CHAPTER 251

DESIGN AND CONSTRUCTION OF THE BOSTON OUTFALL

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ABSTRACT

The Boston Outfall, presently under construction in Massachusetts, U.S.A., is the world's largest tunnel outfall. The outfall represents the latest in tunnel outfall technology and when completed will discharge up to 1300 million gallons per day of secondary treated effluent through a system of seabed diffusers, nine and a half miles off the coast of Boston. Installation of the 55 diffusers and risers are nearing completion, with the construction of the outfall tunnel just commencing. The Outfall is a major component of the Boston Harbor Clean-up Project.

This paper presents a description of the design and construction of the deepwater Boston Outfall.

INTRODUCTION

In 1985 the Massachusetts Water Resources Authority (MWRA) was created with an objective to construct a new secondary wastewater treatment plant in order to end the pollution of Boston Harbor. The Boston Harbor Project is an 11 year $6.1 billion effort, making it the largest wastewater treatment project in the U.S.A. The new facilities, with a capacity to treat more than one billion gallons per day, will replace two antiquated and over-burdened primary sewage treatment plants on Boston's Deer and Nut Islands. In addition to the new treatment plants, the Project also includes a new headworks facility, a five mile hard rock tunnel between the two islands and a nine and a half mile long effluent outfall tunnel from Deer Island. A Site Plan of the Project is shown on Figure 1. Construction on the project began in 1988 and will be completed by 1999. The Boston Harbor Project is being carried out under a "fast track" schedule due to Federal Court mandated milestones.

The outfall construction was bid in July 1990 for a total of $279 million and is scheduled for completion in April 1995.

OUTFALL CONFIGURATION

During initial investigations for the Outfall design, concepts were evaluated for both a seabed pipeline and a tunnel for transport of the effluent. Some of the factors that dictated the selection of a tunnel were:

- Preliminary investigations indicated that the dredging of Boston Harbor for the construction of a large diameter pipeline would not be permitted because of environmental reasons.
- The required internal diameter of the Outfall (24.25 feet) would require massive pipe sections and create enormous logistics, handling and connection problems if a seabed pipe was selected.
- Construction of a large diameter pipeline, nine and a half miles out into the Atlantic Ocean presented significant construction risk in terms of both operations and schedule delays.
- Costs for large diameter tunnels become more competitive against pipelines over longer distances.
- Tunnels have reduced operation and maintenance costs, and provide a longer service life in comparison to a pipeline.

Based on the decision to construct a tunnel in preference to a pipeline, an outfall system was developed which consists of the following principal components and features: (Refer to Figure 2.)

- A vertical dropshaft, 30 feet in diameter to a depth of 420 feet below Deer Island. The tunnel depth was dictated by the requirement to have a minimum of four tunnel diameters of competent rock between the tunnel crown and the surface of the rock.
- A submarine outfall tunnel, 24.25 feet in finished diameter, approximately 43,000 feet long to the start of the diffuser zone. The tunnel has an upward grade to allow ground water to drain back to the shaft.
- A tunnel venturi immediately upstream of the diffuser zone to assist in tunnel purging and prevention of seawater intrusion into the tunnel.
- Tapered tunnel in the diffuser zone, 6600 feet long. Tunnel cross section reduces gradually in area to maintain relatively constant effluent velocity.
- 55 riser offtakes connecting the diffuser tunnel to the seabed risers.
- 55 riser pipes, 30 inches in diameter and 250 feet long to carry the effluent from the tunnel up to the seabed diffuser heads.
- 55 diffuser heads, each comprising eight radial ports with conical nozzles attached. The diffusers are spaced 125 feet apart and disperse the effluent in 110 feet of water.

OUTFALL DESIGN CRITERIA

A prerequisite to the design of the outfall was the establishment of realistic criteria on which to base the design. The key issues influencing the design of any outfall system are:

- Existing and ultimate dry and wet weather flows.
- Internal and external hydraulic performance

- Operational life
- Structural integrity
- Regulatory requirements
- Constructability
- Operations and maintenance (O&M)

Specific quantitative design criteria were developed to meet the site constraints and the regulations of numerous government agencies and local authorities. They reflect multi-disciplinary considerations including oceanography, geology, technical, hydraulics and hydrodynamics, water quality, biology, and empirical observations of existing outfalls.

A summary of the general design criteria assumed by the designers is as follows:

- A design life of 100 years was specified.
- The design water depth took into consideration the greenhouse effect, combined with maximum tide and storm surge.
- The design flows of the system were determined to be 1270 mgd peak to 320 mgd minimum.
- The Outfall was to be designed to allow full seawater purging of the tunnel. Purging flows are 80% of the peak design flows with the specified seawater and effluent densities.
- Minimize sea water intrusion into the tunnel.
- Outfall dewatering. It was a requirement that the outfall be able to withstand being fully dewatered at least 4 times over the 100 year life of the system.
- Maximum surface and seabed currents.
- Design wave height and period typically taken on the 100 year return wave.
- Assessment of accidental impact loads due to anchors, chains or trawling equipment.
- Bedrock and seabed overburden properties.
- Corrosion allowance for steel seabed structures and the elimination of metals as far as possible to reduce the potential for galvanic corrosion.
- Assumed construction guidelines such as installing the riser shafts and diffusers prior to the tunnel construction reaching the diffuser zone.

