.

In summary, the partial array deployed on 17 and 20 August has provided insight into the bottom extent of elevated temperatures under well-mixed, isothermal, downwelling conditions, compared to the stratified, upwelling conditions of the later measurement period. *Potentially, the bottom area covered by a given temperature increment above ambient could be greater by a factor of about 4 to 7 under downwelling conditions.* Against this, however, it must be noted that onshore winds (from the northeast) are rare in late summer, when ambient temperatures are high. Onshore winds are much more frequent during the autumn, winter, and spring, but the water is much colder in these seasons and the plume's effect on benthic organisms is presumably less.

4. CONCLUSIONS

4.1 BOTTOM AREA AFFECTED BY ELEVATED TEMPERATURES

In summary, time series measurements at 59 locations were obtained, with the primary objective of quantifying the mean and time-varying bottom temperature patterns associated with the cooling water discharge. The study was cut short by the shutdown of the PNPS from 29 August to 29 November 1994, limiting detailed observation of the plume to a single weather regime. The spatial resolution of the measurements array was adequate to determine plume area, in spite of instrument losses. However, under the environmental conditions that prevailed, most of the 44 recovered temperature recorders were outside the region of direct plume effect. The measurement of plume extent therefore rests on a relatively few time series measurements.

Relatively calm, warm, upwelling-favorable conditions prevailed during the full-array measurement period (26 -29 August 1994), when the instrument array was fully installed and the PNPS was operating at full power. Ambient bottom water temperature at this time was relatively cold, about 16-17 °C (61-63 °F), and the currents were weak and dominated by tidal-period fluctuations. Under these conditions, the sea floor areas covered by elevated temperatures due to the cooling water discharge were comparatively small, and the following conclusions apply:

- The discharge plume is in contact with the sea floor for significant offshore distances only when the tide height is below Mean Sea Level, that is, during the low-tide half of the tidal cycle. Benthic organisms in the affected area are therefore subjected to repeated thermal cycling, as the seafloor environment alternates between ambient and cooling water discharge temperatures.
- The maximum areal extent of the plume on the bottom, and the highest temperatures, are observed at slack water around low tide.
- The plume begins to extend outward along the bottom about 3 hours before low tide. By about 1 hour prior to low tide, the plume area has reached 75% of its maximum value. After slack water, the plume area declines rapidly, falling to less than 50% of maximum at 1 hour after low tide.
- The maximum offshore extent of the plume at low tide, measured as the +1 °C (+1.8 °F) increment above ambient, did not exceed 170 m from the mouth of the discharge canal.

- The width of the bottom plume at the +1 °C (+1.8 °F) elevation reached a maximum of about 40 m at at distance of 80 m offshore.
- The plume's bottom footprint tended to be skewed to the left (northward), consistent with both the shallower water there and the direction of the mean ambient current.
- The maximum area enclosed by the +1 °C (+1.8 °F) temperature elevation was approximately 4,500 m^2 (49,000 ft^2), $\pm$50%, or about 1.2 acre. Higher temperatures were restricted to smaller areas. For example, the area covered by the +9 °C (+16.2 °F) elevation was typically less than 500 m^2 (5,500 ft^2), or about 0.12 acre. These areas are approximately consistent with the denuded and stunted areas delineated in the benthic monitoring surveys.
- Area calculations are subject to uncertainty due to lack of spatial resolution in regions of sharp gradients. The accuracy of the area calculation, for a given data set, is believed to be 0-5% for small temperature increments over large areas, and 0-200% for core regions.
- During high tide there is no discernable temperature increase at any location, even including stations as close as 50 m from the mouth of the discharge canal. This conclusion probably applies to all environmental conditions, not just the summer conditions characterizing the full-array measurement period.
- The bottom temperature characteristics of the plume are consistent with previous studies, and with analytical models of buoyant plume behavior, such as those conducted by MIT in the early 1970's (Pagenkopf, et al, 1974).

4.2 EXTENSION TO OTHER DYNAMIC CONDITIONS

Due to the short length of the full-array measurement period, the foregoing conclusions cannot be applied directly to assess plume extent or maximum bottom temperatures under other wind, current, and tide conditions. While it is fruitless to speculate on actual temperature extremes and areas affected in numerical terms, it is worthwhile to consider the physical basis for non-observed extremal conditions, in order to place the results of this study in the proper context.

4.2.1 Ambient Temperature Extremes

The data collected in this study are typical of late summer conditions in Cape Cod Bay, and therefore represent the peak of the annual water temperature cycle. However, it is not known whether the observed temperatures are actually close to the long-term maximum. Higher surface-layer ambient temperatures than those observed in this study could result from a prolonged period of warm, sunny weather with light winds. This would cause the circulation to stagnate, and the offshore surface layer to become very warm. If such a period were followed by a downwelling-favorable wind, the coastal waters could become well-mixed and substantially warmer, from top to bottom, as the warm offshore surface water replaces the normal stratification in the coastal zone. This would also raise the average temperature at the intake structure, and result in higher discharge temperatures. The net result would be a higher-temperature plume, discharging into higher-temperature ambient waters. Even without allowing for the additional dynamical effects of the downwelling circulation (see below), this ambient warming would result in higher maximum bottom temperatures and greater plume areas.

4.2.2 Spring Tide Conditions

The full-array measurement period coincided with an average tidal condition, neither spring nor neap. During the spring tide phase, the lowest water level can be nearly 1 m (3 ft) below Mean Low Water. This would not result in significantly higher discharge velocities, because this velocity is limited by internal characteristics of the discharge at its exit (Pagenkopf, et al, 1974). However, the discharge would enter the ocean with greater downward momentum due to the longer drop, and this might prolong the plume's attachment to the bottom. Higher ambient temperatures would be associated with the extreme low water height, further raising the intake water temperature and discharge temperature.

4.2.3 Downwelling Conditions

As discussed in Section 3.2.3, the data suggest that the offshore and lateral extent of the plume may increase during downwelling conditions, when the wind is from the north or northeast. Based on the limited data available, the worst case scenario is inferred to consist of winds from the northeast, which are directed straight onshore at the PNPS location. Under these conditions, the area affected by small temperature increments (+2 °C) could be as much as 4 to 7 times greater than during stratified, upwelling conditions. Presumably, the same factor would apply to greater temperature elevations as well. North and northeast winds are usually associated with atmospheric cooling, which tends to counteract the warming effect of the downwelling circulation; however, warm winds from these directions are possible in summer, and in any case the water temperature at the coast will be governed by the temperature of the offshore surface layer. Higher plume temperatures and greater horizontal extents than those observed on 22 - 23 August are possible, especially if a downwelling event should occur following a prolonged period of warm weather, light winds, and stagnant currents.

4.2.4 Worst-Case Summary

In summary, extremal bottom temperatures and plume areas could result from a combination of spring tide conditions, coincident with unusually warm weather, and downwelling-favorable winds. Under these conditions, it is possible that peak discharge temperatures in excess of 38 °C (100 °F) could occur. Taking account also of the uncertainty in area measurement, a bottom footprint approximately 4 to 7 times larger in area, is also believed possible under these dynamical conditions.

4.3 RECOMMENDATIONS FOR FUTURE STUDIES

If additional studies of the effect of the cooling water discharge on the benthic environment are deemed necessary by Boston Edison Company, they should focus on obtaining bottom temperature time series data over an extended period of time, so as to observe the plume's behavior under a variety of environmental conditions. This was an objective of the present study, but was not achieved due to delays in installing the instrument array, combined with an unexpected PNPS shutdown. The geometry and resolution of the array used in this study would be appropriate for another study aimed at quantifying wider area extents, such as those associated with northeasterly wind events. However, additional resolution in the near-field area is recommended, particularly in the discharge canal mouth and in the waters close to the mouth on both sides, to make analysis and measurement of plume area easier and more precise.

Improvements should also be made to the instrumentation, to enhance the probability of successful instrument recovery. Small, bottom-mounted instrumentation such as these temperature recorders is difficult to maintain, because it is vulnerable to wave action, sediment movement and burial, and damage from fishing activities. Many of these problems could be solved by using much larger platforms, but this would increase the cost and difficulty of installation and recovery. Minor improvements to the proven technology are therefore recommended. Although the cast-concrete bottom platforms proved satisfactory, better techniques are needed for: 1) attaching the temperature recorders; 2) securing the platforms to the sea floor; and 3) relocating buried platforms.

