THREE-DIMENSIONAL FIELD SURVEYS OF THERMAL PLUMES FROM BACKWASHING OPERATIONS AT A COASTAL POWER PLANT SITE IN MASSACHUSETTS

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ABSTRACT

Using specially designed temperature profiling equipment, two surveys were conducted during thermal backwashing operations at Pilgrim Nuclear Power Station to determine the spatial and temporal extent of temperature rises above ambient. Backwashing formed a thermal plume about 5 to 6-ft thick (1.5 to 1.8 m) in front of the intake screenwall. Maximum observed surface temperatures were 101.0 F (38.3 C), representing a ΔT of 43.4 F (24.1 C) above ambient. The frontal zone of the plume spread gradually seaward at about 0.2 kn. Its outer edge became thinner and rapidly cooled, presumably by advection and turbulent diffusion associated with currents from the reverse pumping and local changes from dissipation to the atmosphere. Along the intake shoreline, the plume was often less than 1 ft (0.3 m) thick. Most of the hot water was dissipated within several hundred feet of the intake with ΔT's of about 10.0 to 15.0 F (5.6 to 8.3 C) above ambient. Under the influence of strong southwesterly winds during the second survey, some warmed water was apparently carried beyond the outer breakwaters into Cape Cod Bay. These surveys provided real-time data indicating that the backwashing operation caused a relatively thin thermal plume, which spread rapidly from the intake out across the study area and along the seaward breakwater. Within a few hours these backwash thermal plumes were completely dissipated.

INTRODUCTION

Although thermal backwashing is a commonly used technique for control of biofouling in condenser tubes and intake structures of operating power plants, only limited published information is available on the receiving water temperature structure caused by such operations. Boston Edison Company, Boston, Massachusetts, conducted two thermal surveys of actual mid-summer backwashing operations under varying tidal conditions at Pilgrim Nuclear Power Station during 1977 to establish a synoptic picture of the plume's three-dimensional structure [1].

The Pilgrim Nuclear Power Station, located on the shore of Cape Cod Bay in Plymouth, Massachusetts, is a 655 MW light-water moderated, boiling water nuclear reactor with a once-through condenser cooling water system. Water used for cooling the condenser is removed from Cape Cod Bay through a shoreline intake (Fig. 1). It enters the intake between two breakwaters via a dredged channel which is about 18 to 24 ft deep (5.5 to 7.3 m) at mean low water (MLW).

Under normal operating conditions, the water is drawn into the intake by two pumps (designated herein as east and west), circulated through the condenser system and discharged via a surface canal at a rate of about 510 million gallons/day and a ΔT (difference between the discharge and intake temperatures) averaging 30.0 F (16.7 C). Condenser tubes are cleaned by backwashing on a 1 to 2-week interval, depending upon biofouling severity. Generally 45 to 60 min are required to treat each of the two circulating water pumps, with elevated temperatures averaging around 100.0 F (37.8 C). Occasionally the temperatures peak at from 110.0 F (43.3 C) to 120.0 F (48.9 C), depending upon the amount of heat treating necessary. Because plant load must be reduced during backwashing, the operation is generally conducted at night during off-peak hours.

METHODS

This study conducted by Normandeau Associates, Inc. (NAI), of Bedford, New Hampshire, consisted of overnight three-dimensional temperature and current surveys, supplemented by continuous thermal monitoring. For the first survey on July 9 and 10, 1977, backwashing began at low water and continued into early flood tide. During the second survey on July 16 and 17, 1977, backwashing began at high water and continued into early ebb tide. Both surveys concentrated on the time history of plume build-up and dissipation.

Temperature and depth data were collected at selected stations (Fig. 1) and plotted on board the survey boat using a Naico Model 3100-TD Profiling System (Fig. 2). Current velocity profiles were acquired using Bendix Model Q-15 current meters and Model 270 recorders. Precise location was continuously recorded using a Motorola MiniRanger III System with two shore based transponders.