SITE INVESTIGATIONS

The geotechnical conditions along the outfall alignment presented the design engineers with some challenges. The bedrock is a very competent sedimentary argyllite material of approximately 25,000 psi comprehensive strength, with presence of diabase dikes and fracture zones. Overlying the bedrock, particularly in the diffuser zone are sediments and clays (Boston Blue Clay) in layers up to 100 feet deep. Underlying the clays are bands of glacial till characterized by cobbles and boulders. By any standards, the geology of the area is judged very complex and thus difficult to define precisely.

To assist in the outfall design process, a comprehensive geotechnical and geophysical exploration program was carried out for the Project. In 1988, the

MWRA contracted for the drilling of 25 exploratory borings, geophysical surveys, surface mapping, laboratory tests and other exploratory work in the general vicinity of the alignment. Explorations were also carried out on Deer Island. Based on this information, suitable diffuser sites were selected and a preferred general alignment was established.

In 1989, additional exploration was carried out for the MWRA as part of the outfall design program. These explorations concentrated in a narrower strip along the preferred alignment and included 31 borings, 15 piezocone borings, 96 vibracores, seismic reflection and refraction profiling, a deep digital survey, side scan sonar, and magnetometer profiling, as well as field and laboratory testing. The program represented one of the most intensive geotechnical and marine investigations undertaken for an outfall project.

OUTFALL DESIGN

Shaft

Various methods of ground support were considered for the section of the 30 feet diameter shaft through the glacial till from ground level to -110 feet below Mean Sea Level. These included precast concrete segments, soldier piles and lagging, the New Austrian Tunneling Method (N.A.T.M.) and diaphragm walls. Diaphragm walls were selected by the designers as the most reliable means of support that would meet design criteria and ensure safety during construction operations.

The second section of the shaft, from -110 feet to -365 feet consists of three sections of shaft supported by rock bolts, mesh and a skin of reinforced shotcrete.

The third and lowest portion of the tunnel shaft consists of a back tunnel (Figure 4), a shaft invert and pumping sump and a TBM erection chamber. The final lining for the shaft and the initial length of tunnel up to the point where the main tunnel lining commences is to be unreinforced cast-in-place concrete. This 12 inch thick lining was designed to withstand full external hydrostatic pressure in the temporary condition and full internal hydrostatic pressure in the operational condition. The construction of the shaft commenced in late 1990 and was completed in early 1992.

Tunnel

The 43,000 feet long main outfall tunnel has a 24 feet, 3 inch inside diameter. Approximately 90% of the tunnel was determined to be in competent sedimentary argyllite material, with an approximate compressive strength of 25,000 psi. For the few areas where blocky and seamy rock were encountered, the engineers provided suggested grouting layouts for the Contractor as shown in Figure 5.

Two designs for tunnel lining were provided in the bidding documents:

1) Precast segmental liner erected under a shield;
2) Cast-in-place liner using a precast invert segment.

Both liners were designed to resist full hydrostatic pressure. The Contractor was permitted in the specifications to offer his own liner design subject to the approval of the engineer. The "as bid" precast liner consisted of six segments per each 5 feet deep ring: an invert segment, four side segments and a "keystone wedge" trapezoidal shaped top segment. The longitudinal joints were "ship-lap" type and the transverse ones were "knuckle" joints. The Contractor submitted his own design for a variation of the precast liner. After passing physical testing and analysis, this liner system was accepted for use. The Contractor's design utilizes equal and interchangeable trapezoidal shaped segments held together longitudinally with pins and held together transversely with guiding rods (see Figures 6 & 7). The precast units are presently being manufactured in Hudson, New Hampshire approximately 50 miles from the outfall site.

Diffuser and Riser

Like all large marine construction projects, the installation method has a major bearing on the design. Because of the high operating spread cost of the equipment involved, the designers sought a configuration that would lend itself to a "production line" installation method. This was especially relevant considering the large number of repetitive tasks involved. Construction issues considered during design included:

- All component makeup was to be performed on shore or on the barge in controlled conditions.
- Critical inspection and QA activities were able to be performed by ROV or by electronic survey instruments.
- Critical path downtime, e.g., such as that typically occurring while waiting on concrete curing, was reduced to a minimum.
- Diver intervention (a major cause of downtime) would be minimized.
- Potential downtime scenarios for several construction methods were analyzed, and allowances made in the design to mitigate their occurrence.
- Installation tolerances were set at achievable levels based on recent historical precedent.

The designers were fortunate in that they had just been involved in the design and construction of the Sydney Ocean Outfalls, which involved the fabrication and installation of 96 diffusers in 250 feet of water off Sydney, Australia, and were then able to take advantage of the experience gained from that project.

Conditions Affecting Design. The combination of site conditions (thick sediment of overlying clay) and loads resulting from external conditions (storm activity, shipping activity) has determined the overall diffuser and riser design from the bedrock to the seabed. Because of the proximity of the diffuser zone to the US Coast Guard Navigation Buoy 'B' and hence the high likelihood of shipping activity in the area, the risk of high impact loads from anchors as well as anchor drag has been taken into account. Another factor that has been considered is the storm activity in the area and the effect of the resulting environmental action (e.g., scour) upon the structure.

The internal and external hydraulic requirements of the outfall have determined the configuration required for the diffuser, while the internal hydraulics (purging and anti-intrusion) have determined the elevation of the diffuser above the seabed.

