Design of a recovery ventilation system for the Deer Island Outfall Tunnel

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ABSTRACT: This paper describes a study to establish ventilation in a sewage outfall tunnel in Boston, Massachusetts. During construction of the outfall tunnel, ventilation was achieved by means of an auxiliary forcing duct and multiple, high-pressure fans. At the end of the main tunnel are small diameter tunnels connecting to risers that each terminate at a diffuser head on the sea floor. All services, including ventilation and power were removed from the tunnel prior to the final step of removing safety plugs from the diffuser tunnels. Oxygen at the end of tunnel reduced to below 10%. The plug removal work was to be accomplished by personnel under oxygen apparatus. Work commenced in 1999 to remove the temporary plugs. After three plugs were successfully removed, a problem developed with the workers breathing apparatus resulting in fatalities. After the fatalities it was mandated by OSHA that active ventilation be re-established in the tunnel. This paper describes the options considered in establishing the tunnel ventilation system. The system chosen consisted of using an ocean barge to connect a caisson to one of the first three risers that had the temporary plug removed. Seawater was pumped out of the caisson and a ventilation pipe was installed to fit over the manhole cover on the diffuser head. The ventilation pipe was connected to an exhaust fan built on the barge. Ventilation was established on July 13, 2000. Measurements confirmed that the airflow predicted by modeling was within 3%. Acceptable oxygen levels were established in the tunnel within 16 hours and all temporary plugs were removed within five days.

1 INTRODUCTION

In early 2000, Mine Ventilation Services, Inc. (MVS) was requested by the joint venture Kiewit-Atkinson-Kenny to review and recommend a ventilation system for the Deer Island Outfall Tunnel. The Boston outfall is the largest ocean sewer outfall in the world. This tunneled outfall is 15 km (9.5 miles) long, and 7.3 m (24 feet) in diameter. The peak design capacity is over 55 l/s (one billion gallons per day). The diffuser system consists of risers that extend from the tunnel, about 75 m (250 ft) to the seabed. The treated sewage is then released from the riser caps as radial jets. The risers were constructed using an oil-drilling rig from the seabed down to the tunnel. . Figure 1 shows a location map for the tunnel and Figure 2 shows an approximate cross-section of the tunnel.

The outfall tunnel was part of the $4 billion Boston Harbor project that included construction of a sewage treatment plant, renovation of existing sewers, tunnels for transportation of raw sewage, and drilling of the tunnel. During construction of the outfall tunnel, ventilation was achieved by means of an auxiliary forcing duct and multiple, high-pressure fans.

At the end of the main tunnel are 53 short, small diameter tunnels connecting to risers that each terminate at a diffuser head on the sea floor.

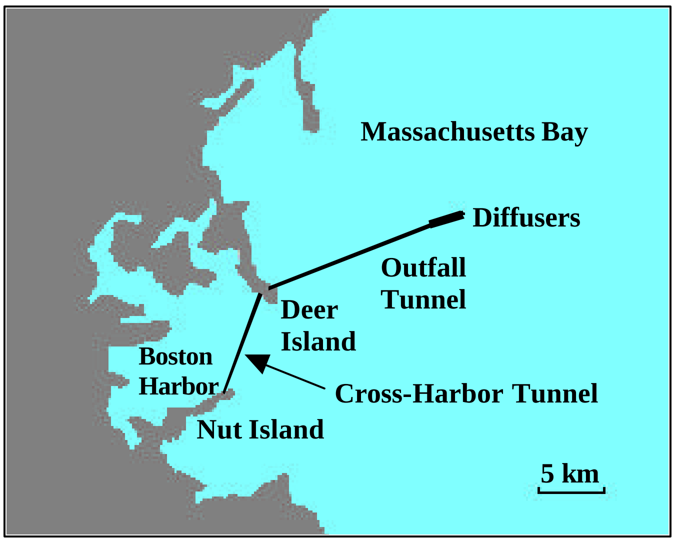

Figure 1. Location map of the Deer Island Outfall Tunnel.