5. REFERENCES

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APPENDIX A

BOTTOM TEMPERATURE RECORDER DEPLOYMENT AND RECOVERY INFORMATION

BOSTON EDISON COMPANY
PILGRIM NUCLEAR POWER STATION
COOLING WATER DISCHARGE PLUME STUDY

HOBO TEMPERATURE RECORDER DEPLOYMENT, AUGUST - SEPTEMBER 1994

Station Names:

Names are descriptive of station location in a coordinate system centered on the discharge canal.
"Rxx-yyy" refers to: xx meters to the right of the centerline
yyy meters offshore from the mouth of the discharge canal.
"Lxx-yyy" refers to stations to the left of the centerline.
"CO" refers to the array center line extending directly offshore from the discharge canal.
"CURRENT" *refers to current meter station*

ACTUAL DEPLOYED POSITIONS

STATUS: OK means HOBO sensor recovered

STATION NAME	LATITUDE 41 deg N + Minutes	LONGITUDE 70 deg W + Minutes	DATE DEPLOYED (Aug 1994)	BASE TYPE	DATE FOUND (Sept/Oct 1994)	STATUS
L30-50	56.901	34.742	08/26	60 lb steel plate	09/21	OK
L15-50	56.888	34.733	08/26	60 lb steel plate	09/21	OK
C0-50	56.891	34.723	08/26	60 lb steel plate	09/21	OK
R15-50	56.888	34.714	08/26	60 lb steel plate	09/21	OK
R30-50	56.885	34.704	08/26	60 lb steel plate	09/21	OK
L60-80	56.924	34.748	08/26	60 lb steel plate	09/21	OK
L30-80	56.917	34.735	08/26	60 lb steel plate	09/21	OK
L15-80	56.911	34.719	08/26	60 lb steel plate	09/21	OK
R15-80	56.903	34.702	08/20	12" flanged jet pipe	10/14	base found, HOBO missing, unscr
R30-80	56.895	34.693	08/20	18" flanged jet pipe	09/21	base found, HOBO broken off
R60-80	56.891	34.676	08/20	60 lb steel plate	09/21	OK
L120-110	56.953	34.774	08/26	60 lb steel plate	09/22	OK
L90-110	56.946	34.757	08/26	60 lb steel plate	09/20	OK
L60-110	56.940	34.739	08/26	60 lb steel plate	10/14	OK
L45-110	56.934	34.730	08/26	60 lb steel plate	09/20	OK
L30-110	56.928	34.720	08/26	60 lb steel plate	-	not found
L15-110	56.925	34.715	08/26	60 lb steel plate	09/20	OK
R15-110	56.918	34.692	08/26	60 lb steel plate	09/20	OK
R30-110	56.914	34.683	08/20	18" flanged jet pipe	10/14	base found, HOBO broken off
R45-110	56.905	34.673	08/20	18" flanged jet pipe	10/14	OK
R60-110	56.906	34.667	08/20	18" flanged jet pipe	09/20	OK
R90-110	56.899	34.643	08/20	36" straight jet pipe	-	not found
R120-110	56.893	34.626	08/20	12" flanged jet pipe	returned by CG	OK - broken off
L150-140	56.975	34.784	08/26	60 lb steel plate	09/22	OK
L120-140	56.971	34.769	08/26	60 lb steel plate	09/22	OK
L90-140	56.961	34.747	08/26	60 lb steel plate	10/14	OK
L60-140	56.952	34.728	08/26	60 lb steel plate	10/14	OK
L30-140	56.945	34.711	08/26	60 lb steel plate	09/21	OK
L15-140	56.939	34.702	08/26	60 lb steel plate	09/20	OK
C0-140	56.938	34.690	08/26	60 lb steel plate	09/20	OK
R15-140	56.934	34.683	08/26	60 lb steel plate	-	not found
R30-140	56.928	34.672	08/20	12" flanged jet pipe	09/20	OK
R60-140	56.922	34.653	08/20	18" flanged jet pipe	09/21	OK
R90-140	56.913	34.632	08/20	36" straight jet pipe	09/20	OK
R120-140	56.903	34.614	08/20	36" straight jet pipe	-	not found
R150-140	56.897	34.598	08/20	36" straight jet pipe	10/14	base found, HOBO broken off
L120-170	56.980	34.749	08/26	60 lb steel plate	09/22	OK
L90-170	56.973	34.741	08/26	60 lb steel plate	10/14	OK
L60-170	56.970	34.717	08/26	60 lb steel plate	09/21	OK
L30-170	56.959	34.702	08/26	60 lb steel plate	09/20	OK
C0-170	56.953	34.680	08/26	60 lb steel plate	09/21	OK
R30-170	56.942	34.660	08/20	not recorded	09/21,09/22	OK
R60-170	56.934	34.643	08/20	not recorded	-	not found
R90-170	56.929	34.623	08/20	not recorded	09/20	OK
R120-170	56.917	34.604	08/20	36" straight jet pipe	10/14	base found, HOBO broken off
L90-200	56.988	34.727	08/26	60 lb steel plate	09/20	OK
L60-200	56.982	34.703	08/20	12" flanged jet pipe	09/20	OK
L30-200	56.975	34.689	08/20	18" flanged jet pipe	09/22	OK
C0-200	56.966	34.671	08/20	12" flanged jet pipe	-	not found
R30-200	56.958	34.653	08/17	36" straight jet pipe	09/21	base found, HOBO broken off
R60-200	56.944	34.631	08/17	36" straight jet pipe	09/21	OK
R90-200	56.941	34.616	08/17	36" straight jet pipe	09/20	OK
L60-230	56.994	34.698	08/26	not recorded	10/14	OK
L30-230	56.989	34.679	08/17	36" straight jet pipe	09/21	OK
C0-230	56.981	34.652	08/17	36" straight jet pipe	09/21	base found, HOBO broken off
R30-230	56.970	34.633	08/17	36" straight jet pipe	returned by CG	OK - broken off
R60-230	56.965	34.620	08/17	36" straight jet pipe	10/14	base found, HOBO broken off
L30-260	57.002	34.669	08/17	36" straight jet pipe	09/21	OK
R30-260	56.986	34.633	08/17	36" straight jet pipe	09/21	base found, HOBO broken off
CURRENT	57.065	34.601	08/26	subsurface mooring	09/20	OK

APPENDIX B

LONG TIME SERIES PLOTS

Plots in this appendix show:

- Bottom temperature
- Ocean current speed, direction, and temperature
- Tide Height (Boston)
- Wind speed, direction, and air temperature (160' tower)
- Cooling water exit velocity and temperature

NOTE: On these plots, wind direction is shown as the direction <u>from</u> which the wind is blowing. Current directions are the direction <u>toward</u> which the current is flowing.

