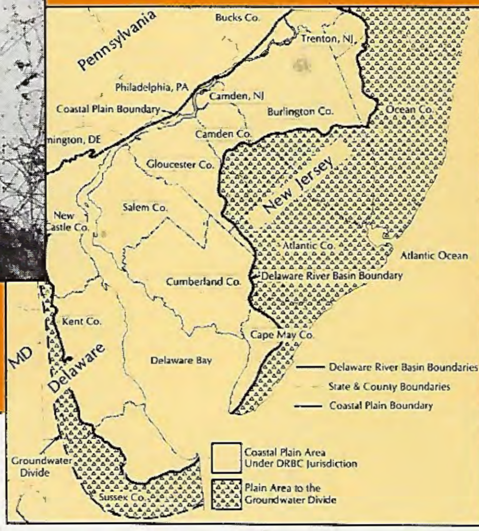
CIVIL ENGINEERING PRACTICE

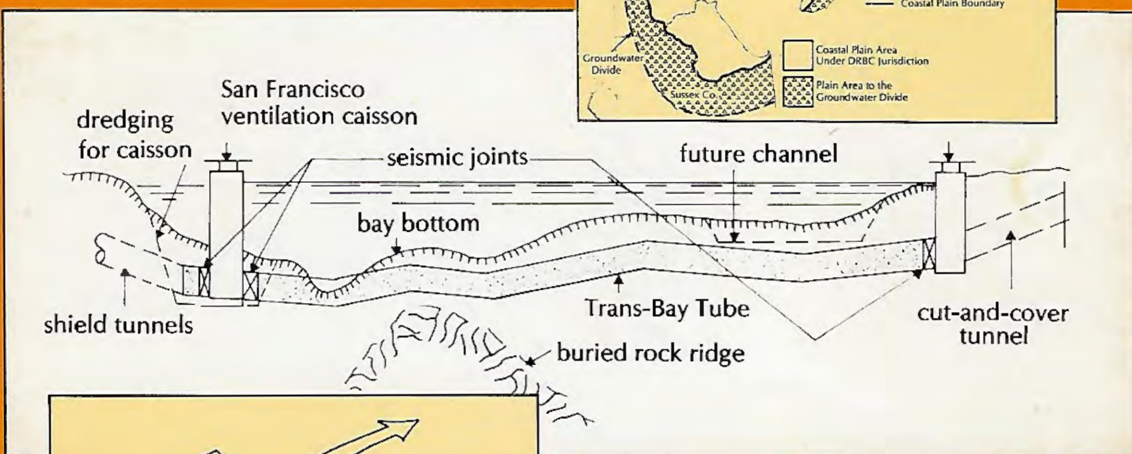
JOURNAL OF THE BOSTON SOCIETY OF CIVIL ENGINEERS SECTION/ASCE

SPRING 1986 VOLUME 1, NUMBER 1 ISSN: 0886-9685

Aerobic & Anaerobic Treatment of Waste

Managing an Interstate Aquifer





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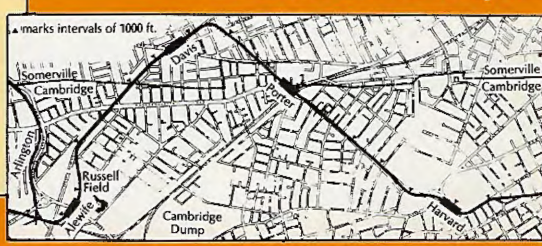

CIVIL ENGINEERING
PRACTICE • JOURNAL OF THE BOSTON SOCIETY OF CIVIL ENGINEERS SECTION/ASCE

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CIVIL ENGINEERING PRACTICE: JOURNAL OF THE BOSTON SOCIETY OF CIVIL ENGINEERS SECTION/ASCE (ISSN: 0886-9685) is published twice yearly by the Boston Society of Civil Engineers Section/ASCE (founded 1848). Editorial, circulation and advertising activities are located at: Boston Society of Civil Engineers Section/ASCE, The Engineering Center, 236 Huntington Ave., Boston, MA 02115-4701; (617) 536-2576. Known as *The Journal of the Boston Society of Civil Engineers Section/ASCE* until 1985. Third-class non-profit bulk postage paid at Boston, MA.

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Civil Engineering Practice seeks to capture the spirit and substance of contemporary civil engineering through articles that emphasize techniques now being applied successfully in the analysis, justification, design, construction, operation and maintenance of civil engineering works. Views and opinions expressed in *Civil Engineering Practice* do not necessarily represent those of the Society. *Civil Engineering Practice* welcomes the submission of unsolicited papers as well as comments on published articles.

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Welcome

It is with great pleasure that we present our newly revised journal, *Civil Engineering Practice: Journal of the Boston Society of Civil Engineers Section/ASCE.* This inaugural issue represents the culmination of three years of introspection, generation of ideas, analysis, discussion and a renewed commitment of energy and resources. We hope that you will find the focus of *Civil Engineering Practice* to be exciting and the articles to be appealing and useful.

With this issue, our Journal, which made its initial appearance in January 1914, begins its 72nd year of publication. As with any publication that has appeared for such a length of time, the Journal has seen its share of changes in character and emphasis. A review of past issues offers testimony to times when the Journal was everything we now hope *Civil Engineering Practice* will be.

Founded in 1848, and having merged with the American Society of Civil Engineers in 1974, the Boston Society of Civil Engineers (BSCE) is the oldest engineering society in the United States. Examination of the Society's history yields a proud record of involvement and leadership in both technical and professional endeavors within the civil engineering profession. Underlying the activities of the Society since its founding is a firm resolve to provide the means for civil engineers to communicate advances in the art and science of civil engineering. The creation of the Journal in 1914 resulted from that resolve, and *Civil Engineering Practice* demonstrates our continued commitment.

In *Civil Engineering Practice* we are seeking to capture the spirit and substance of contemporary civil engineering practice in a careful selection of articles which are comprehensive in scope while remaining readily understandable to the non-specialist. Typically using a case-study approach, *Civil Engineering Practice* will place key emphasis on the presentation of techniques being applied successfully in the analysis, justification, design, construction, operation and maintenance of civil engineering works.

Initially, *Civil Engineering Practice* will appear twice yearly, in the Spring and Fall. This first issue contains articles dealing with the successful management of an interstate aquifer that could serve as a model for other environmental problems that cross political boundaries, the Massachusetts Bay Transportation Authority's nationally recognized and awarded public participation program for public works projects, ways to control the urban wind environment and head off costly errors in building design and operation, a discussion of the growing use of immersed tubes in tunnel design and construction, and a review of biological waste treatment methods by a well-known author on the subject. Articles in future issues will treat such topics as semiconductor clean room design, the Vaiont Dam slide, a history of the Society, hazardous waste treatment, project benefit/cost analysis, various national historic civil engineering landmarks and an examination of the engineering as an expert witness in court. We plan to continue presenting topics that will address the ever increasing need to understand and appreciate the manifold aspects of a wide range of civil engineering projects.

You, both readers and authors, will ultimately determine the success of this journal. We request your participation in every way. Subscriptions are welcomed. Society members will continue to receive the journal as part of their membership fees. If you aren't a Society member and wish to receive *Civil Engineering Practice* regularly, please fill out the subscription card that can be found in this issue (or write or call), and mail it to us. While many of the articles that appear in this first issue were prepared by authors at the invitation of our Editorial Board, we encourage the submission of outlines and papers for consideration. We will make every effort to respond promptly. After all, our goal is to have practitioners relaying information to other practitioners.