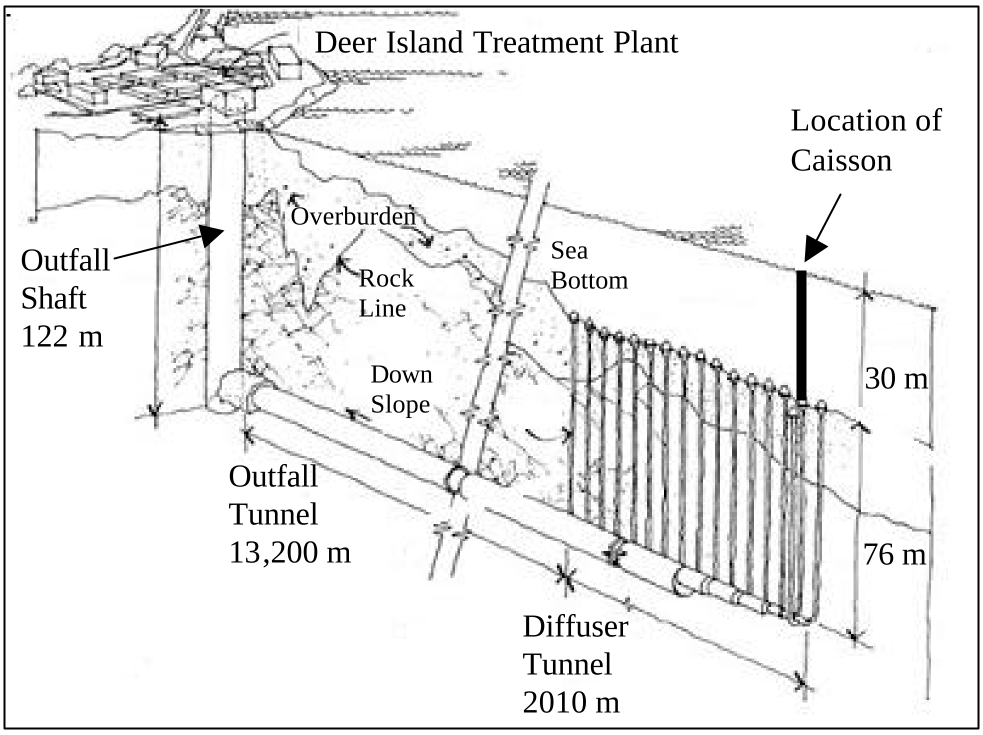

Figure 2. Approximate cross-section of the Outfall Tunnel.

Figure 3 shows the connection tunnel to the main tunnel. The original design consisted of maintaining ventilation during all construction activities except the final step of removing temporary safety plugs in each short tunnel. All services, including ventilation and power were removed from the tunnel prior to the final step. Oxygen at the end of tunnel reduced to below 10%. The plug removal work was to be accomplished by personnel under oxygen bottle apparatus. Work commenced in the summer of 1999 to remove the temporary plugs.

On July 12, after the removal of three plugs, the tragic deaths of two divers in the outfall tunnel brought the tunnel portion of the project to a halt. The divers, who were experienced and certified, were victims of a failure of their bottled air during the removal of the safety plugs. The U.S. Occupational Safety & Health Administration (OSHA) proposed fines of $410,900 for two dive firms, the joint venture Kiewit-Atkinson-Kenny, and the project's construction manager. The accident caused OSHA to demand that the final steps to bring the tunnel on line could be done only by ventilating the entire tunnel.

Two scenarios were investigated to establish ventilation in the tunnel. MVS assisted Kiewit-Atkinson-Kenny in reviewing options for this ventilation. The options included the re-installation of an auxiliary ventilation system or the incorporation of a through-flow ventilation system.

The through-flow system was selected. This system consisted of using an IB909 jack-up barge to install a caisson to one of the first three risers that had the temporary plug removed. Seawater was pumped out of the caisson and a ventilation pipe was installed to fit over the manhole cover on the diffuser head. The ventilation pipe was connected to an exhaust fan built on the IB909 barge. Ventilation was established on July 13, 2000. Measurements confirmed that the airflow predicted by modeling was within 3%. Acceptable oxygen levels were established in the tunnel within 16 hours and all temporary plugs were removed within five days.