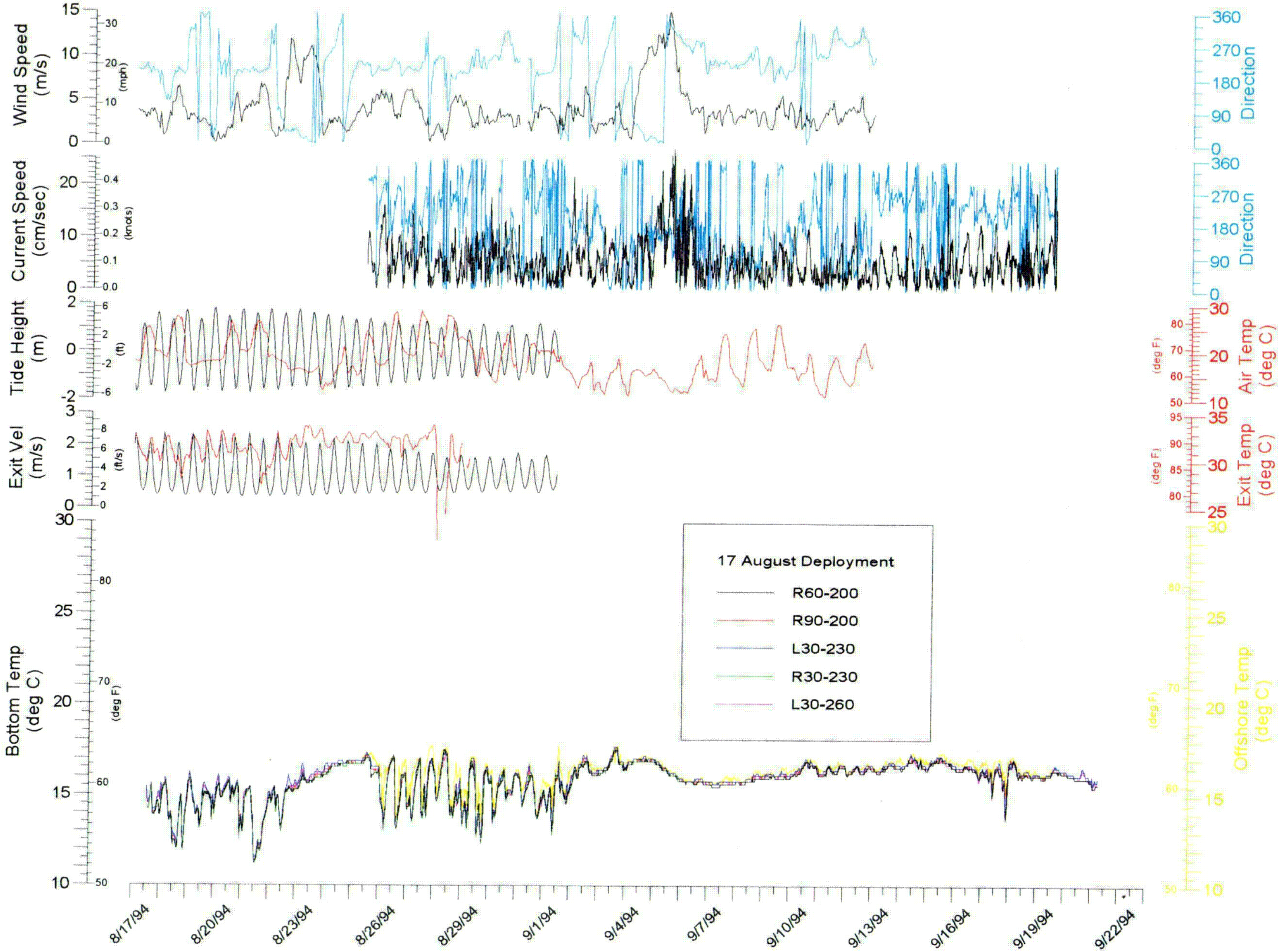

Figure B-1. Time series plot of all data collected by bottom temperature recorders deployed on 17 August 1994.

C24

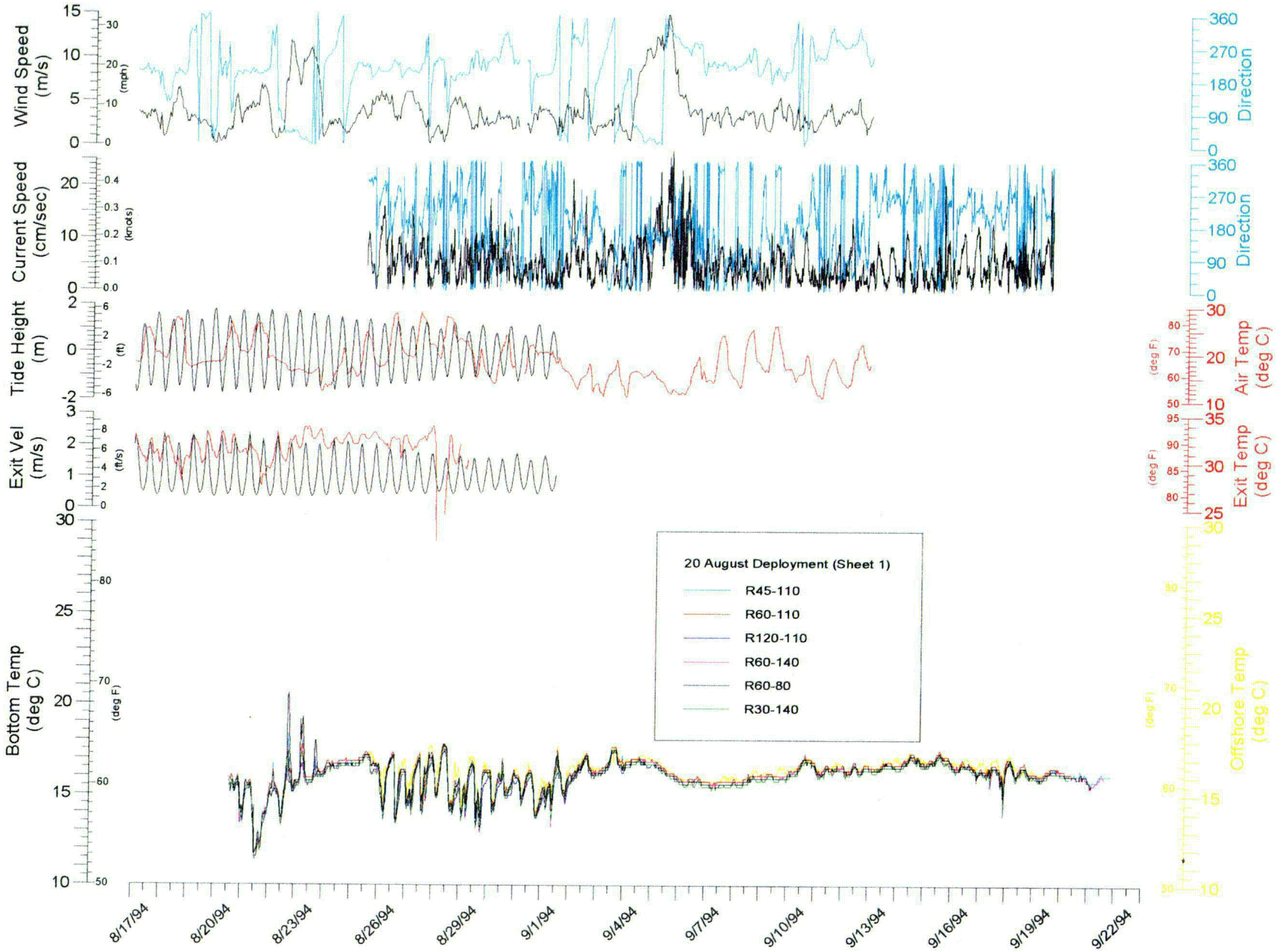

Figure B-2. Time series plot of all data collected by bottom temperature recorders deployed on 20 August 1994 (Sheet 1 of 2).