Reader comments are also encouraged. For your convenience reader response cards can be found in the back pages of this issue. Please let us know what you like about *Civil Engineering Practice,* what you don't like, what changes we should consider in content or format, and what other articles you would like to see. In short, your comments on any and all aspects of the journal will help us retain and refine our focus on *practice.* We look forward to hearing from you.

Welcome to *Civil Engineering Practice.* In it, we hope you find the same promise of filling a serious void in contemporary civil engineering literature that has encouraged us to produce it. Read it. Enjoy it. Learn from it. Criticize it. Help us build it.

Richard J. Scranton

Richard J. Scranton
Chairman, BSCES Editorial Board

Managing the Coastal Plain Aquifers of the Delaware River Basin

Effective management of an interstate aquifer requires technical expertise, legislative support, legal enforcement and cooperation among various competing and controlling governmental agencies.

DAVID C. NOONAN

PUBLIC AWARENESS of our groundwater resources has increased greatly in the last two decades, and all levels of government are responding to the need for greater control and more effective management of underground reservoirs. Speaking before the U.S. Senate Subcommittee on the Environment, Energy, and Natural Resources back in 1980, Eckardt Beck, of the Environmental Protection Agency (EPA), underscored both the importance and the vulnerability of our groundwater resources:

"With the slow patience that only nature knows, groundwater inches its way through a maze of infinitesimal cracks and fissures, through compacted beds of sand and gravel, sometimes taking a year to traverse a mere thirty yards, a human lifetime to travel a mile or two. A given drop of today's rain that soaks through permeable soils into one of our aquifers may not see daylight again until the 22nd century or beyond, then to replenish a lake or stream a few miles away. Groundwater, then, is almost everywhere beneath us, a virtual ocean of freshwater, oozing through the earth, an awesome natural resource more susceptible to long-term damage than the air we breathe."

Aquifers are porous soil deposits that store and transport large quantities of water, and, like rivers, have no regard for political boundaries; they just flow across them. Aquifers that flow across state boundaries can pose especially difficult institutional and legal problems for would-be managers. The Coastal Plain formations of the Delaware River Basin, which underlie New Jersey, Delaware and Pennsylvania, are such interstate aquifers. In order to manage these formations effectively, the Delaware River Basin Commission (DRBC) has adopted several policies aimed at improving the region's utilization of its underlying aquifers and preserving their usefulness.

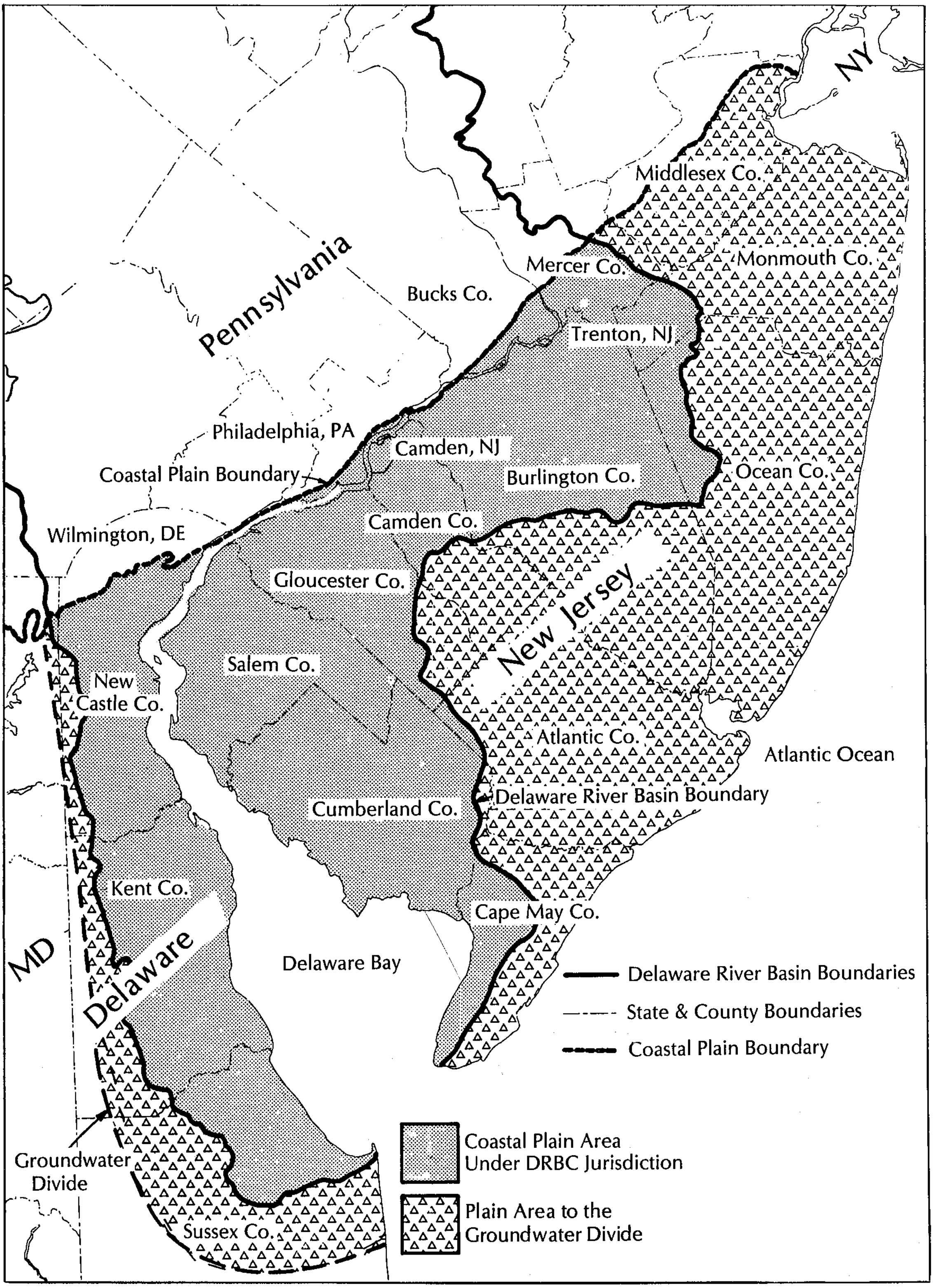

FIGURE 1. The Coastal Plain of the Delaware Basin (and surrounding areas) showing the area of DRBC authority.