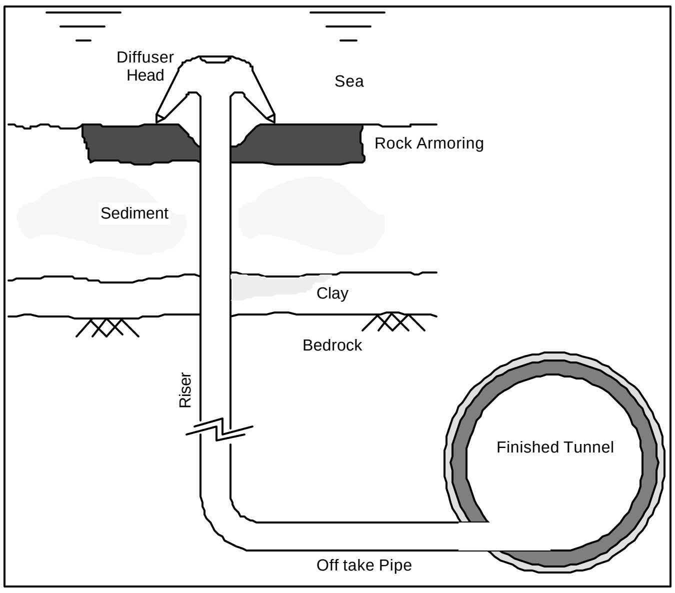

Figure 3. Detail of tunnel with riser to diffuser.

2 DESIGN INFORMATION AND CRITERIA

The following design information and criteria were used to analyze the two ventilation schemes:

Geometry of shaft (from drawings):
- Depth = 128 m (420 ft)
- Diameter = 9.1 m (29.9 ft)

Geometry of tunnel (from drawings):

- Total Length = 15,210 m (49,900 ft)
- Area (0 to 13,198 m [43,300 ft]) = 42.9 m^2 (462 ft^2)
- Area (13,198 [43,300 ft] to end) = Reducing to 9.3 m^2 (100 ft^2)

Minimum air velocity criteria for tunnel:

- 0.51 m/s (100 fpm per contractor)
- 0.15 m/s (30 fpm per OSHA)

Air quantity required at the end of the tunnel

- Duct scheme – 21.7 m^3/s (46,000 cfm based on 0.51 m/s [100 fpm] and diesel requirements)
- Barge scheme – 14.2 m^3/s (30,000 cfm based on reduced diesel requirements)

Oxygen concentration (data provided by contractor from measurements):

- Surface Ambient = 21.5 %
- End of tunnel = 8 %

Atkinson friction factors (assumed):

- Duct = 0.0037 kg/m^3 (20×10^{-10} lbfmin^2/ft^4)
- Tunnel = 0.0093 kg/m^3 (50×10^{-10} lbfmin^2/ft^4)

Assumed dilution of diesel exhaust:

- 0.06 m^3/s/kW (100 cfm/BHP)

Shock losses for bends, entry and exit:

- Per ASHRAE (1989) reference

3 VENTILATION STUDY

Two alternatives were considered for re-establishing ventilation in the tunnel. The first was to re-install nearly 16 kilometers (9 miles) of ventilation tubing and auxiliary fans. Because power had been removed from the tunnel, staging additional fans along the tunnel was not considered to be feasible. A multiple-fan system at the portal was considered to provide for the entire duct length. Studies were also performed to determine the rate at which the ventilation tubing could be advanced and maintain acceptable oxygen rates at the work place. It was determined that this alternative would take many months to re-establish ventilation in the tunnel.

The second alternative was to install a through-flow ventilation system by establishing a connection to surface close to the end of the tunnel. This connection required significant engineering to design a safe means of installing a duct from one of the risers where the temporary plug had been removed. The following sections describe the two alternatives and the ventilation analyses conducted for each case.