Casing. A steel casing was selected to support the weight of the diffuser and to resist the lateral loads predicted by the anchor risk analysis. The casing also serves various functions during the installation process. These include:

a) Stabilizes the upper seabed formation and any weathered or fractured bedrock;
b) Supports the installed riser and diffuser assembly while the riser cement is curing;
c) Provides vertical restraint against riser buoyancy forces during the riser cementing and cement curing processes;
d) Provides an installation reference datum to ensure that the diffusers are at the same elevation relative to seabed. Port elevations are fixed with regard to casing height.

Because the casing is a structural component and is required for the full design life, allowances have been included in the form of increased wall thickness and internal and external coatings in the upper section.

Riser Assembly. The riser functions as a conduit for the effluent. It has been designed to be strong enough to withstand the external hydrostatic pressures both in the long-term (over 100 years) and in the initial dewatered conditions. The riser was also analyzed for installation loads from wave action, offshore transport and hydrostatic loads from the 250 feet grout column. Fiberglass reinforced plastic (FRP) was chosen for the riser material for its ease of handling, durability, non-corrosive properties and to provide a hydraulically smooth conduit. A riser unit length of 40 feet was selected as a standard length for ease of handling onshore during road transport and offshore on the installation vessels. The riser is to be supported in the drilled hole by a fully grouted annulus of cement.

Diffuser Head. The diffuser head has been designed in four components: base, cap, ringwall and protective dome. Concrete has been selected as the main structural element of the base and cap. For durability, the concrete mix is designed for high strength, high density and low permeability. The components are held together by Inconel high nickel alloy rods. These fasteners also double as lifting attachment points for installation purposes.

Diffuser Base. The base acts as a foundation for the diffuser cap and transmits all vertical and lateral impact loads to the drilled and grouted casing. To prevent the diffuser head and riser from being "pumped" out of the hole by hydrostatic forces during cementing, the base incorporates a latching mechanism that positively locks and anchors the base to the casing.

Diffuser Cap. The cap accommodates the FRP manifold, which is the primary dispersion structure for the effluent. The cap is replaceable in the unlikely event it needs recovery and repair through damage, and it also incorporates a manhole cover to facilitate future inspection. The manifold consists of eight ports with detachable nozzles and sealing caps to be removed upon commissioning. The material used for the nozzles, cast nylon, has been selected for its high durability and machinable properties, abrasion resistance and low magnitude of roughness.

To assist in installation and commissioning, each diffuser has a pressure gauge to monitor the internal pressure and an internal air bleed-off assembly to equalize pressure prior to removing port caps. The cap and base are locked together with tie rods prior to installation.

Diffuser Dome. The primary concern for the designers with the diffuser structure was the potential for vertical and horizontal impact loads. To accommodate these concerns, the designers developed a durable, flexible, energy-absorbing shell. The principal material requirement of the dome shell is good ductility, corrosion resistance and high impact resistance. Cross-linked high density polyethylene (HDPEX) was selected as the most suitable material for the intended application.

Ringwall. The ringwall provides protection to the nozzles, as well as support for the HDPEX dome. Its design as a separate component allows the manifold and/or dome to be replaced without requiring the removal of the permanently grouted base. The ringwall is made of reinforced concrete. Extra protection to the exterior concrete is provided by a coating of urethane which displays excellent abrasion resistance as well as a low friction coefficient. The diffuser base is similarly coated on all surfaces likely to experience ground tackle or trawl board contact.

The entire diffuser assembly including dome ringwall and base is designed to present as smooth a profile as possible to minimize snagging by anchors, mooring lines or fishing equipment. In the event that anchors or anchor chains do snag or wrap around the diffuser structures, the riser casing and diffuser system has been designed to resist a lateral load of up to 200 tons.

Rock Armor and Filter Layer. The surrounding rock protection is provided to guard against potential scour and undermining of the diffuser cap and dome, and thereby eliminates the possibility of an anchor chain snagging under the diffuser. The rock protection also provides a smooth seabed profile in the vicinity of each diffuser. To prevent migration between the rock armor and the natural sediments, a 1.5/feet minimum sand/gravel filter layer was specified.

Riser Offtake. The riser offtakes provide the link between the pre-installed risers and the outfall tunnel. As this is essentially a horizontal extension of the riser pipe, FRP was the logical choice for material.

Of major importance in the design of any tunnel which is to connect with seabed structures (e.g., power station cooling water intakes, outfalls and ship loading facilities), is the protection of the tunnel worker from accidental flooding through the riser shafts. There are several devices designed to ensure sealing of the risers from the ocean. They are:

a) Manifold Port Caps - installed with the riser and diffuser. These employ an O-ring fitting to effect a seal. Each port cap and nozzle is individually pressure tested to twice working pressure prior to installation.

b) Riser Plug and Sealing Mechanism - a secondary sealing mechanism designed to prevent flooding due to loss of a seal at the port caps during initial stages of offtake installation. It is installed with the riser assembly and removed immediately prior to offtake installation.

c) Offtake Elbow Sealing Plug - this plug fits into a recessed groove in the offtake elbow pipe and guards against flooding in the event of a loss of seal at the port caps after the riser plug is removed.

OUTFALL CONSTRUCTION

Contract Package

The construction contract packages for the tunnel and seabed diffuser work were issued for bid in two ways:

1) A contractor could bid for all of the work in both packages.
2) A contractor could bid for just one of the packages, diffusers or tunnel.