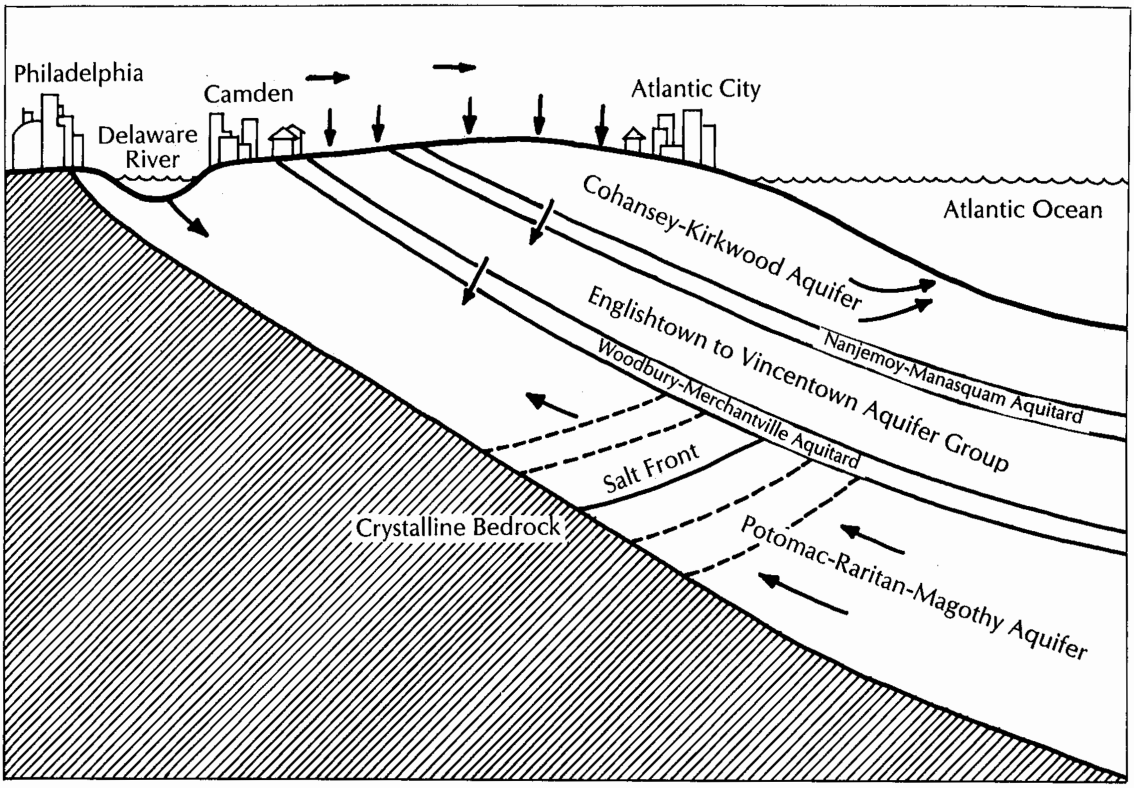

FIGURE 2. Typical cross section of the Coastal Plain aquifer system. Arrows note directions of rain and water flow.

However, these policies are flexible enough to allow the individual states to address their more localized groundwater management issues. In the case of New Jersey's salinity intrusion problem, that state has worked on its problem from the framework of the interstate agency and has undertaken its own actions to solve its own crucial groundwater problem within its jurisdiction.

An essential part of DRBC's success in managing the Coastal Plain formations is its thorough understanding of the particular sedimentary formations that comprise the Coastal Plain, the water management issues associated with each aquifer, and the technology required to address water management problems.

The Coastal Plain Formations

The Coastal Plain area of the Delaware River Basin is shown in Figure 1. Within it lie the major urban centers of Wilmington, DE, Philadelphia, PA, Camden, NJ, and Trenton, NJ. Over 2 million people live in the Coastal Plain portion of the basin. The dominant physical feature of the area, the Delaware River, drains 12,675 square miles, approximately one percent of the U.S. land area.

The Coastal Plain consists of stacked layers of unconsolidated sedimentary sands, clays and gravels, as shown in Figure 2. These layers may be thought of as pie-wedges that range in thickness from a feather's edge at the "fall line" (the geologic break between the Coastal Plain and the Appalachian Highlands where rivers make a sudden descent from the upland to the lowland and that is characterized by numerous cascading waterfalls) to a thickness of over 8,000 feet off the New Jersey shoreline.

The aquifer formation nearest the surface, the Cohansey-Kirkwood aquifer, covers the largest area. Groundwater pumped from this aquifer totals about 185 million gallons per day (mgd) — about 35% of total groundwater demand, and is used primarily for irrigation.

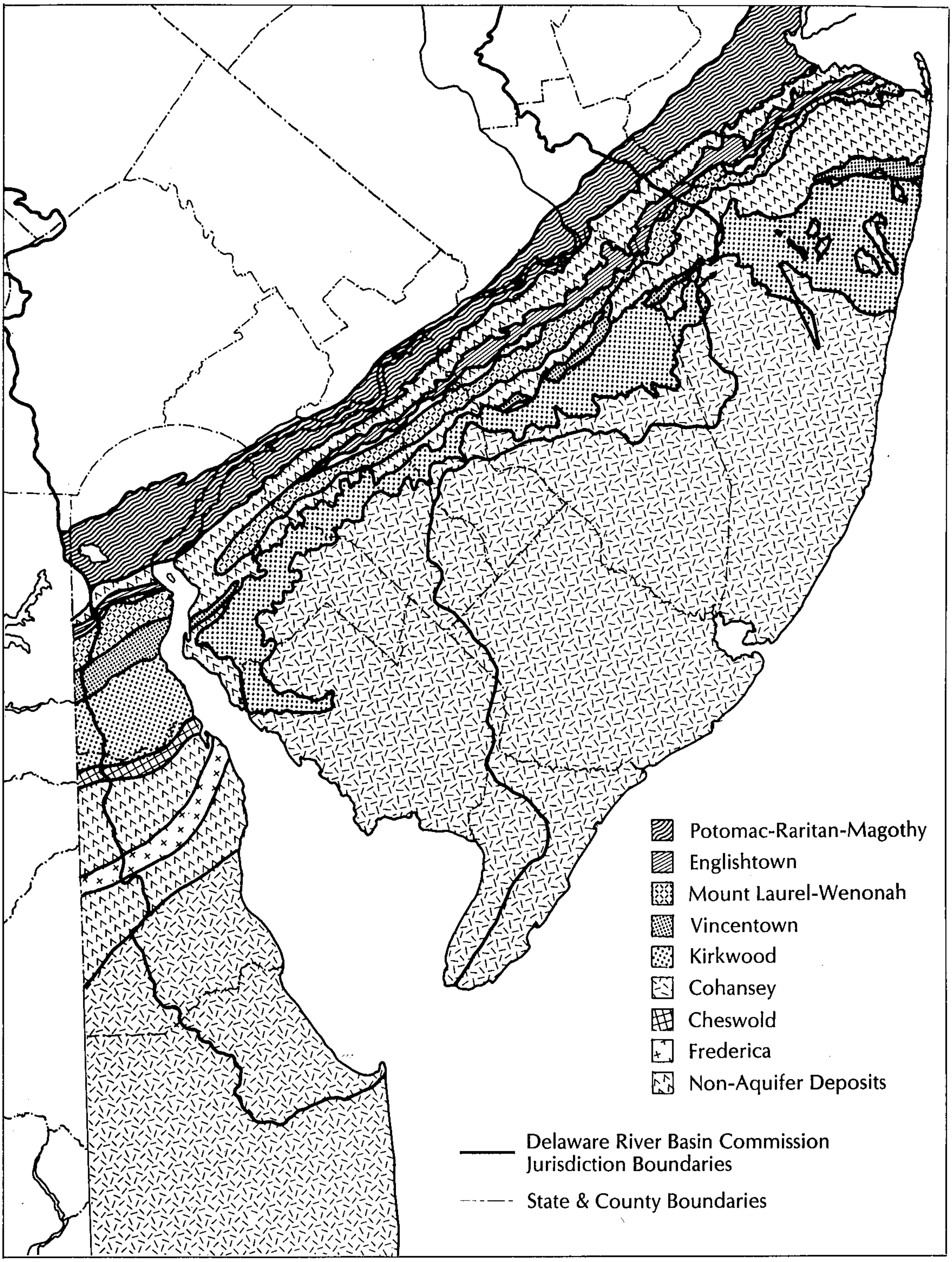

FIGURE 3. Outcrops of different Coastal Plain formations. Please note that coastal plain deposits do extend out onto the continental shelf and in NY and MD, but are not shown on this map. Outcrop areas shown are locations where the named aquifers are in contact with surficial (Pleistocene) deposits or the ground surface directly.