3.1 *Auxiliary ventilation alternative*

This scheme proposes that cassette-type ventilation duct be advanced in the tunnel with ventilation being gradually reestablished with the duct. The main section of duct would be 1.8 m (72 inch) diameter. Based on a mass balance calculation, evaluating the amount of delivered and displaced air to give a mixed quantity along the tunnel, it was determined that a maximum advance rate of 4.6 m (15 ft) per minute could be applied while still maintaining +19.5% oxygen in the air along the tunnel. It was assumed that the entire unventilated tunnel would have an oxygen content of 8% (worst case). For this system continuous oxygen monitors would be required on all personnel working near the end of the duct.

In the literature provided by the contractor, the duct manufacturer recommended a safety zone of 12 to 15 m (40 to 50 ft) ahead of the duct. This advice was supported by reference to The Committee on Industrial Ventilation (1984), which states that a blowing duct should achieve 10 % of the exit velocity at 30 duct diameters away from the discharge point.

Independent calculations were conducted on the duct design offered by the duct manufacturer. In assessing this system there were three main concerns:

1 Can the duct withstand the high operating pressures predicted by the manufacturer?
2 Can the duct achieve the extremely low leakage that was used in the duct calculations?
3 The friction factor used by the manufacturer of 0.0022 kg/m^3 (12×10^{-10} lbfmin^2/ft^4) was very low. This could only be achieved if the duct were perfectly straight.

Independent ventilation analyses indicated that at the fan pressure provided by the manufacturer (9.3 kPa [37 inch w.g.]), and with all the fans at the start of the duct, a maximum airflow of 16.5 m^3/s (35,000 cfm) would be achieved at the end of the duct. It was determined that if the duct were allowed to deteriorate even slightly, then the face quantity would drop considerably. Under such high pressure, it would be vital that the duct be installed and maintained in excellent condition.

3.2 *Through-Flow ventilation alternative*

This design proposed that a 1.22 m (48 inch) diameter pipe be installed at the end of the tunnel, such that it could be used to either intake air into, or exhaust air from the tunnel. Such a layout would include 128 m (420 ft) of pipe to pass air through the overlying rock and sea. This scheme would utilize a jack-up barge and ventilation riser to connect a fan to the end of the tunnel. This layout is shown in Figure 4. For this scheme the airflow would take the following route:

- Enter through the effluent shaft (on Deer Island).
- Pass along approximately 13,198 m (43,300 ft) of tunnel.

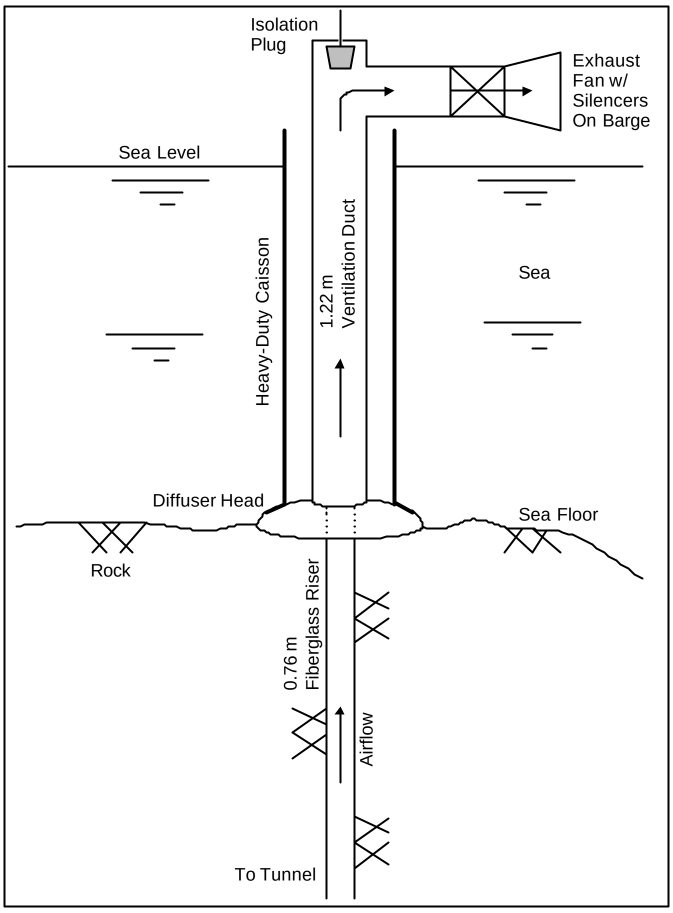

Figure 4. Detail showing through flow ventilation scheme.