The reasoning behind this was that it was thought that bidding all the work in one package would reduce the competition among bidders as only very large construction companies would have the resources to undertake all of the work. On the other hand, the designers recognized the potential savings involved if the contractor was to coordinate all of the work, and hence, this option was left open. As expected, the second option (separate contracts) was pursued by the Client upon bid opening. The tunnel contract was awarded to a joint venture of Kiewit Construction Company, Guy F. Atkinson Construction Co., and Kenny Construction Company for $202 million and the diffuser fabrication and installation contract to a joint venture of J.M. Cashman of Boston and Interbetton of the Netherlands for $77 million.

Tunnel Construction

The Robbins tunnel boring machine (TBM) purchased for this project is a double shield hard rock rotary machine. The TBM was refurbished by Robbins at their Chicago site and arrived by barge at Deer Island in October 1991. The machine has high thrust capability for hard rock application and a shield to support poor ground while tunnel supports are installed. (For the TBM's Technical Specifications, see Table 1.)

The cutterhead provides basic face stability while cutting. The two piece shield provides full ground support back to the rear of the lining installation area. A forward shield surrounds the cutterhead support structure providing ground support immediately behind the gauge cutters. A large area gripper system provides low unit ground loading for reacting machine thrust, torque and steering forces. All the major machine structure pieces can be disassembled for removal from a lined tunnel. Included with the TBM is the machine conveyor which terminates approximately 90 feet from the face. The conveyor is supported in the rear on a trailing gantry. Also included is a wheel mounted gantry approximately 30 feet long, a rotary segment erector, segment transport hoist, segment car platform, and the hydraulic and electric power modules for the machine. These modules are mounted on the conveyor structure and trailing gantry.

The TBM has now been fully assembled at the bottom of the shaft and tunneling has begun. The average rate of advance of the TBM including lining is expected to be about 100 feet per day using two 10 hour shifts.

To ensure accurate positional control over the 9 mile length of the drive, the tunneling contractor has elected to use a 3 second gyroscope for tunnel surveying. This instrument is the most accurate available, with a claimed accuracy of 3 seconds of arc. A second system, yet to be determined, will be used to provide an independent parallel check on the gyroscope survey system.

Tunneling in the diffuser zone, which will start at about 43,000 feet east of the shaft, will offer the Contractor special challenges, mainly because of the requirement for the finished tunnel to reduce in cross section. The Contractor has not yet specified what method of construction will be used to form this 6600 feet long tapered section of tunnel. Several options are available including, precast concrete segments, cast in place concrete or concrete pipe segments of reducing diameter. Options for excavation in this zone include continuation of the TBM or use of drill and blast methods to excavate a smaller diameter tunnel. The use of cast in place concrete will require special concrete mixes, including retardants and accelerators because of the long transportation distance. When the tunnel is complete, the off-take adits will be excavated from the main tunnel to the previously drilled and capped risers, the connecting pipes and elbows installed and the off-take adits backfilled. (Figure 8 shows the tunnel and offtake section in the diffuser zone.)

Tunnel Offtakes

The final operation which connects the underground work to offshore work is the installation of the tunnel offtakes.

Probe holes are drilled from the tunnel to ascertain the riser location and to tap and drain the risers of ballast water. (The risers have been installed and filled with fresh water containing green dye - this provides positive proof that the probe drill has intersected the riser and not a ground fault or cement void.) The offtake adits are then excavated horizontally from the tunnel to the pre-installed risers which will be exposed. The risers are then cut and an elbow section installed followed by the offtake pipework linking the riser to the tunnel. The void surrounding the pipework and exposed riser is to be backfilled with concrete (see Figure 8).

Diffuser and Riser.

The contractor chose as his principal construction vessel a 4 leg jackup vessel assisted by a dredge barge, specially equipped grout barge, supply/anchor handling tugs and material barges. The jackup barge is equipped with 2 Wirth pile top shaft drilling rigs, a Manitowoc 4100 ringer crane, a smaller all terrain crane, helideck and construction offices. The grout barge was fitted out with bulk cement and water tanks, mixing equipment and oil field style high pressure cement pumps.

Prior to the jackup commencing installation, the sediment in the immediate vicinity of the riser is excavated by the dredge barge. Typical dredge depths are 6 feet below seabed over a 30 feet radius. Once dredging is complete at a riser site, the dredge continues along the Outfall while the jackup is floated into position using its mooring lines and jacked up over location. To expedite operations, two riser holes are drilled concurrently from the one site. Two sided mounted drilling templates, able to be moved along opposite sides of the barge, are accurately positioned to ensure the risers are within the alignment tolerance and at the correct spacing.

After positioning, a temporary casing is driven into the sediment and restrained laterally at barge level by the drilling templates. The casing is used to support the drilling and stabilize the upper sediments to prevent hole collapse. A 67 inch hole is drilled by reverse circulation air-lift methods and the 61 inch permanent casing is installed. Permanent casing lengths were specified to be a minimum length of 40 feet and 10 feet into solid rock. To date most casings have been 40 feet with several 60 feet and even 100 feet long casings installed to cope with the deeper sediments along the alignment. The casing elevation is checked by lead line, then grouted in stages via four grout lines attached to and lowered with the casing. The first stage forms a neat cement plug at the toe of the casing; this grout is allowed to set up and then the remainder of the annulus is grouted up to the top of the casing. The Designers provided a suggested float shoe design in the bid package, however, the Contractor selected to use a two-stage method.