C25

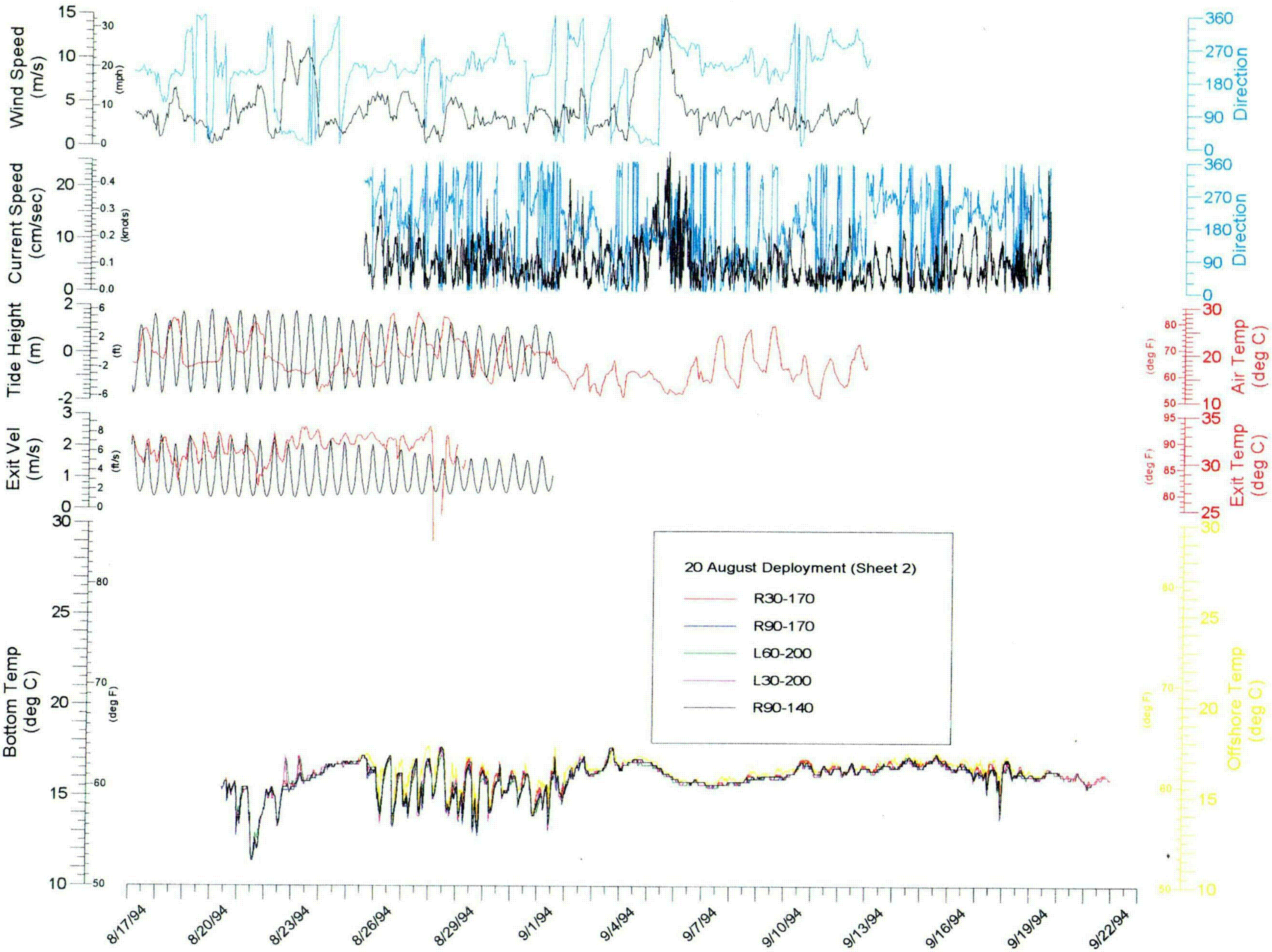

Figure B-3. Time series plot of all data collected by bottom temperature recorders deployed on 20 August 1994 (Sheet 2 of 2).

C26

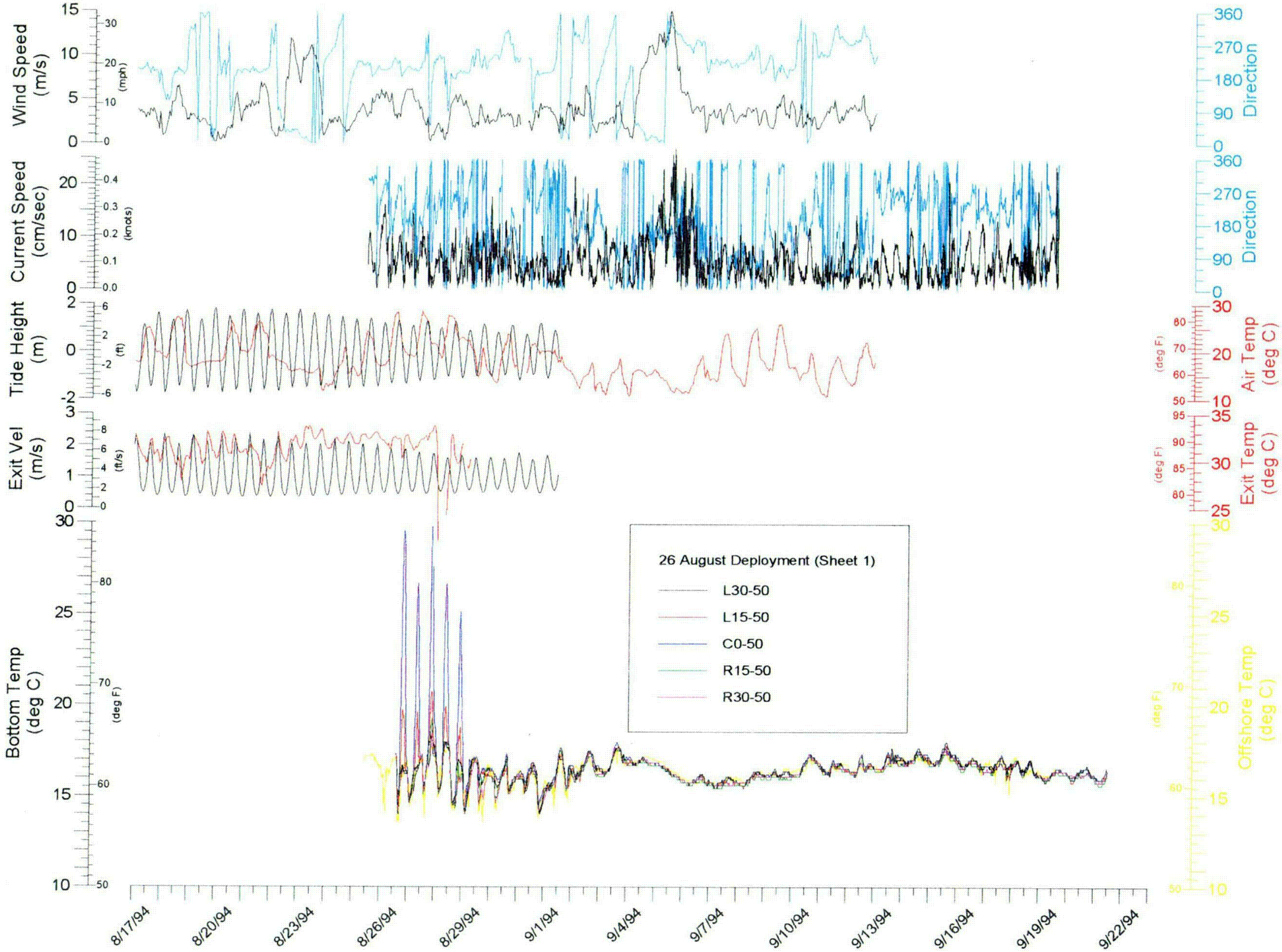

Figure B-4. Time series plot of all data collected by bottom temperature recorders deployed on 26 August 1994 (Sheet 1 of 5).