Various experts estimate that this formation contains as much as one trillion gallons of water as pure as melted glacial ice. In addition, the Cohansey-Kirkwood aquifer underlies the Pinelands National Reserve, 368,800 acres of environmentally sensitive and ecologically important land.

The next aquifer formation consists of several minor aquifers including the Englishtown, Mount Laurel-Wenonah, Vincentown, Cheswold and Frederica aquifers. These aquifers are discontinuous and contain soils that yield water grudgingly, so they are not extensively used for water supply except in localized instances. Most of these aquifers are hydraulically connected with each other, so that pumping one of these aquifers causes drawdowns in others. For this reason these aquifers can be considered as a single aquifer formation that is referred to as the Englishtown to Vincentown formation. This formation is separated from the overlying Cohansey-Kirkwood aquifer by the Nanjemoy-Manasquam aquitard, a less porous soil formation that bounds aquifers and constrains waterflow.

The deepest aquifer formation, the Potomac-Raritan-Magothy aquifer (PRM) is the real work horse of the region. It supplies over 215 mgd within the Delaware River Basin alone, and 350 mgd over the entire Coastal Plain. It is separated from the Englishtown to Vincentown aquifer group by the Woodbury-Merchantville aquitard. The PRM rises, or outcrops, to the ground surface in one of the Northeast's most heavily urbanized and industrialized corridors — the area that runs along both sides of the Delaware River, and extends from Wilmington, DE, to New York City (as shown in Figure 3). Because the PRM aquifer is the largest single groundwater supplier in Delaware and New Jersey, it is greatly stressed.

Stress: Overpumping Too Small an Area

Intense localized pumping in the PRM has resulted in several large areas of lowered groundwater level, called cones of depression. Figure 4 (on the next page) shows the location of three major cones. The largest cone is located near Camden, NJ, where water levels at certain locations have dropped from 40 feet below mean sea level to 100 feet below mean sea level in the past twenty years. Other cones have formed near Penns Grove, NJ, and Wilmington, DE. Normally, these cones of depression do not pose a grave threat, but their proximity to two salt water sources is of great concern. These two salt water sources are the Delaware Estuary and the large body of unpotable water that resides deep (downdip) in the PRM at the Atlantic Ocean end. Salt water movement from each source is governed by two distinct and interesting sets of geophysical characteristics.

The Delaware estuary is tidal as far upstream as Trenton, NJ. During a drought, freshwater flows in the estuary decrease, and brackish water from Delaware Bay migrates upstream. The existing cones of depression draw water from the estuary into the groundwater. Although existing data do not conclusively confirm it, brackish water induced from the estuary near Wilmington may be the cause of excessive chloride concentrations in four wells located in the area. In the Camden area, measurements show periodic increases in chloride concentrations in wells near the river. These increases reveal the consequences of induced brackish water during a drought. Figure 5 presents measurement data from two wells in the Camden, NJ, area.

A second source of saline water occurs downdip in the PRM. Two factors may contribute to this particular source of salt water. First, the salt water may have been trapped within the sediments as they were deposited and is only now being released. The second factor may be that the saline water is actually sea water that entered the sediments at the continental shelf and is now slowly moving inland. These factors are not mutually exclusive and both may be correct.

Whatever its origin, this deep salt water is believed to be hydraulically connected to the Atlantic Ocean, and moving inland under the density gradient associated with the comparatively recent (geologically speaking) rise in sea level. Various estimates suggest that as recently as 18,000 years ago, the sea level was between 250 and 300 feet lower

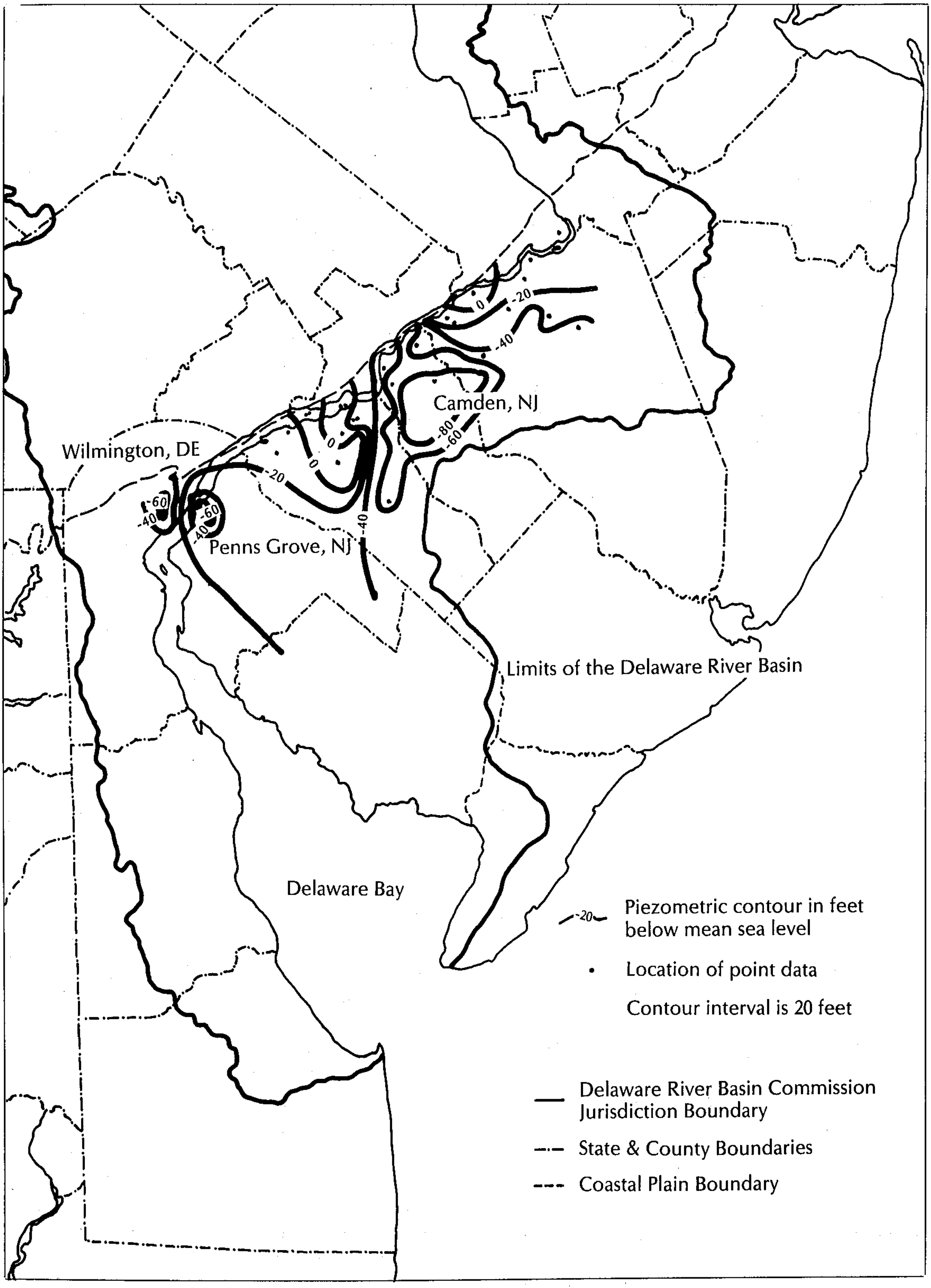

FIGURE 4. Piezometric surface of the PRM aquifer noting locations of cones of depression in Camden and Penns Grove, NJ, and Wilmington, DE.