Two Naico Model 200 Digital Field Temperature Recorders were utilized to periodically measure temperature profiles from water surface to bottom at two stations in the intake channel. The arrays were assembled so they could be moved quickly within the survey area to check thermal anomalies. In addition, two Naico Model 1001-T Temperature Recorders were installed to monitor water temperatures 1) inside the intake screenwall and the discharge canal, and 2) in ambient receiving waters of adjacent Cape Cod Bay.

Observed temperatures were transformed to true temperatures using regression equations based on calibration data for each respective field instrument. From measurements of ambient near-bottom waters mid channel between the two intake breakwaters (Fig. 1), a ΔT or approximate temperature rise above ambient was calculated for each temperature observation.

FIELD SURVEYS

Low-Water Backwash Survey

The July 9 and 10 low-water backwash survey consisted of five sampling runs keyed to actual plant operations. For this survey, NAI's ambient temperature measurements along the bottom of the intake channel started around 49.0 to 50.0 F (9.4 to 10.0 C) and then gradually rose to about 58.0 F (14.4 C) by the time of low water. Throughout the rest of the night, ambient temperatures continued to rise slowly, reaching about 60.0 F (15.6 C) by the end of the survey. This rise may represent some recirculation of the discharge plume toward the intake area because of local winds and coastal currents.

As backwashing was initiated, plant load was gradually brought down. NAI's readings of discharge canal temperatures showed a drop from 87.0 F (30.6 C) to 74.6 F (23.6 C; Fig. 3). Next, the west pump was backwashed from about 0030 to 0119 EST. The *in situ* temperature monitors recorded a sudden rise in discharge temperature to about 83.0 F (28.3 C), followed by a sharp drop to about 65.3 F (18.5 C). Simultaneously water box temperatures rose quickly to about 104.0 F (40.0 C) and remained at this level for much of the backwashing period (Fig. 3). As backwashing of the first pump neared completion, discharge temperatures rose again to 83.2 F (28.4 C) and water box temperatures dropped back down to below 70.0 F (21.1 C). From about 0150 to 0227 EST the east pump was backwashed in the same way with similar backwash temperatures observed for both pumps. During this backwashing period, discharge temperatures dropped to about 70.6 F (21.4 C), then rose to 87.0 F (30.6 C) for a short time, dropped back down to about 75.0 F (23.9 C), and finally rose back toward normal operational levels (Fig. 3).

A prebackwash survey conducted during late-ebb showed surface temperature rises (ΔT) ranging from 9.1 F (4.1 C) near the offshore discharge to 4.9 F (2.7 C) near the plant intake.

As backwashing started, the first visible evidence was a sudden rush of hot, turbulent water marked by foam and a steamy vapor right in front of the intake. With continuing backwashing, the hot water formed a surface layer about 5-ft (1.5 m) thick, which reached temperatures as high as 100.0 F (37.8 C) in front of the intake screenwall. A distinct frontal zone moved slowly northward (or seaward) away from the intake, bulging in the middle and slightly restrained along shore due to frictional effects. The water temperatures in the near-surface thermal plume gradually decreased with both distance away from the intake and time, presumably due to evaporative heat loss and dilution (mixing with ambient waters).

At the surface, ΔT's of 42.1 F (23.4 C) in front of the west pump and 24.8 F (13.8 C) in front of the east pump were observed (Fig. 4). Within less than 100 ft (30.5 m), the ΔT from the western pump was 28.0 F (18.6 C) or less. High ΔT water hugged the outer breakwater, apparently because of momentum effects and southwesterly winds during the night. Surface ΔT's of 10.0 F (5.6 C) and higher were confined to the western third of the intake area between the breakwaters (Fig. 4). The remainder of the area experienced ΔT's equal to or colder than observed prior to backwashing.

At the 3.3 ft (1.0 m) depth level, observed ΔT's were 23.4 to 24.3 F (13.0 to 13.5 C) in front of the intake. Within less than 200 ft (61.0 m), ΔT's were down to 18.2 F (10.1 C). Beyond that distance they dropped from 14.8 to 6.7 F (8.2 to 3.7 C). Near the outer end of the breakwaters, ΔT's were only 2.4 to 3.3 F (1.3 to 1.8 C).