C27

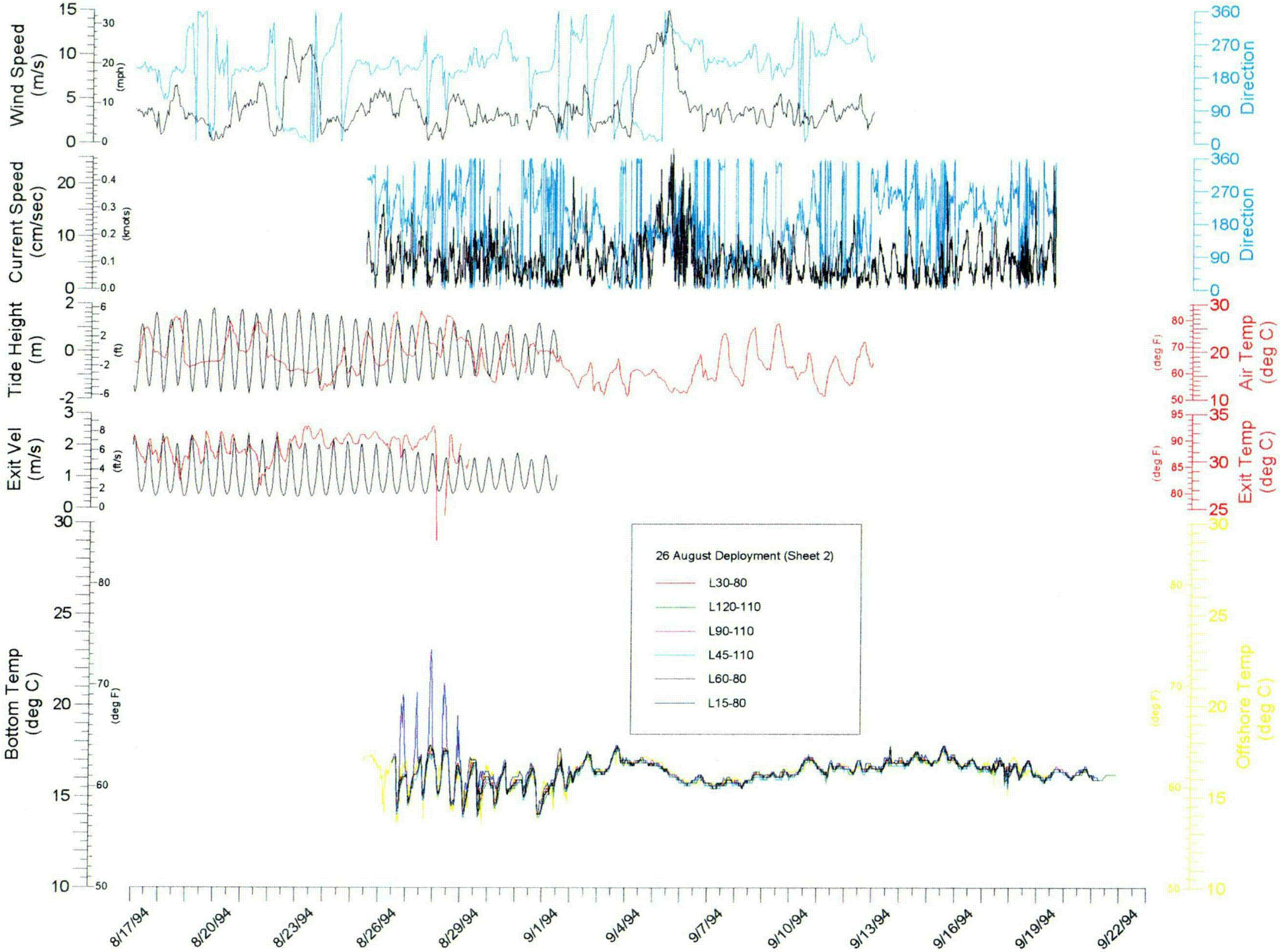

Figure B-5. Time series plot of all data collected by bottom temperature recorders deployed on 26 August 1994 (Sheet 2 of 5).

C28

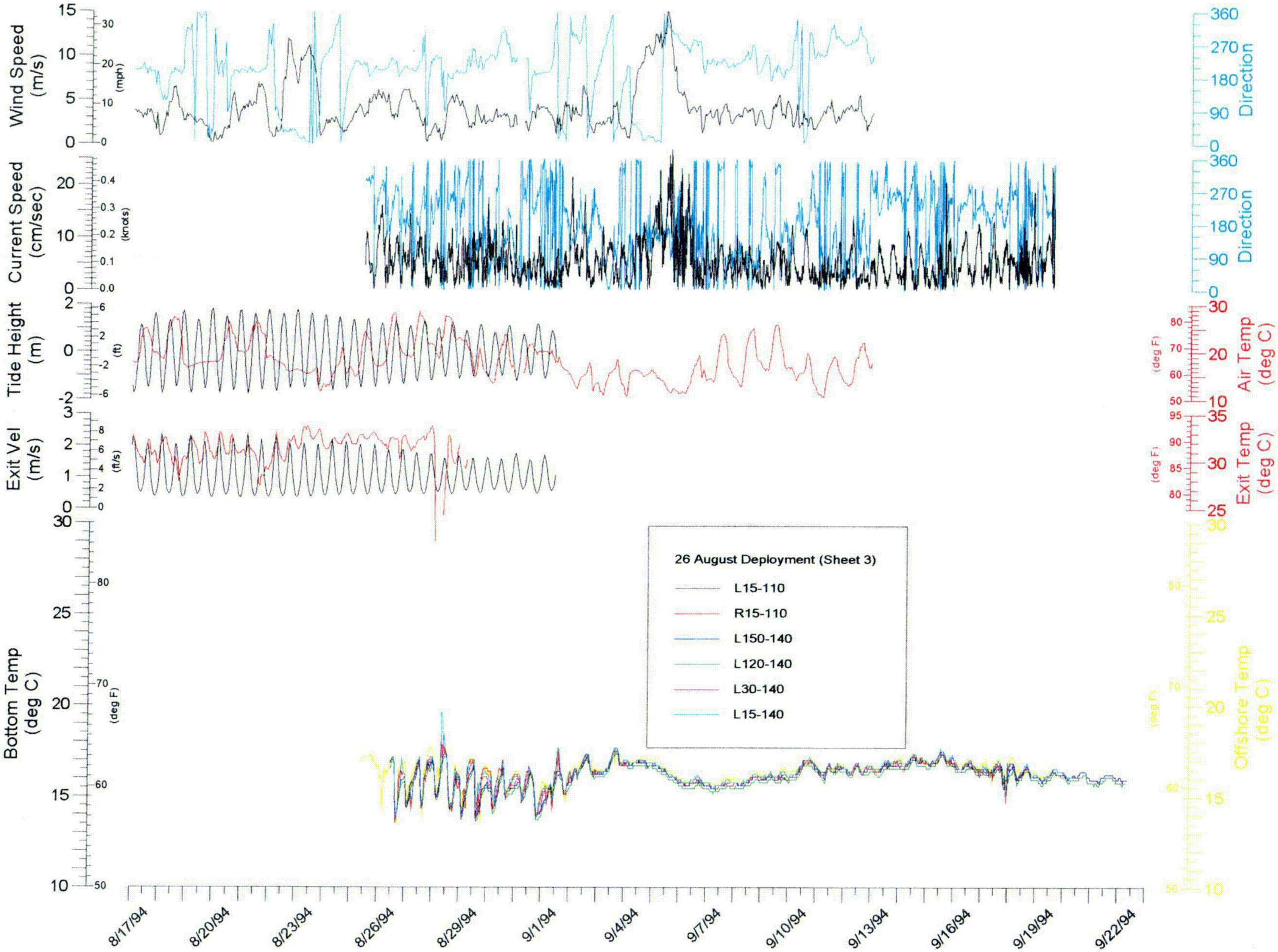

Figure B-6. Time series plot of all data collected by bottom temperature recorders deployed on 26 August 1994 (Sheet 3 of 5).