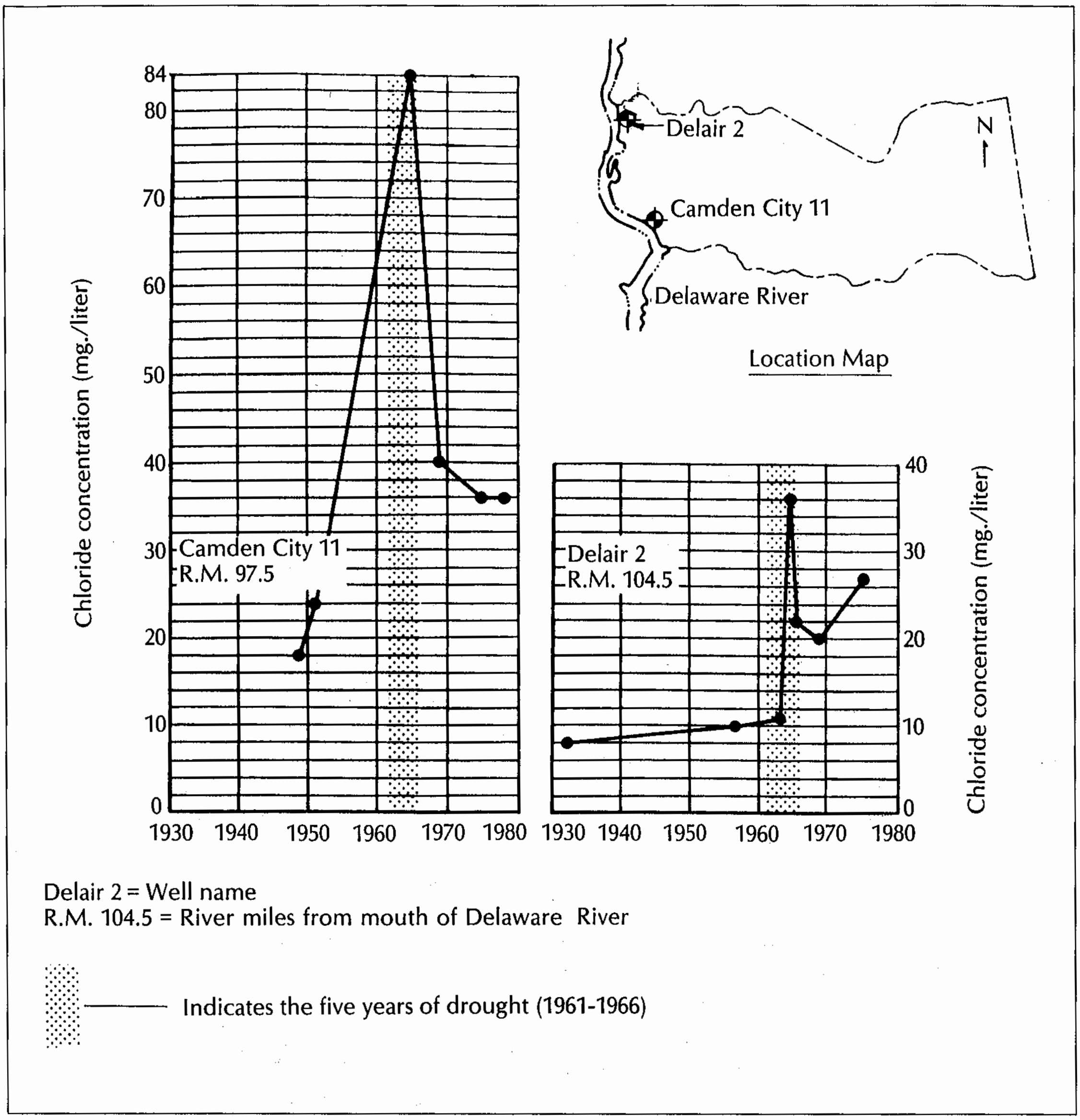

FIGURE 5. Chloride concentrations at two wells in the vicinity of Camden, NJ.

than at present, and did not reach its present position until about 4,500 years ago. The sea level has risen 0.7 feet in the past 80 years and appears to be still rising.[1]

The deep salt water has apparently reached equilibrium along other coastlines in the United States, but is still intruding on the Coastal Plain of the Delaware River Basin. The connection between groundwater at the continental shelf and sea water is quite restricted. Because this hydraulic connection is so limited, the equilibrium rate along the Mid-Atlantic Coast has slowed down significantly. Consequently, the inland movement of the deep salt water is a natural, but delayed, response to the rise in sea level.

The salt concentrations in the aquifer progressively diminish in the PRM as it moves from east to west. As groundwater moves up through the aquifer in a landward direction, the salt concentrations eventually become minimal. The location where the salt water becomes fresh water is usually not a sharp, distinct interface, but rather a broad zone of

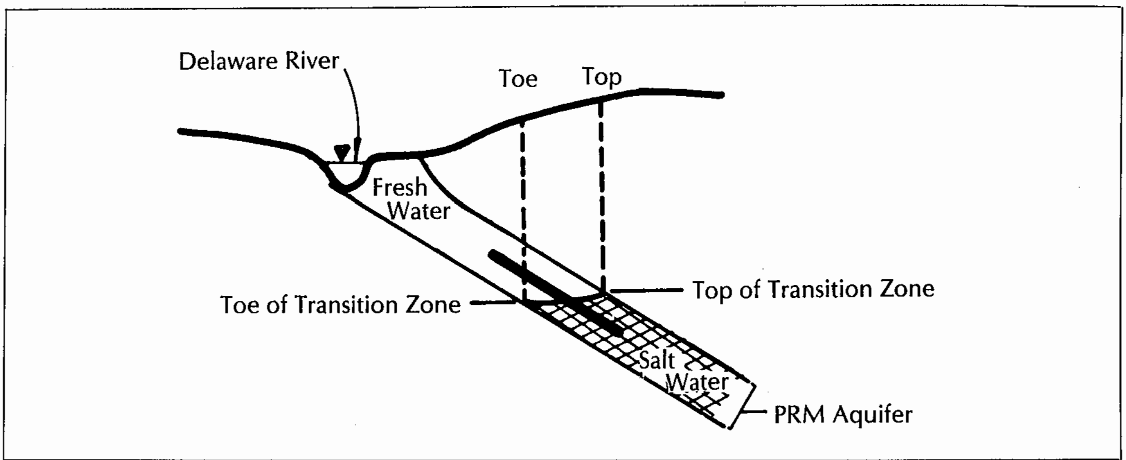

FIGURE 6. A vertical view of a typical part of the PRM aquifer.

diffusion that stretches over ten to twelve miles. It is commonly referred to as the transition zone. The 250 parts per million (ppm) isochlor is used as the demarcation between saline and fresh water. Since the transition zone is not currently in equilibrium, it is sloped, and exhibits a distinct top and toe (see Figure 6). The top of the transition zone is where it intersects the top of the PRM aquifer; the toe, where it intersects the bottom of the aquifer. Its present location is shown in Figure 7.