At the 9.8 ft (3.0 m) level, ΔT's were 4.6 F (2.6 C) or less in front of the intake and 1.2 to 2.1 F (0.7 to 1.2 C) along the dredged channel. Along the bottom all of the ΔT's were negative, or colder than conditions at the outer end of the breakwaters. At Station 6 minimum values were -4.4 F or -2.4 C (Fig. 5).

The detailed profiles at Station 6 showed that the backwashing from the western pump formed a distinct slug or pulse of hot water along the surface, which eventually extended down to about 7 ft (2.1 m). The heated effluent apparently took about 15 min to reach and about 75 min to pass the anchored boat in its seaward progression (Fig. 5). Maximum observed ΔT at the surface was 22.6 (12.5 C), which represented an actual temperature of 79.0 F (26.1 C). Near-bottom temperatures were 53.4 to 56.2 F (11.9 to 13.4 C) which represented negative ΔT's of up to -4.7 F (-2.6 C). By about 0119 EST backwashing of the west pump was complete.

At about 0150 EST backwashing of the east circulating water pump started. As before, there was a sudden surge of hot, turbulent and steamy water at the surface. Within minutes a thin thermal plume and a distinct seaward-moving frontal zone was observed. At the surface, ΔT's were essentially the same as during backwashing of the west pump, averaging 20.0 F (11.1 C) and more across the western third of the study area, 10.0 to 20.0 F (5.6 to 11.1 C) in the middle, and 5.0 to 10.0 F (2.8 to 5.6 C) across the eastern third. As before, the highest temperatures were along the outer breakwater. At 3.3 ft (1.0 m) ΔT's were 15.5 to 23.4 F (8.6 to 13.0 C) next to the intake and gradually decreased seaward. Below this level there was no evidence of the backwash plume, whereas along the bottom ΔT's remained negative.

At Station 6 the second backwash manifested itself as another pulse of hot water, which was warmer than before (up to 81.1 F or 27.3 C) but slightly thinner and shorter-lived (Fig. 5). This plume had surface ΔT's of up to 23.5 F (13.1 C). Apparently it took about 10 to 15 min for this second plume to reach the anchored boat, but its effects were only evident for about 60 min. By the time the plume had passed, it was only about 1 to 2 ft (0.3 to 0.6 m) thick. Near-bottom temperatures showed little change, ranging from 54.1 to 56.2 F (12.3 to 13.4 C) and representing negative ΔT's (down to -3.4 F or -1.9 C). By about 0227 EST backwashing of the east pump was complete and the plant began to return to normal operation.

Subsequent surveys for the rest of the night showed that the elevated surface temperatures from the backwashing operation persisted for only about 2 to 2.5 hrs in the western portion of the study area and even less in the eastern portion, before being completely dissipated.

High-Water Backwash Survey

One week later on July 16 and 17, a second survey was conducted under high-water tidal conditions. Throughout this survey ambient temperature measurements along the bottom of the intake channel showed very little variation, ranging from 52.0 to 55.0 F (11.1 to 12.8 C). Backwash temperatures were about the same for both pumps (peak of 107.0 F or 41.7 C); however, this series of backwashes lasted 20 to 25 min longer than respective ones the week before because of increased fouling of the condenser tubes.

At about 2354 EST on July 16, backwashing started on the west pump. This time, in sharp contrast to the low-water backwashing, the surface appearance of the backwash waters was much less dramatic. The thermal plume was somewhat turbulent and steamy, but the thermal front along the interface with Cape Cod Bay waters was much less distinct than it had been the week before. Apparently this was because more dilution or "receiving" water was available at high tide.