C29

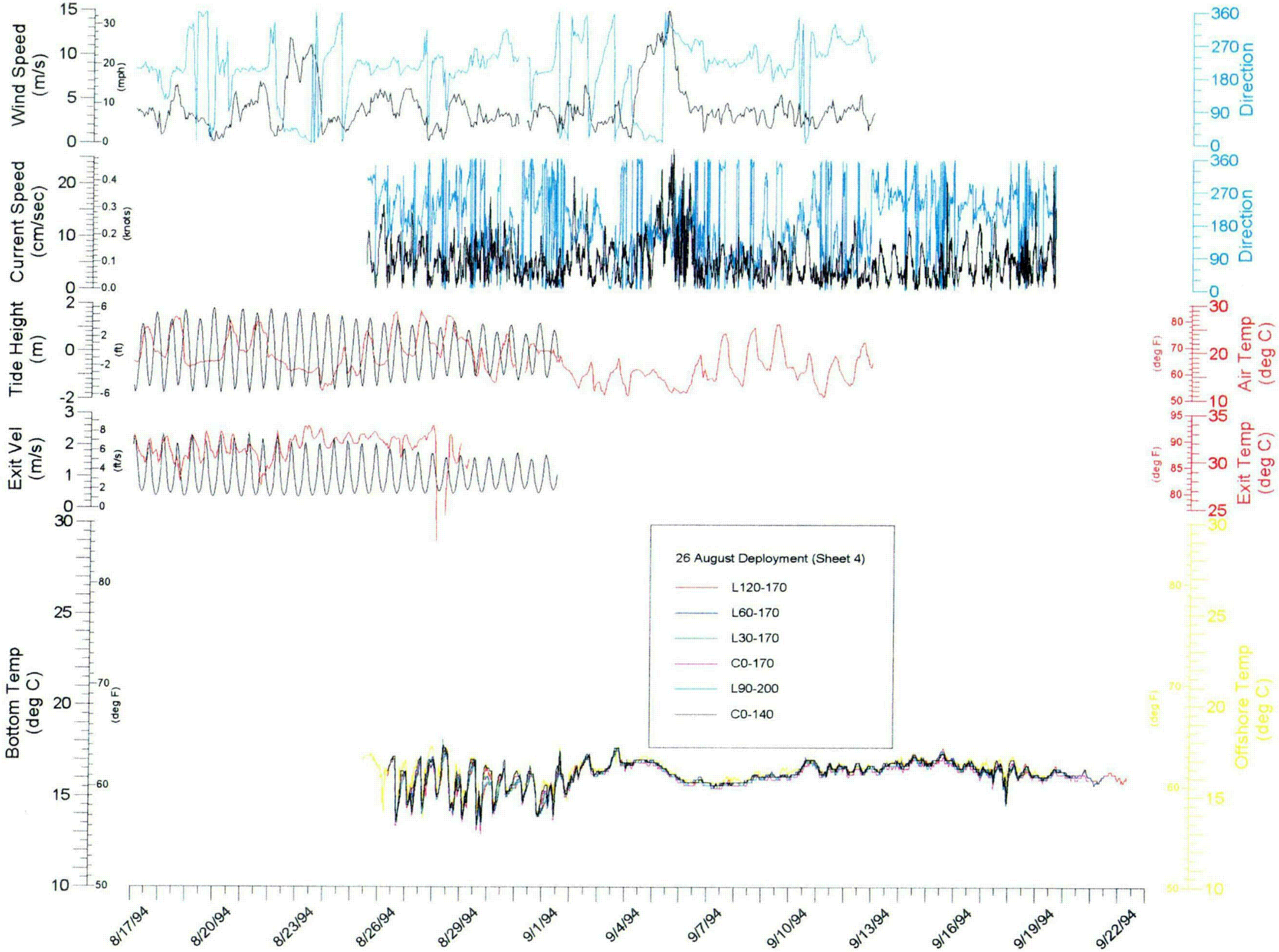

Figure B-7. Time series plot of all data collected by bottom temperature recorders deployed on 26 August 1994 (Sheet 4 of 5).

C30

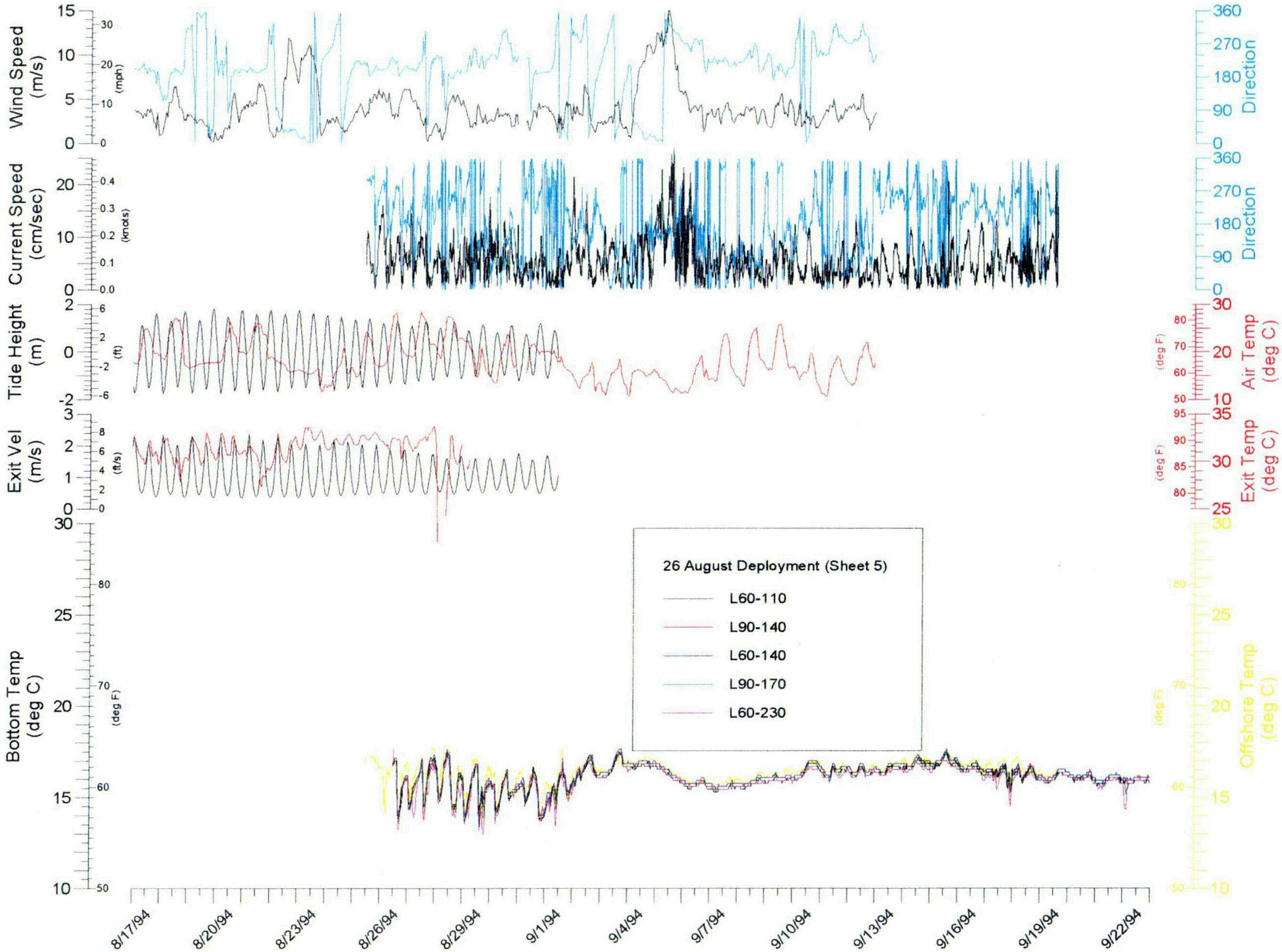

Figure B-8. Time series plot of all data collected by bottom temperature recorders deployed on 26 August 1994 (Sheet 5 of 5).

C31

APPENDIX C

AREA CALCULATION METHODS AND ERROR ANALYSIS

APPENDIX C

AREA CALCULATION METHODS AND ERROR ANALYSIS

Additional Constraints Applied to Contoured Data

SURFER, a commercial data visualization package by Golden Software, Inc., was used to map and measure the area of seafloor covered by various temperature elevations in this study. SURFER accepts irregularly spaced measurements within a rectangular domain, and interpolates/extrapolates to a closely-spaced regular grid using any one of several optimal interpolation methods (Kriging was used for this study). For this study, all 44 bottom temperatures at a given time were input to the program. The program calculates the temperature at each grid point, and smooths and contours the gridded data. Grid spacing and contour smoothing are chosen to give a map consistent with the resolution of the actual data. Use of such commercial off-the-shelf software greatly speeds the analysis and display of oceanographic data.

SURFER also measures the area encompassed by temperatures equal to or greater than any specified value. This measurement is made directly from the gridded values, and is independent of the contouring. Use is made of this capability to determine the area enclosed within various temperature elevations above ambient.

SURFER generally produces reasonable contours and area measurements in the interior of the mapped domain, that is, in regions surrounded by actual data points, and where the spatial resolution of the data points is adequate to resolve the structure. However, in regions where data are sparse, the program attempts to "fan out" the contours as smoothly as possible between actual observations, in order to minimize gradients. For the PNPS cooling water discharge study, this caused significant problems because there was no data in the shallow water to the left and right of the discharge canal, and the array spacing was inadequate to resolve the abrupt horizontal gradient of temperature across the edge of the plume. The result was contour maps like Figure C-1, which represents the first attempt to contour the bottom temperature at 2200 EST, 27 August