The cones of depression in the PRM reverse the natural fresh water gradients and accelerate the movement of the deep salt water. Years ago, the deep salt water was not moving fast. In 1890, people in the area were using the Delaware River for water supply and aquifers were so full that fresh groundwater was discharging to the Delaware River. The USGS estimated that under these natural, non-pumping conditions, the deep salt water was creeping inland at the minimal rate of 10 feet per year.[2] Pollution of the Delaware River, however, has forced communities to abandon it as a source of direct water supply and to substitute groundwater supplies. As pumping has increased, groundwater levels have declined so much that today the deep salt water is estimated to be moving at a rate of 100 feet per year.[3] Another USGS report concluded that chloride concentrations in wells located in and around the transition zone have increased 10 to 20 ppm over the last decade.[4] If the present pattern of pumping continues, groundwater levels will decline and the advance of the deep salt water will accelerate.

Solving the groundwater salinity problem, and stabilizing and minimizing the depression cones are formidable and related tasks, but not impossible ones. These man-made problems are largely correctable through man-made action. Several agencies are working towards solutions, including the Delaware River Basin Commission (DRBC), the sole regional authority responsible for managing groundwater resources within the Coastal Plain.

DRBC: Regional Authority With a Regional Perspective

Established by a federal-interstate compact in 1962, the Delaware River Commission was formed to manage the water resources of the entire Delaware River Basin. By Congressional action, the United States joined the compact with the four states — Delaware, New Jersey, New York and Pennsylvania — as an equal partner. The Commission members are the basin states' governors as well as a special Presidential appointee, traditionally the U.S. Secretary of the Interior, representing all federal agencies. Not wholly autonomous, DRBC acts for, and only with the concurrence of, its members.

The Commission, acting in concert with the states, engages in comprehensive water

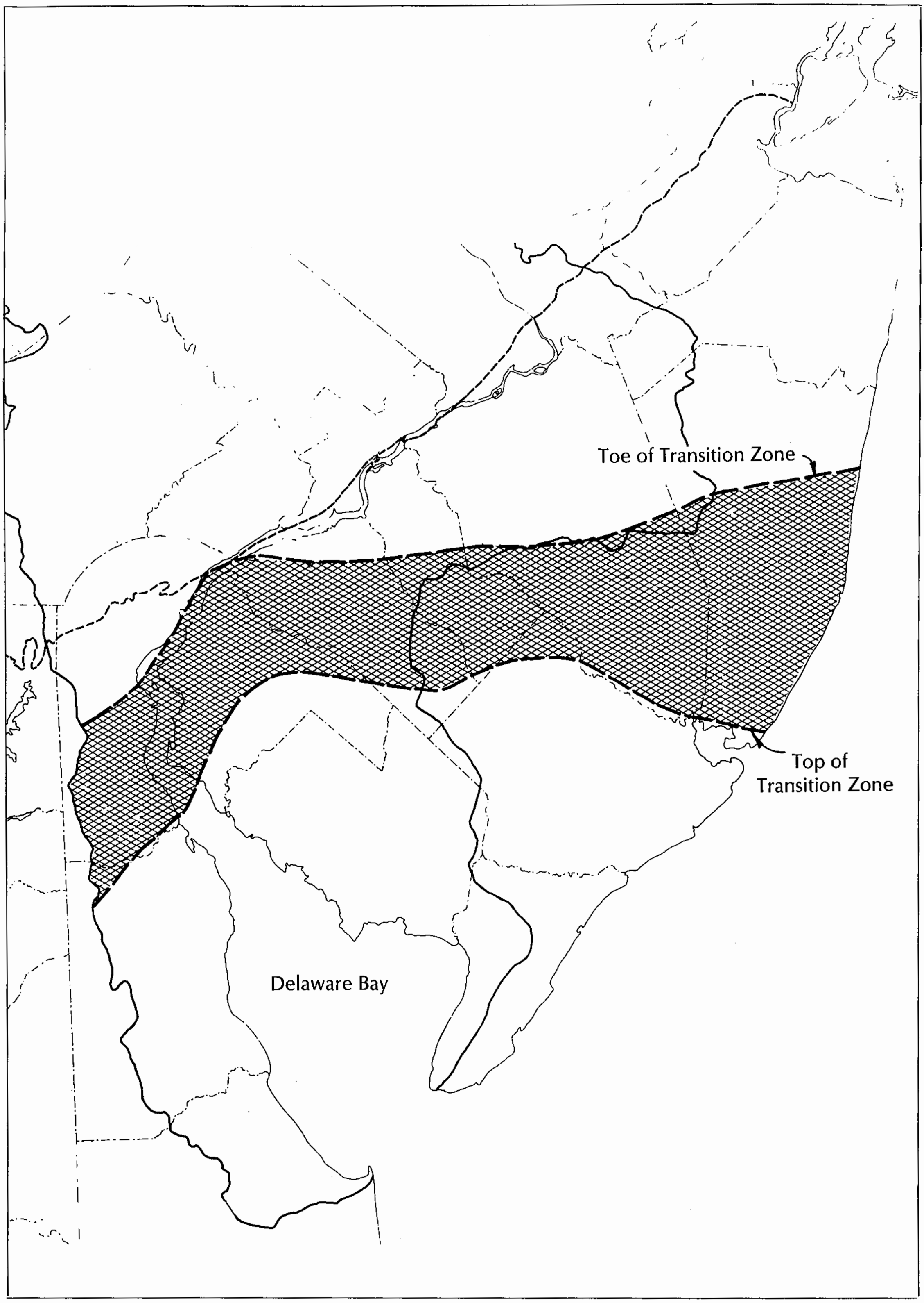

FIGURE 7. Location of the 250 ppm isochlor transition zone in the PRM aquifer is shown.

resources planning and management activities at the interstate level. Backed by strong regulatory powers, DRBC is unique among water management agencies in the United States because it has both the *responsibility* as well as the *legal authority* to control the basin's resources.

Solving the Coastal Plain Problems

Recognizing the threat to the Camden well fields (as well as the City of Philadelphia's surface water intake) posed by brackish water advancing up the Delaware estuary during a drought, DRBC has coordinated the design, construction and control of multi-purpose fresh water reservoirs in upstream portions of the basin. During periods of low runoff, water is released from these reservoirs to augment the fresh water flow down the estuary and to concomitantly repel salinity from Delaware Bay. A fresh water flow of 3,000 cubic feet per second (cfs) at Trenton adequately protects the Camden well fields. Without DRBC, reservoirs located in Pennsylvania and New York would probably have never been built or operated as effectively for low flow augmentation.