The observed surface ΔT's were 28.2 F (15.7 C) in front of the west pump and 17.1 F (9.5 C) in front of the east pump (Fig. 6). Warmest temperatures were along the west side of the study area with ΔT's from 28.0 F down to about 14.8 F (15.6 to 8.2 C). Across the middle portion of the study area, ΔT's ranged from 15.0 to 10.0 F (18.3 to 15.6 C), with most of the warmed water apparently being blown against the outer breakwater by the strong southwesterly winds which persisted throughout the survey. Much lower ΔT's were seen along the shore in front of the power plant (6.1 to 9.1 F or 3.4 to 5.1 C). In the eastern portion of the study area, some warm water was observed along the outer breakwater (8.7 to 11.8 F or 4.8 to 6.6 C); but, close to shore temperatures remained unchanged. At the discharge the temperature rise was 14.8 F (8.2 C). At the 3.3 ft (1.0 m) level, ΔT's were lower than at the surface, but the general distribution of the backwash plume was about the same. At 9.8 ft (3.0 m) ΔT's were small, while near-bottom ΔT's were negative apparently due to cold water being drawn into the intake area.

ADH

Temperature measurements from the boat anchored at Station 6 showed that the west pump's backwash plume arrived within 5 to 10 min of the start of backwashing (Fig. 7). The ΔT's rose sharply to 14.4 F (8.0 C) or an actual temperature of 69.1 F (20.6 C). The resulting thermal plume seemed to be about 2 to 3 ft (0.6 to 0.9 m) thick and persisted for almost 90 min. Actual backwashing of the west pump was completed around 0113 EST.

At about 0159 EST backwashing of the east pump started. Surface ΔT's were 43.2 F (24.0 C) in front of the east pump and 25.2 F (14.0 C) in front of the west pump. Elsewhere ΔT's were generally higher than during the previous sampling run. Temperature rises of 20.0 F (11.1 C) and more were found across the channel to the outer breakwater. As before the elevated ΔT's were observed along the outer breakwater (ΔT's of 15.0 to 20.0 F or 8.3 to 11.1 C), possibly due to continuing wind influence. Slightly deeper at 3.3 ft (1.0 m), the temperature distribution was about the same as at the surface; but deeper down and along the bottom, temperatures were much warmer than earlier in the evening.

At Station 6 the passage of the east pump thermal plume was very evident (Fig. 7). It took less than 10 min for the backwash water to arrive and, as before, it persisted for about 90 min. The temperatures were slightly higher this time, with the greatest rise occurring after backwashing was complete. At about 0307 EST backwashing of the east pump was completed and the plant started to return to normal operation.

Subsequent surveys during the rest of the night showed that the elevated surface temperatures and thermal backwashing plumes persisted for almost 4 hrs in the western portion of the study area and somewhat less in the eastern portion, before dissipating. Backwashing momentum effects, as well as local winds, seemed to play a role in forcing the warmed water along the outer breakwater and keeping it away from the shore in front of Unit 1 (Fig. 6).

DISCUSSION

Each backwashing was first evidenced by a pulse of warmed water at depth from the intake (Fig. 8). As the pumping continued, the hot buoyant water rose to the surface and within a few minutes formed a warm thermal plume averaging 3 to 5 ft (0.9 to 1.5 m) thick. Below the plume was a steep gradient to the colder near-ambient waters along the bottom of the intake channel. During the first weekend survey, the thermal plume formed a distinct frontal zone of foam and turbulent, steaming water which could be easily tracked by eye. Under the influence of the reverse intake flows, the initial jet momentum, the plume buoyancy effect and the localized hydrostatic head in front of the screenwall, the frontal zone moved slowly across the study area. Along shore and in shallow water, frictional effects slowed the frontal zone, causing the plume to bulge in the center. The hot water propagated toward the western portion of the study area and the outer breakwater; but relatively little hot water contacted the shoreline area in front of Unit 1 during both of the surveys (Figs. 4 and 6). During the second survey the frontal zone behaved in a similar manner; but was much less distinct, probably because of the increased volume of receiving water (high-water condition).