The next phase comprises the installation of the diffuser and riser. A smaller (53") drill bit is used to drill a hole approximately 250 feet down from the seabed. The hole is surveyed by wire-line tools to ascertain bottom hole coordinates. The Bottom Hole Assembly (BHA) and drill string are now removed from the hole and laid down on the deck of the barge. The pile top rig is removed from the conductor casing, which is now cut off just above the (dredged) seabed and removed. The contractor chose to assemble the FRP riser joints into 120 feet lengths at the onshore staging area to reduce the offshore installation time, hence only two field joints were necessary to make up the 240 feet string. The riser, diffuser base, manifold and ringwall are made up on the drilling template, lowered into the drilled hole and latched into the permanent casing as one unit. Pressure gauges on the diffuser port caps record the internal pressure of the riser, thus detecting any leaks between the sealing caps or between FRP joints. The annulus between the riser and drilled hole is then grouted through two grout lines installed with the riser assembly. A cement slurry of equal parts cement, sand and slag is used to reduce heat of hydration temperatures of the curing cement to less than 160 degrees Fahrenheit and thus avoid heat induced damage to the FRP. A downhole nuclear density gauge installed in the riser/casing annulus provides real time recording of in situ grout densities, while specially designed overflow ports located in the diffuser base allow for visual observation of cement returns. The entire operation of riser installation is observed using an ROV and recorded on video.

With the riser installed and grouted, the jackup moves onto the next two risers and all that remains is for the installation of the HDPEX protective dome and placement of the sand/gravel and rock armor. These activities are performed from the dredge barge, with divers assisting in dome placement and any topping up of cement levels which have dropped due to slump.

One of the most critical offshore operations is the positioning survey of the seabed diffusers and corresponding riser shafts. The tunnelers will be required to locate the toe of these risers more than nine miles out along the tunnel alignment and 30 feet from the tunnel center line. To minimize the amount of probe drilling that must be performed and to align the tunnel to ensure the correct riser offtake distances can be achieved, it is imperative that the bottom hole coordinates of all risers are within a specified tolerance of one riser diameter, 34 inches.

The offshore surveying is carried out in two stages:

a) High accuracy survey of the jackup rig position and drilling templates to the baseline coordinates.
b) Separate downhole surveys providing relative position of the bottom hole coordinates to the drilling platform.

Because the jackup rig was essentially stationary, the contractor was able to employ differential G.P.S. backed up by conventional geodetic survey methods (E.D.M.'s and theodolites) to tie in the rig position to the base line coordinates. As the drilling templates were moved slightly on every riser site, these were surveyed relative to the jackup survey control points on each location.

The bottom hole coordinates of the drilled riser hole were obtained using a two axis wireline deployed gyroscope. Such tools were developed and are commonly used for steering and navigation of directionally drilled oil and gas wells. This survey also had a backup by means of an inverted pendulum shaft survey tool. This method, developed for surveying the verticality of mine ventilation and access shafts, relies on the plumb-bob effect of a suspended mass to move a surface float. The surface float assumes the same horizontal coordinates as the drill bit. Vertical measurements, although not as critical as horizontal accuracy, are obtained by lead line and drill string length.

Because of the number of surveys performed in each loop from the bottom hole survey to positioning the tunnel probe drilling equipment, it is imperative that the same baseline network is used for both tunneling and the diffuser installation. A separate high precision baseline network has been established for use by both contractors.

At the time of writing, the Contractor had installed all 55 of the risers from the jackup barge. The dredge barge will remain on site to finalize dome and rock placement on those sites not completed.

Material Fabrication

There are very few structures built anywhere in the world where the expected service life and environmental conditions are as demanding as for ocean outfalls. With the exception of some parts of the diffuser structure, the riser and diffuser assembly are permanent installations and must remain serviceable for the design life of the system, in this case, 100 years.

Because of this, it is considered essential that a fairly stringent series of quality control tests are specified by the engineer to ensure that the materials selected for the outfall components are of the highest standard and meet specification design requirements. Evaluation of components made from plastics and exotic alloys as opposed to steel and concrete requires specialized testing methods.

For the Boston Outfall Project, specific items in the manufacture of the components were strictly controlled. These include:

- FRP Riser Pipes and Manifolds. Riser bend tests and diffuser cap (External) pressure tests were conducted while specimens were monitored by acoustic emission tests. Barcol Hardness and cube strength tests were performed on the glass and resin samples respectively.
- Cast Nylon Nozzles and Port Caps. Mechanical strength tests on specimens were performed to confirm physical properties with respect to tensile and impact loads.
- HDPEX Dome. Low temperature impact, tensile and density tests were performed on specimens cut from this component.
- Inconel Fasteners. Accelerated corrosion tests were performed to evaluate the resistance of these components to pitting and crevice corrosion.
- Riser Clamps. Tensile and chemical composition tests were performed on samples and radiographic tests were performed on completed cast steel items.

CONCLUSION

The designers of the Boston Outfall sought a configuration that allowed for a rapid installation cycle while exposing the Contractor to as minimum risk as possible. Proof of the success of this approach was borne out by the recent completion of diffuser installation almost a year ahead of schedule, despite the Contractor electing to shut down in the winter months to reduce weather risk to equipment and personnel.