- Pass through the diffuser tunnel area to diffuser #3 (2,010 m [6,600 ft] long, tunnel reduces to approximately 2.4 m [8 ft] diameter at diffuser #3).
- Abrupt transition from the tunnel into a horizontal, 0.76 m (2.5 ft) diameter fiberglass pipe.
- Swept 90° bend followed by 69 m (225 ft) long, 0.76 m (2.5 ft) diameter fiberglass pipe to the sea bed.
- Transition from smaller fiberglass pipe to 1.22 m steel ventilation duct (1.22 m [48 inch] diameter).
- Pass through steel ventilation duct to the barge (52 m [170 ft] vertical), then through a mitered bend to the fan.

The ventilation requirement for the tunnel was reduced for the barge scheme due to less diesel and fewer people (no duct installation). The airflow requirement was determined to be 14.2 m^3/s (30,000 cfm), based on the diesel equipment, eight people, and a minimum tunnel velocity of 0.15 m/s (30 fpm as dictated by OSHA).

A ventilation network was established for this configuration (using the VnetPC 2000 ventilation simulation program). As expected, the model showed that the frictional pressure losses (and subsequent fan power requirements) to move the air through the tunnel and shaft sections would be low. The majority of the fan pressure would be utilized in moving the air through the smaller pipes, which connect the main tunnel to the barge (due to losses at the transitions, bends, and along the pipes themselves). The modeling assumed that the fan(s) will be placed on the barge and exhaust air from the tunnel and that the fiberglass and steel pipes will be smooth-walled. The following fan operating requirements were predicted:

- 17.2 m^3/s (36,500 cfm – increased to account for leakage).
- 3,064 Pa (12.3 inch w.g.) fan total pressure.

This operating point was for two Joy Model 38-26-1770 fans placed in series (or a single two-stage fan) at blade setting #2. Approximately the same operating characteristics were predicted if the fans were placed on a forcing system. This would push the air from the barge region through the tunnel, to exhaust via the effluent shaft. When considering the option of either exhausting or intaking from the barge, the following issues were taken into account:

- An exhaust system would ensure that the fresh air base is expanded from the shaft towards the diffuser area, which is the direction of re-entry for personnel.
- It will be easier to monitor and control the discharge of the low oxygen tunnel air if an exhaust system is used. The region immediately around the fan discharge can be cordoned-off, and sampling can be conducted while the air is in the ventilation duct.
- If there are any leakage points in the fiberglass or steel pipes, and there is a build-up of water, then the exhaust system would draw more water into the pipes due to the system being on negative pressure. A forcing system will tend to help prevent the ingress of water or gases. However, since a caisson system is proposed, water leakage should not be a critical issue.

3.3 *Selected alternative*

The exhausting through-flow alternative was selected for the recovery ventilation system in the tunnel. The main reasons for this decision were:

- The ducting would take a significant period of time to procure and install.
- During the period of installation and recovery, workers would still be placed in a potentially hazardous environment near the duct discharge.
- There was uncertainty in the ability of the auxiliary duct system to provide sufficient airflow over the entire length of the tunnel.

In early July 2000, the IB909 jack-up barge was positioned over the third diffuser head. The sequence required to open the diffuser was as follows:

1. Divers were sent to the diffuser head to remove loose debris and loosen the bolts on the manhole cover on top of the diffuser.
2. The caisson was positioned over the diffuser head. The caisson was fitted with an inflatable gasket to minimize water inflow into the pipe.
3. A pump was positioned into the caisson and the water pumped out.
4. The ventilation pipe was installed in the caisson.
5. A crane with a grappling hook was positioned over the caisson and used to remove the manhole cover.
6. Once the manhole cover was removed, the fan system was connected to the ventilation pipe.