Because of the relative thinness of the thermal plume and the pronounced stratification it created, it appeared to be highly susceptible to wind-shear effects. During both weekend surveys, momentum effects and southwesterly winds apparently forced much of the plume against the outer breakwater, leaving the shoreline area much less affected. During the second weekend some warmed water was apparently forced out into Cape Cod Bay beyond the outer breakwater by transient wind effects (estimated to be only a small percentage of the surface backwash thermal plume). In general, the eastern portion of the study area remained relatively unaffected by the hot water during both studies. Where the thermal plume impinged the shoreline, such as along the breakwaters, it was generally less than 2 ft (0.6 m) thick.

SUMMARY AND CONCLUSIONS

These surveys showed that backwashing operations at Pilgrim Station form a relatively thin thermal plume averaging 3 to 5 ft (0.9 to 1.5 m) thick. Higher temperatures were observed during the low-water backwashing than during the high-water backwashing, presumably due to lesser amounts of available entrainment water. During the first survey the thermal plume persisted for about 2 to 2.5 hrs before being completely dissipated. The second weekend more heat treatment was required due to accumulated biofouling and the thermal plume persisted for almost 4 hrs. Initial momentum effects of the backwashing flows apparently tend to carry the thermal plume northward and along the outer breakwater, with little tendency for warmed water to impinge the shoreline in front of Unit 1. During both surveys local winds also appeared to play a role in pushing the thermal plume seaward. Finally, observed near-bottom ambient temperature variations suggest that some water from the plant discharge can recirculate into the intake area.

REFERENCE

Normandeau Associates, Inc. 1977. Thermal surveys of backwashing operations at Pilgrim Station during July 1977. Conducted for Boston Edison Company, Boston, Massachusetts. 73 pp.

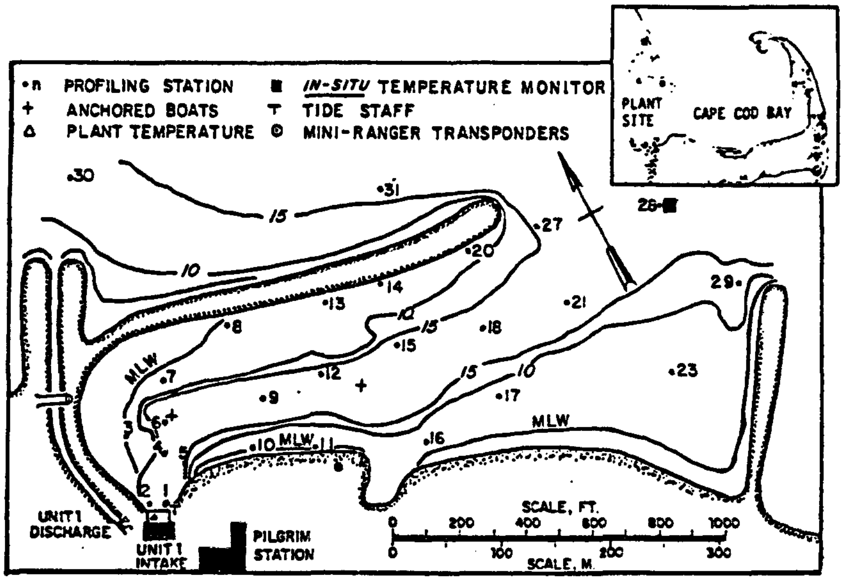

Fig. 1 Location map showing approximate sampling stations and *in situ* instrumentation for the July 1977 Pilgrim Station backwashing studies.