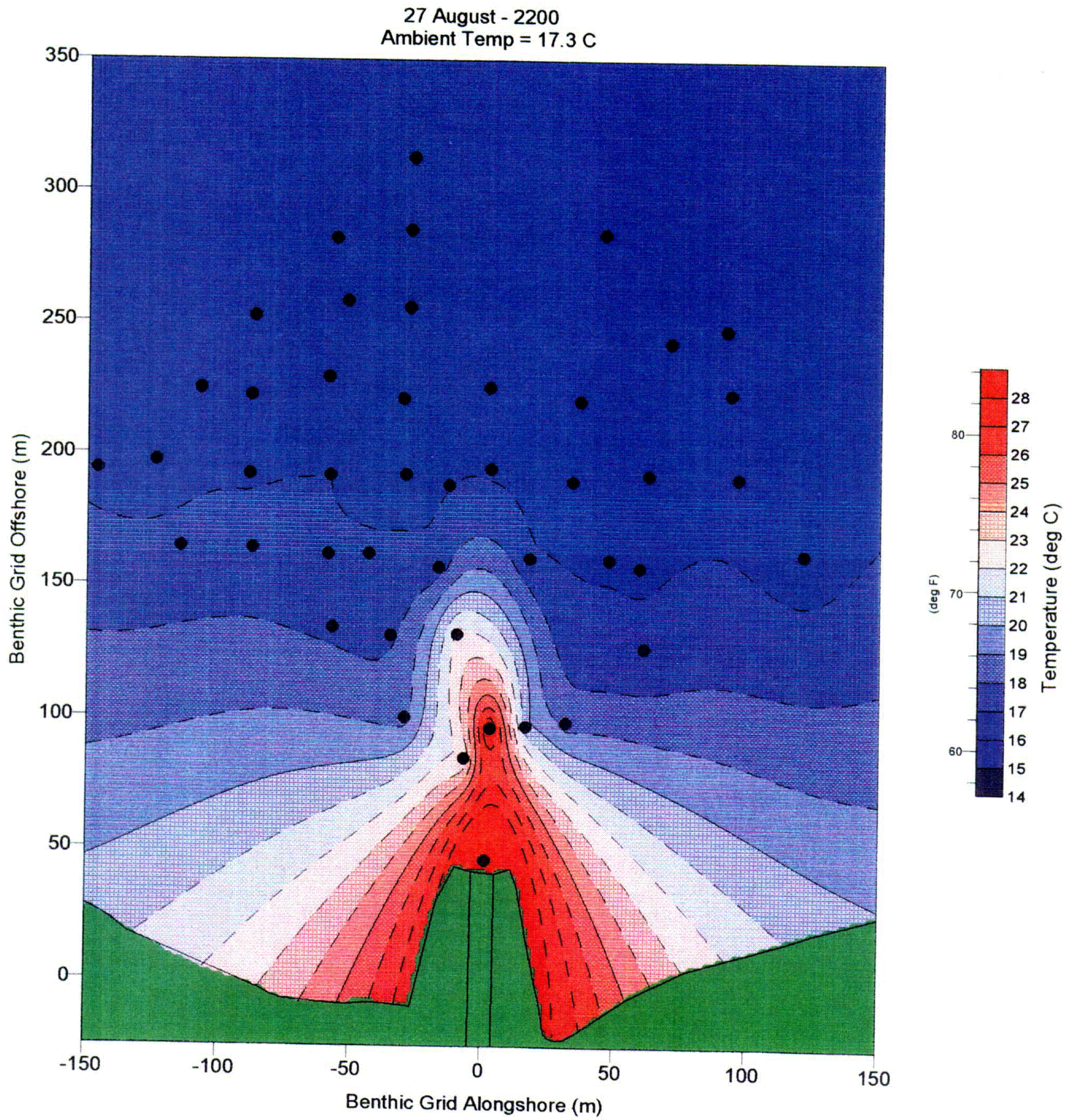

Figure C-1. Color-coded SURFER contour plot for 2200 EST, 27 August 1994, without pseudo-points to control placement of contour lines in areas where data are sparse

C32

1994. This map is not physically reasonable, and cannot be used effectively to measure the area covered by elevated temperatures. SURFER's contouring fails to resolve the plume sharply enough in the alongshore direction near the discharge, while on the other hand it performs insufficient smoothing in the cross-shore direction. The fan-out of high temperatures into the nearshore area is clearly an artifice of the distribution (or lack) of actual observation points. Nothing in the selection of gridding or smoothing parameters in the software improves this plot significantly.

The solution adopted for this study was to add pseudo-points in the immediate vicinity of the discharge canal (Figure C-2) to improve the resolution there. The criteria for selection of pseudo-point values was to produce contours comparable to what a skilled oceanographer would have produced manually, given the data and a knowledge of the discharge characteristics. Specifically, temperatures at these pseudo-points were selected to force the contours to conform to a narrow, sharply defined plume near the discharge canal. Three "hot" pseudo-points were placed along the centerline extending outward from the canal, and were interpolated between the measured discharge temperature and the nearest bottom observation point (C0-50). These points provide continuity between the discharge temperature (taken as located inside the canal mouth) and the nearest actual data points; otherwise, SURFER tended to treat each of these points as separate maxima, with colder water in between them. "Cold" pseudo-points were placed along along the edges of the expected plume, and these points were assigned temperatures representative of the ambient background, taken to be station L120-110. The result, shown in Figure 22 in the text, is roughly consistent with physical concepts of plume spreading across the sea floor (Doret, et al, 1973) and permits effective measurement of the plume area. The constraints imposed by the pseudo-points affect only a very small region around the mouth of the discharge canal, and do not significantly affect the area calculated by the SURFER program over the full extent of the plume.

<u>Area Calculation Error Estimation</u>

The gridding and contouring performed by SURFER in the interior of the domain are optimized in the sense of interpolating as smoothly as possible over grid points between actual observations. However, this does not necessarily match the physical realities of the plume, especially in regions where data gaps exist or the resolution is inadequate. It also tends to result in contours that bulge out between data points, even when long correlation length scales and heavy smoothing are used. Other contour patterns are possible in such regions, consistent with the data, and might yield different estimates of the area covered by elevated temperatures.

To estimate the accuracy of SURFER's area measurements, several alternative contouring schemes were assessed. Figure C-2 shows one possible alternative contouring for 2200 EST, 27 August 1994, designed to give the longest and narrowest possible plume shape consistent with the actual temperature points. Only three contour lines are shown: 18 °C, 22 °C and 26 °C. Ambient temperature is close to 17 °C, so these three temperatures represent a range from the minimum identifiable temperature increment to a high-temperature value characteristic of the plume core. On this figure, the alternative contour lines are black, while SURFER's contours (with pseudo-points) are shown in blue. This is the same data and contouring as in Figure 22. A second alternative contouring (Figure C-3), is designed to allow maximum intrusion of warm water into the gap in the array to the right of the centerline. For both of these alternatives, the areas within the three temperature contours were then estimated by digitizing the plots and using AUTOCAD. These areas were then compared with SURFER's estimates for the same absolute contours (note: this is different from the method used to estimate areas in Section 3.2.2, which used fixed temperature increments above a variable ambient temperature). Table C-1 compares the areas calculated in these ways..

Table C-1 shows that the alternative contourings both exhibited much larger areas within the 26 °C isotherm (9 °C above ambient). This is a consequence of the different objectives of these manual contourings, combined with the fact that only a few actual data points define this core region. While both alternatives are consistent with the data, in attempting to make the plume as long as possible (alternative 1), or as wide as possible (alternative 2), they achieve these objectives at the cost of enlarging the highest temperature region and causing sharper temperature gradients at the edges of the core region. It is concluded, therefore, that the variance in these alternatives is a direct result of the inability of the measurement array to resolve small features such as the plume core.

Table C-1. Area differences corresponding to three alternative contour mappings of bottom temperature data, 2200 EST, 27 August 1994.

	Temperature Contour 18 °C	22 °C	26 °C
SURFER optimal interpolation	5636 m^2	1595 m^2	502 m^2
Alternative 1: Narrowest plume	5386 m^2	1365 m^2	720 m^2
Percentage of SURFER	96%	86%	143%
Alternative 2: Maximum warm extent	5673 m^2	2156 m^2	925 m^2
Percentage of SURFER	101%	135%	184%

In contrast, neither alternative contouring scheme made any appreciable difference in the area enclosed by the minimum temperature increment (1 °C above ambient). This is because many actual data points are available to define this large area, and there is no viable alternative to SURFER's contouring.

In summary, the three contouring methods yield area measurements that agree quite closely for small temperature elevations, moderately well for for intermediate elevations, and within a factor of 1.5 to 2.0 for large temperature elevations. For the higher temperature elevations, SURFER's area estimates tend to be low, since the program has the effect of minimizing the area within each contour. The alternative contourings do not share this objective. Since the variance at large temperature elevations is a consequence of trying to force an extreme solution on the data, it is reasonable to infer that the actual uncertainty is lower, perhaps +100%.