With the sea level continually rising slowly, the current flow of 3,000 cfs will be insufficient to deter the advance of brackish water in the coming years. If the present trend continues, the sea level will rise an additional 0.4 feet by the year 2000. To offset increases in the brackish water, DRBC estimates that this will require an additional 150 cfs of fresh water flow by the year 2000 (or, a total of 3,150 cfs would have to be supplied) to protect the Camden well fields.[5] Since multiple demands on existing reservoirs permit no margin for additional low flow augmentation, construction of additional reservoirs is needed. In order to provide funding, DRBC is considering taxing present water users to create a fund for this new construction.

In 1962, as part of the DRBC compact, existing Delaware River water users were exempted from any tax or surcharge. New users were — and still are — required to pay a surcharge. Revenue from this surcharge has been earmarked for continued reservoir construction. At present, DRBC is examining the option of taxing both pre-compact surface water users *and* groundwater users in the basin. This is a progressive concept, since a large portion of the groundwater pumped from the PRM aquifer (essentially a "reservoir" in itself) is induced infiltration; i.e., river water "removed" through the ground.

Developing Management Zones

Controlling salinity in the estuary solves but one aspect of the salinity problem facing the Coastal Plain aquifer system. To more effectively address the deep salt water threat, DRBC has divided the area into the nine management zones as shown in Figure 8. These zones recognize the inherent characteristics of the Coastal Plain formations. Zones 1, 4, 5 and 6 correspond to the outcrop area of the PRM aquifer; Zones 2, 7, 5 and 8 to the Englishtown to Vincentown aquifer group; and, Zones 3 and 9 to the Cohansey-Kirkwood aquifer. DRBC has adopted several recommendations for reversing groundwater declines and reducing the risk posed by the deep salt:

- Discourage new well permits in the PRM aquifer in Zones 1, 4 and 5 where cones of depression exist.
- Encourage new wells to be drilled in the PRM aquifer in Zone 6.
- Encourage new well development in the Cohansey-Kirkwood aquifer in Zones 3 and 9.

There has been no legal action invoked to force the states to comply with these recommendations at present. In this instance, DRBC has taken an advisory role, suggesting but not interfering, counselling without coercing. Nevertheless, these recommendations do offer a blueprint for resolving the states' deep salt water advance problem and suggest future courses of action.

One such delineation for future action is DRBC's definition of what it considers to be acceptable withdrawal limits. This definition, adopted as Resolution 80-23, states:

"Withdrawal Limits. Except as may be otherwise determined by the Commission

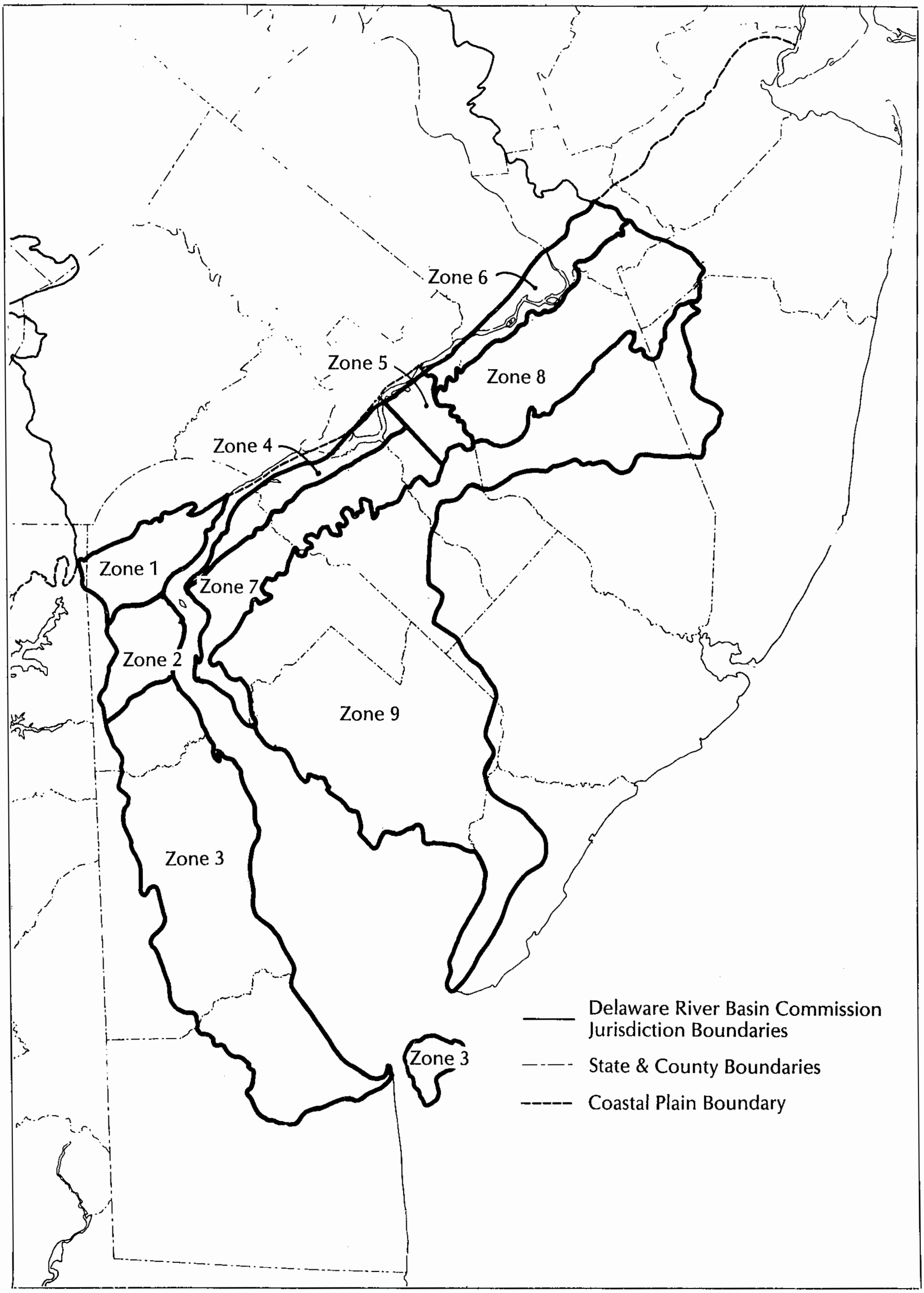

FIGURE 8. Location of the nine DRBC groundwater management zones.

to be in the public interest, withdrawals from the underground waters of the basin shall be limited to the maximum draft of all withdrawals from a groundwater basin, aquifer, or aquifer system that can be sustained without rendering supplies unreliable, causing long-term progressive lowering of groundwater levels, water quality degradation, permanent loss of storage capacity, or substantial impact on low flows of perennial streams. In confined coastal plain aquifers, the Commission shall consider and apply aquifer management levels, if any, established by a signatory state in determining compliance with criteria relating to 'long-term progressive lowering of groundwater levels'."

This resolution, despite its failure to quantify such terms as "unreliable" and "substantial," nonetheless does provide strong guidance as to the significant issues each state must address when deciding whether to grant a permit for a new well or restrict a permit for an existing well.