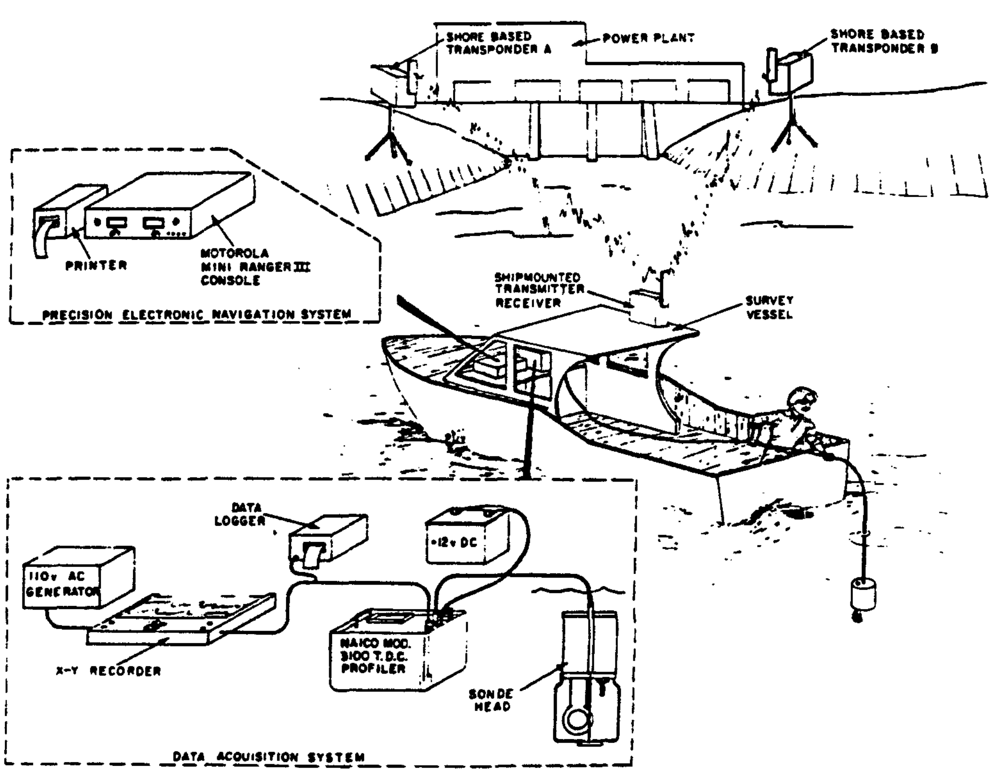

Fig. 2 Instrumentation set up for field surveys.

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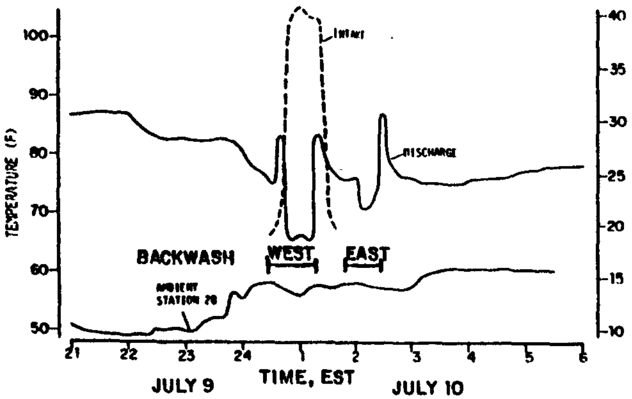

Fig. 3 Temperature monitor data from the west pump waterbox, the discharge canal and the ambient *in situ* unit at Station 28 during backwashing operations on July 9 and 10, 1977.

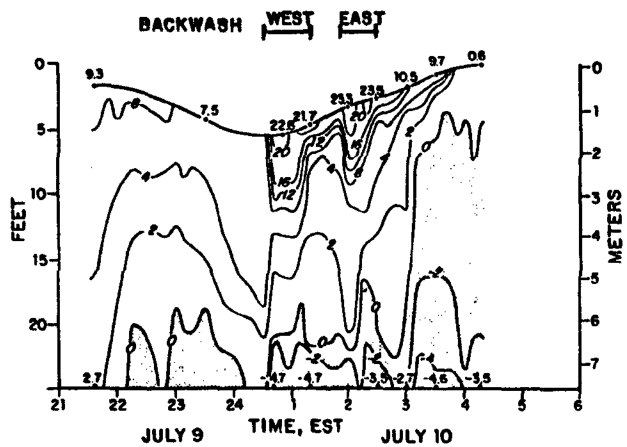

Fig. 5 Temperature data from an anchored survey boat at Station 6 on July 9 and 10, 1977 showing actual temperatures and corresponding ΔT's above ambient in degrees F.