Figure 5 shows the fan system on the barge. A heavy plug was suspended out of the airstream above the diffuser opening such that it could be dropped into the manhole upon loss of caisson integrity. In the event of rough seas, collision with another vessel, or excessive leakage into the tunnel, the plug would be lowered by the crane and inserted into the manhole cover. If necessary the caisson and ventilation pipe could be removed and replaced at a later date.

4 INSTALLATION OF VENTILATION SYSTEM

On July 13, 2000 the final connection was made to the fan (two-stage) on the IB909 jack-up barge. The fan was commissioned and a series of measurements were performed to determine the airflow exhausting the Deer Island Outfall Tunnel. The measurements involved determining the fan total exhaust pressure, traversing the duct upstream of the silencers to calculate air velocity, measuring the dry bulb temperature, relative humidity and barometric pressure of the air in the duct, taking oxygen readings at the fan exhaust, and recording the fan amperage. The duct was traversed in two directions and the average velocity readings were recorded. These measurements were taken two times and the average used in the calculation of airflow exhausting through the fan. The exhaust duct at the fan was 0.97 m (38 in.) in diameter.

The measured data was as follows:

- Average velocity pressure (two traverses): 0.315 kPa (1.266 in. w.g.)
- Fan total pressure: 3.21 kPa (12.873 in. w.g.) measured upstream of silencers.
- Air exhaust dry bulb temperature: 8.5 °C (47.4
- Air exhaust relative humidity: 98 %
- Surface barometric pressure: 101.25 kPa (29.90 in. Hg.).
- Fan amperage meter: 154 Amps
- Fan voltage: 440 V (assumed, not measured)
- Exhaust oxygen spot reading: < 12% O_2 (sensor withdrawn because of high moisture content of the air).

Figure 5. Fan on IB909 jack-up barge.

From these data the following parameters were calculated:

- Air density exhausting duct: 1.21 kg/m^3 (0.0756 lbm/ft^3).
- Air velocity in duct: 22.8 m/s (4,494 ft/min)
- Airflow in duct: 16.7 m^3/s (35,400 cfm)
- Fan efficiency: 59 %
- Motor input power: 138 hp (103 kW)

The computer simulations predicted the airflow through the tunnel at 17.2 m^3/s (36,500 cfm). The actual airflow was slightly less than this value by 3%. This result proved the benefit of modeling the system prior to installation. It also showed that there were minimal obstructions in the ventilation pipe (e.g. flooding of the elbow, etc.) that were not accounted for in the ventilation model. The predicted fan operating pressure was within 4% of actual. The results indicate that the ventilation models were interpreting and representing the actual fan operating characteristic curve correctly, and that the manufacturers provided curves closely fit actual performance.

It was noted that there was some air leakage around the surface "T", plug, connections and probably where the ventilation tube connects to the diffuser. However, no obvious large leakage points were noted and it was difficult to determine if significant airflow was passing through the annulus between the ventilation pipe and the caisson. Another factor influencing the airflow rate was a large quantity of water exhausting the fan. This water is likely coming from the tunnel horizon.

From the air quality measurements it was determined that a significant portion of the exhaust air must have originated from the tunnel since the oxygen levels at the fan exhaust were low (below 12%). The low oxygen levels indicated an unacceptable tunnel environment for unprotected workers.

Providing over 14.2 m^3/s (30,000 cfm) to the tunnel over a 12 to 13 hour time period restored normal oxygen levels for the entire tunnel length (to Diffuser #3). Re-entry to the tunnel was achieved on July 15, 2001. Work commenced and all remaining tunnel plugs were removed in five days. This was five weeks ahead of schedule. The tunnel was commissioned for use in September. The total cost of the recovery ventilation system was approximately $15 million. While this value seems high, it was considered cost effective when factoring in the lengthy delay associated with the commissioning the auxiliary ventilation alternative.

5 SUMMARY

This paper describes an innovative ventilation system for rapid recovery of a long sub-aqueous tunnel. The system was safely installed and the airflows predicted through the tunnel were within 3% of the actual airflow. The project represented collaboration between contractor, consultant, local authorities, federal authorities and the unions. Future outfall projects may consider this type of active ventilation system when commissioning similar tunnels.

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