The successful low bid for the offshore construction was $70 million below the independent engineers estimate; with the construction bids ranging from $77 to $173 million dollars. The large spread of bids can be explained by the uncertainty of method in offshore construction and the wider variety of unknowns for this type of project. Other factors contributing to this effect are:

- increased risk to the Contractor from the marine environment.
- differing construction methods assumed during the bidding process.
- the unique nature of the project, with few contractors having experience and few similar projects for the engineer to base comparisons on.

Tunneling bids, by comparison, were much closer together despite the greater cost magnitude (low bid $202 million, engineers estimate $216 million, high bid $246 million). This reflects a greater familiarity and precedent of this type of work amongst contractors. The tunnel completion date is scheduled for mid-1995, while the entire offshore installation will be complete in September 1992.

Deepwater tunnelled outfalls are proving to be increasingly cost effective when compared to conventional large diameter cut-and-cover pipeline outfalls. Not only is it possible to keep all but a small portion of the system from being exposed to the marine environment and thus achieve the specified longer design life, but per unit costs of recent tunneled outfalls have been lower than an equivalent sized seabed pipeline systems. In this case, the designers ought to achieve a low maintenance system that will still be operational in the year 2100 while keeping costs and construction durations below that of more conventional systems.

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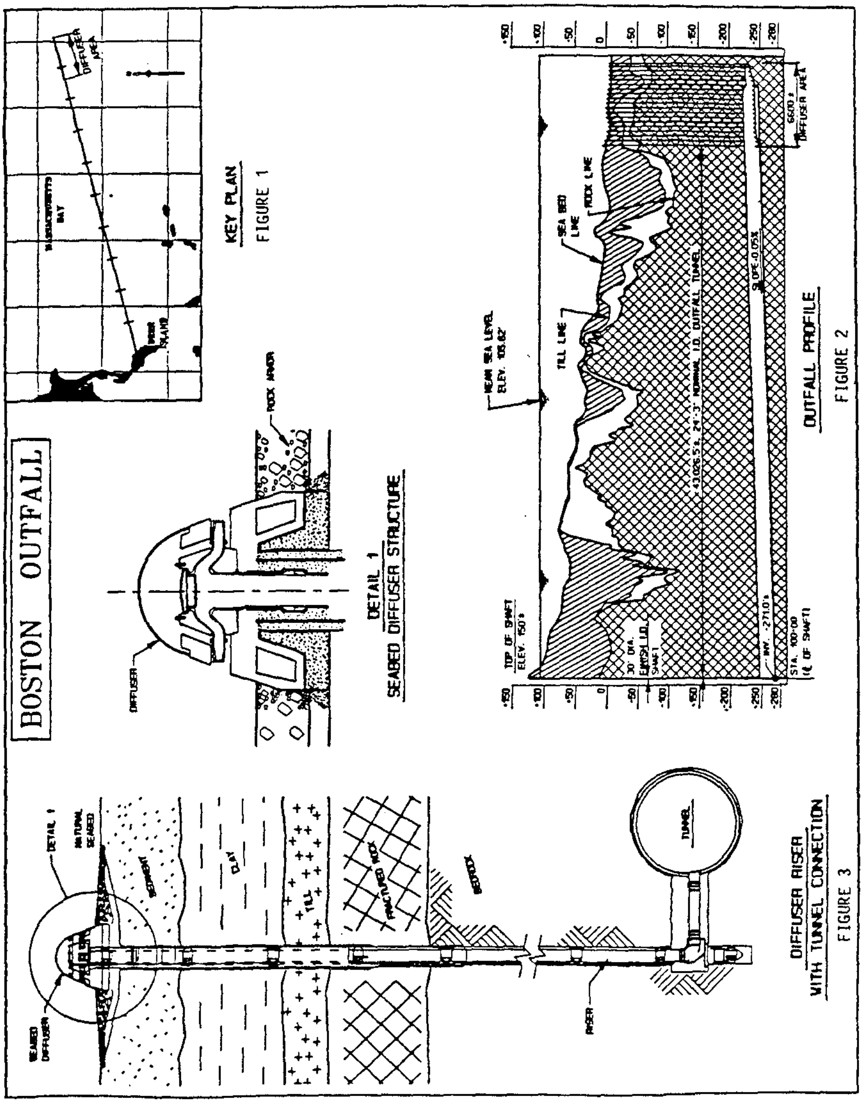

BOSTON OUTFALL
KEY PLAN
FIGURE 1
MASSACHUSETTS BAY
DIFFUSER AREA
DETAIL 1
SEABED DIFFUSER STRUCTURE
DIFFUSER
ROCK ARMOR
OUTFALL PROFILE
FIGURE 2
TOP OF SHAFT ELEV. 150±
MEAN SEA LEVEL ELEV. 103.62'
TILL LINE
SEA BED LINE
ROCK LINE
SLOPE-0.05%
INV. -271.0±
STA. 100+00 (℄ OF SHAFT)
6600 ± DIFFUSER AREA
DIFFUSER RISER WITH TUNNEL CONNECTION
FIGURE 3
SEABED DIFFUSER
NATURAL SEABED
SEDIMENT
CLAY
TILL
FRACTURED ROCK
BEDROCK
RISER
TUNNEL