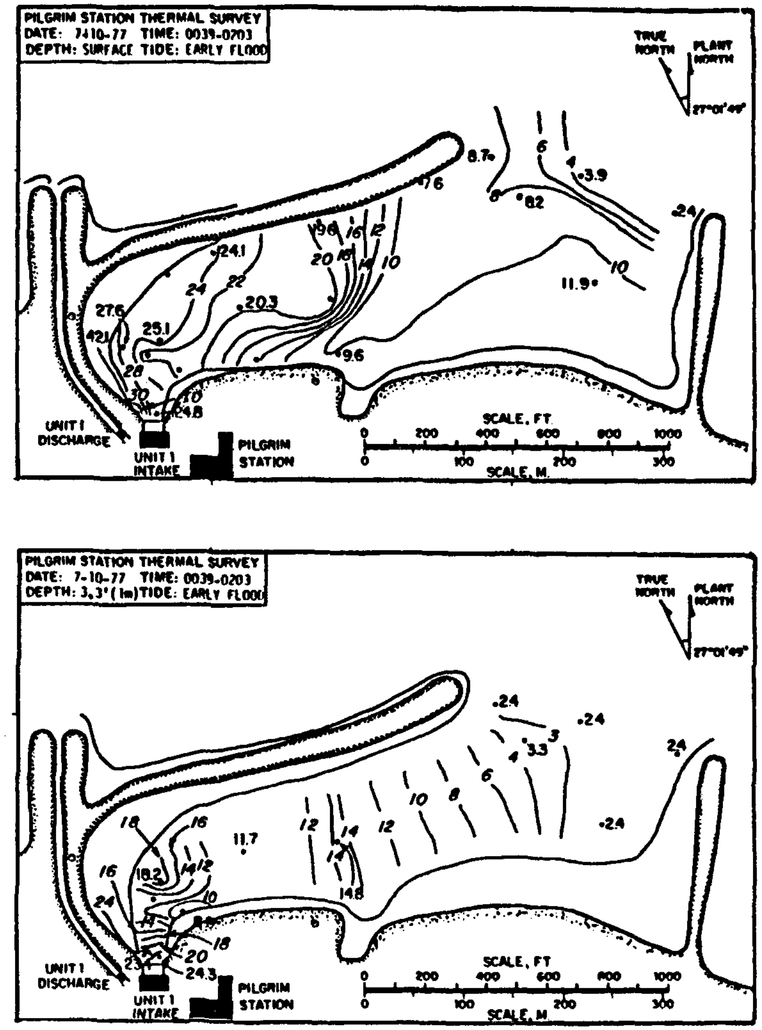

Fig. 4 Contour maps of observed temperature rises (ΔT) in degrees F above ambient during early flood (backwash west pump) at surface and 3.3 ft (1.0m) on July 10, 1977.