While this analysis is far from a statistically valid determination of error, it provides at least a bound on the accuracy of SURFER's area estimates, for a given data set. Note, however, that much greater uncertainty may be associated with different environmental conditions, such as onshore winds, which can cause the plume to extend much farther.

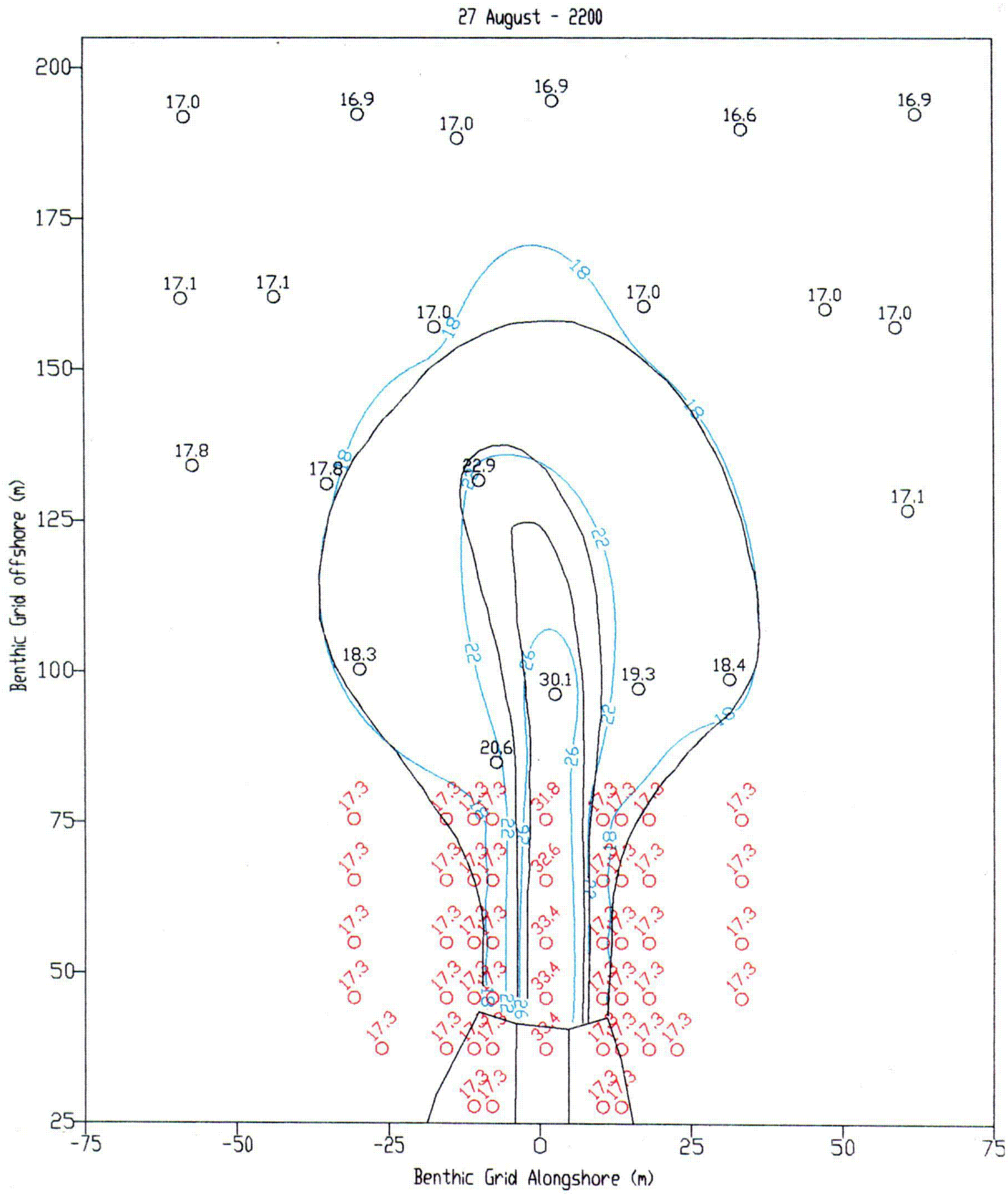

Figure C-2. Alternative contouring #1 for 2200 EST, 27 August 1994: narrowest plume. Blue lines show SURFER contours with pseudo-points (same as Figure 23).

C33

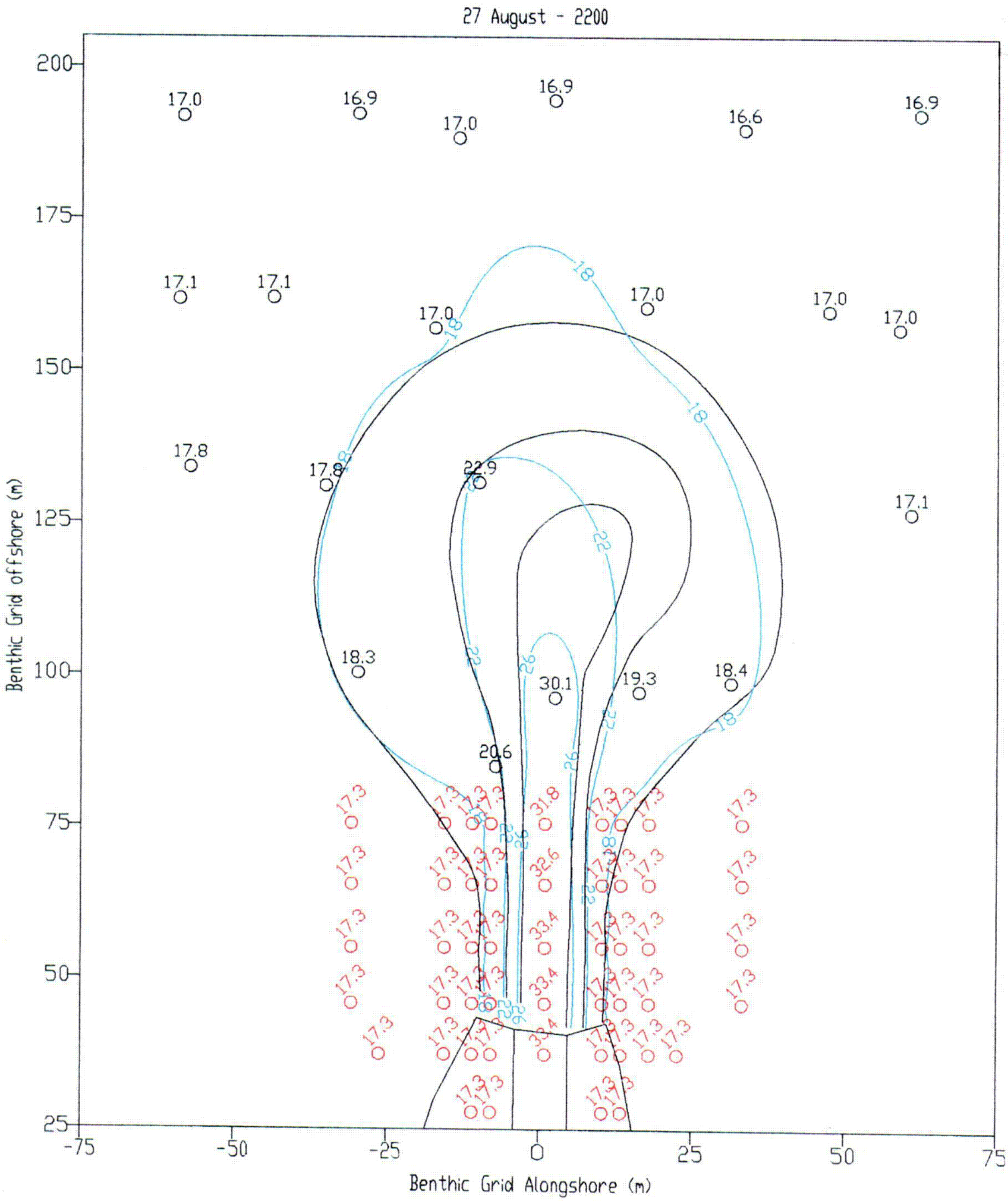

Figure C-3. Alternative contouring #2 for 2200 EST, 27 August 1994: plume widest to right. Blue lines show SURFER contours with pseudo-points (same as Figure 23).

C34