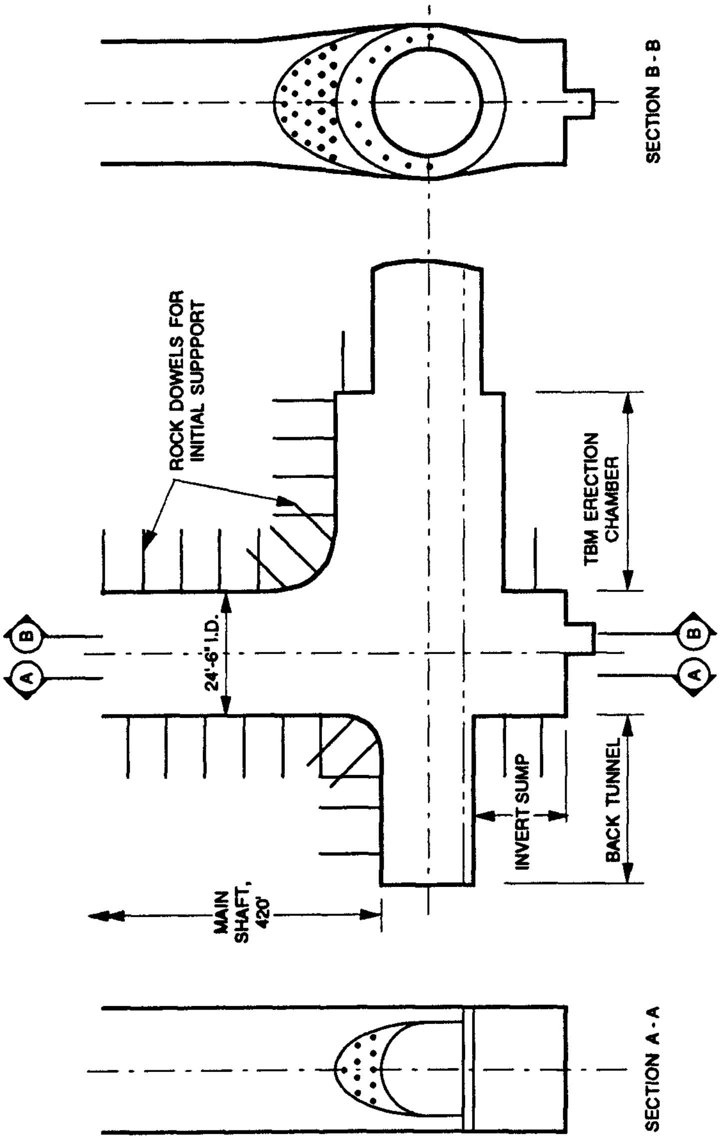
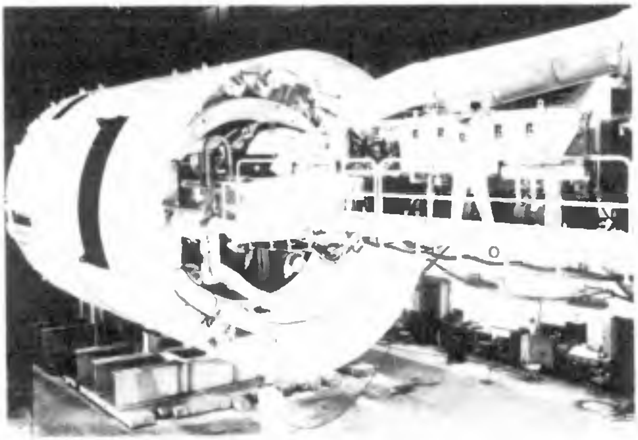


FIGURE 4. ACCESS SHAFT



The Robbins 8.1 m diameter double shield built for the Boston Harbor Sewer Outfall project.

TABLE 1

TBM TECHNICAL SPECIFICATIONS

Machine Diameter		26 ft. – 6 in.
Cutters		Series 17 Front/Back Loading
	Number of disc cutters	50
	Maximum recommended Individual cutterload	50,000 lb.
Cutterhead		
	Maximum operating Cutterhead thrust	2,500,000 lb.
	Maximum shield thrust	6,670,000 lb.
	Cutterhead drive	Electric motors with hydraulic clutches
	Cutterhead power	3,360 HP (8 @ 420 HP)
	Cutterhead speed (approx.)	6.4 RPM
	Cutterhead torque (constant power)	2,700,000 lb. – ft.
Conveyor Capacity (nominal)		350 Ft. 3/min
Machine Weight (approx.)		1,540,000 lbs.