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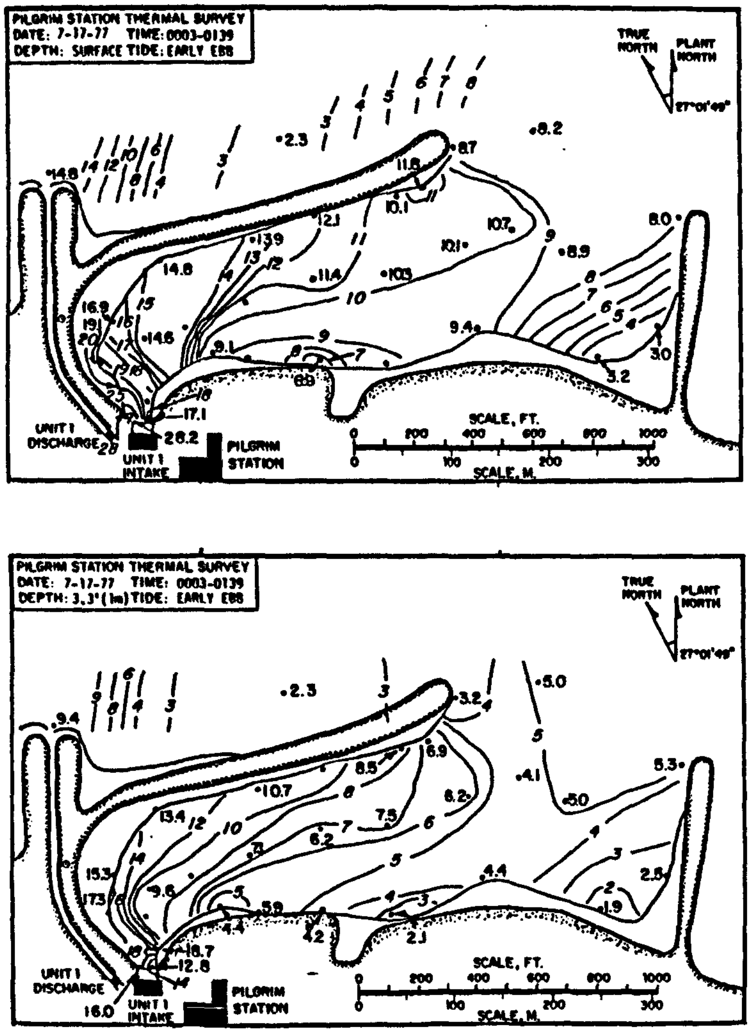

Fig. 6 Contour maps of observed temperature rises (ΔT) in degrees F above ambient during early ebb (backwash west pump) at surface and 3.3 ft. (1.0m) on July 17, 1977.

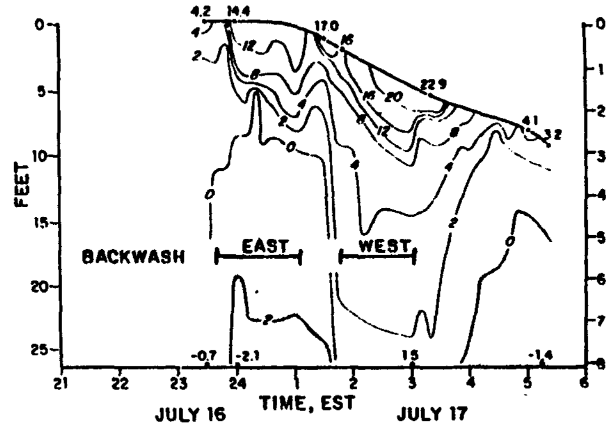

Fig. 7 Temperature data from an anchored survey boat at Station 6 on July 16 and 17, 1977 showing actual temperatures and corresponding ΔT's above ambient in degrees F.

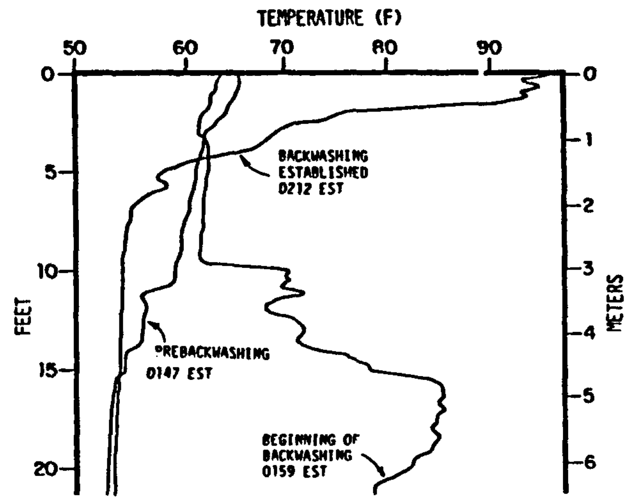

Fig. 8 Temperature profiles from Station 1 during the start of backwashing of the east circulating water pump on July 17, 1977.