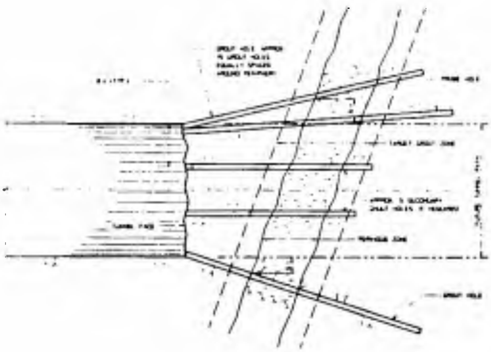


Figure 5

SECTIONAL ELEVATION SHOWING TYPICAL PROPOSED GROUTING LAYOUT AHEAD OF TUNNEL FACE

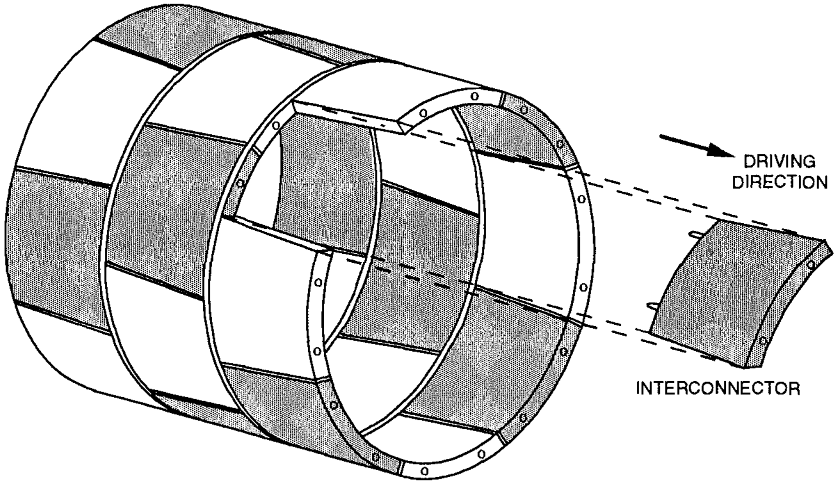


FIGURE 6. PRECAST TUNNEL LINER
(AS BUILT DESIGN)

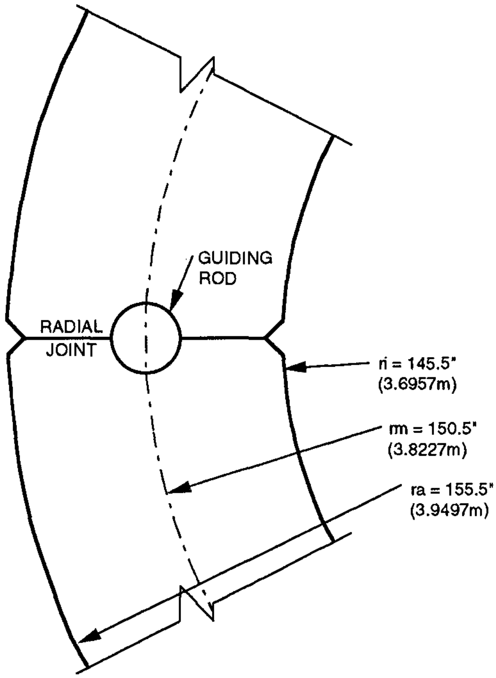


FIGURE 7. PRECAST TUNNEL LINER JOINT DETAIL
(AS BUILT DESIGN)

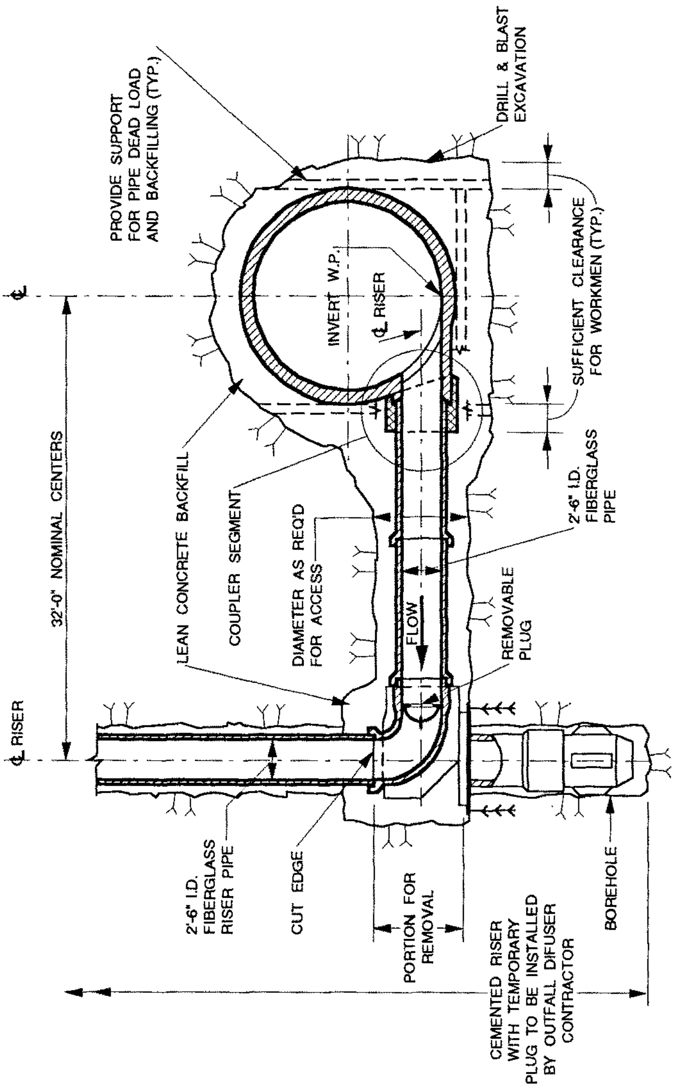


FIGURE 8. TUNNEL-DIFFUSER CROSS SECTION

JACKUP BARGE
DRILLING OFFSHORE
BOSTON

FIGURE 9
(left)

FRP RISER PIPES
MADE UP INTO 120'
STRINGS CAN BE
SEEN ON THE RIGHT
SIDE OF THE JACK-
UP RIG

FIGURE 10
(below)

DIFFUSER AND DOME
PRIOR TO TRANSPORT
OFFSHORE

FIGURE 11
(bottom left)