These actions represent the major activities that the DRBC has undertaken to manage the area's water resources from a regional perspective. It is up to the individual states to work within the framework of DRBC policy to implement localized management that will mesh with the overall plan to solve water supply problems and preserve resources.

New Jersey: Leadership by Necessity

Founding father Benjamin Franklin referred to New Jersey as "a barrel tapped at either end by Philadelphia and New York." New Jersey has its share of water supply problems. However, the state and the New Jersey Department of Environmental Protection (NJDEP) are taking responsive, sweeping action to correct past and present deficiencies. Taking DRBC's definition of an acceptable groundwater withdrawal limit one step further, NJDEP developed its own definition of what it considers to be the *dependable yield* of an aquifer:

"[Dependable yield is] that yield of water from a subsurface source or sources available continuously during future conditions including a repetition of the worst drought of record without creating undesirable effects. Undesirable effects may include adverse impact upon other wells of depth of 50 feet or more, increased risk of introducing saline or polluted water into the aquifer or unacceptable reduction of surface flow of streams. Adverse impact upon wells means a forced reduction in pumping rate or a required change in construction of an affected well."

Armed with this expanded definition, NJDEP was able to evaluate groundwater resources in the Camden metropolitan area and work to bring withdrawals back in line with dependable yield. Passage of the New Jersey Water Supply Management Act in 1984 was an important step in controlling aquifer usage. Under this act, NJDEP can take necessary actions to remedy a threatening water supply situation such as the one found in the Camden metropolitan area. Specifically, the Water Supply Management Act Rules allow for the designation of "critical areas" for water supply management purposes.

Critical water supply areas are determined by NJDEP, after public notice and a public meeting. These areas experience adverse conditions related to the groundwater or surface water supplies that require special measures to achieve the act's objectives. These adverse conditions may include one or more of the following:

1. Shortage of groundwater by overdraft on at least ten square miles of an aquifer beyond its permanent, dependable yield. This may be demonstrated by a verified mathematical groundwater model.
2. A progressive lowering of groundwater to the extent that existing wells of 50 feet or more in depth are threatened or rendered inoperative.
3. Reduction of the annual, average potentiometric surface in a ten-square-mile area or other given area of a confined aquifer to at least 30 feet below mean sea level (MSL), a portion of which area is within five miles of the sea or which contains 250 parts per million or more of

isochlor.

4. Aquifer pollution, where actual pollution contaminates a substantial part of the aquifer or where major source(s) of hazardous or toxic pollution may be reasonably anticipated to contaminate the aquifer.

Groundwater conditions in the Camden metropolitan area, for example, satisfy several of these criteria and NJDEP is moving towards declaring the region a "critical area." Once a critical area has been established, NJDEP can, by law, require any number of remedial or data collecting activities including:

- special water testing;
- cutbacks in present groundwater production; and,
- switching to other water sources (either surface water or groundwater).

NJDEP has already declared a moratorium on new wells in the Camden area so that no new permits in the PRM are being issued. Several water suppliers who are serving growing populations are now negotiating with neighboring public water departments that have surplus capacity. The decrease in new well permits has caused a corresponding increase in requests for interconnections and hook-ups. Furthermore, NJDEP intends to cut production in the heavily stressed area by 10 to 40%, increasing the demand for new supplies still more.

There are several options for new supplies. Philadelphia's surface water intake on the Delaware River has significant surplus capacity. Water could be piped across the river to the critical area. Other portions of the PRM are relatively underdeveloped and could provide significant supplies. NJDEP is evaluating the PRM north of the critical area along the river (Zone 6 of the DRBC management zones). Finally, the Cohansey Sand (Zone 9) could offer large amounts of relatively inexpensive water. Each of these alternatives is being priced, and screened for environmental and political feasibility. A final recommendation is expected by Spring of this year.

With these actions, NJDEP will have made significant progress in reversing some of the trends caused by years of overpumping near Camden, and significant progress in beginning to restore a balance to the groundwater system in this region.

Successful Management

The Coastal Plain experience demonstrates that complex interstate water resource management problems can, above all, be tackled; and innovative and coordinated solutions can be implemented. Without the mechanism of the DRBC, it would have been virtually impossible to have all the states and the federal government agree on the present and planned upstream Delaware River reservoirs in New York and Pennsylvania. As agreed upon by all parties involved, these reservoirs are and will be designed and controlled to permit balanced use of stored water for both public surface water supplies and to ensure that flows into the Delaware Estuary are always sufficient to prevent the harmful intrusion of saline water from Delaware Bay. DRBC, recognizing the strong sense of self-rule and self-interest that exists within its member states, has elected to provide *recommendations,* not *directives,* to each state to help solve their problems. The states are free to pursue — in their own fashion — courses of action to solve their own groundwater problems guided by the context of DRBC recommendations.

Legislative authority and legal enforcement are essential to any effort, regional or statewide, to manage groundwater resources and rectify existing problems. With the existence of DRBC, the states involved have a mechanism with which they can handle any type of water resource problem that affects all or one of them as well as the means to cooperatively manage the Coastal Plain aquifers. This legal support, combined with a clear and more complete understanding of all of the pertinent hydrogeologic factors involved in the aquifers under consideration as well as the appropriate engineering methods to control surface water quality, and the full cooperation of all affected parties, both private and public, can ensure that the rain that enters our aquifers today will be just as suitable to drink when it emerges in the 22nd century.

DAVID C. NOONAN is a water resources specialist with Camp Dresser & McKee Inc. His educational background includes an undergraduate degree in Civil Engineering from Northeastern University and an M.B.A. from New Hampshire College. His professional background includes work on aquifer protection, groundwater management and hazardous waste remediation.

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Community Participation in Public Works Projects

Due to increasing public awareness of the impact of large public works projects, key components of a successful large-scale public works project are community participation and citizen involvement in planning, design and construction phases.

FRANCIS M. KEVILLE & CHARLENE D. PIZZO

SINCE THE MID-1960s communities and citizens have taken increasingly larger roles in determining the course and scope of projects that affect them. Citizens have become more adept at organizing themselves into citizen action groups and these groups have become more effective in representing their interests. Significant consideration in the planning, design and construction of major public works projects has been granted to communities and citizens through extensive community participation processes and programs in order to ensure timely and successful project completion. In some cases, this participation has been solicited on a voluntary basis; in others, agencies undertaking major projects have been required to be responsive to the needs and desires of citizens.

One such agency, the Massachusetts Bay Transportation Authority (MBTA), recognized that such participation was a vital ingredient to the success of two major projects that affected many communities that, in turn, had differing constituencies. Initially creating and developing formalized community participation programs within its construction project budgets, the agency sought to provide ample opportunities for citizens and communities to participate in the planning, design and construction of two of the MBTA's most significant and challenging construction works — the Red Line Northwest Extension and the Southwest Corridor Project. In fact, community participation has become an integral part of all major MBTA construction projects.

MBTA: Background

The MBTA serves 78 cities and towns in the Boston, MA, metropolitan area with a population of 2.6 million. The oldest and fifth largest transit authority in the United States, the MBTA has provided transportation services since the construction of the first subway in 1897. The growing need for more widespread public transportation in the Boston metropolitan area — due to population growth and the flourishing activity of the area's numerous educational, cultural and medical centers, and the business community — required improvement and expansion of the area's public transportation system over the years. The MBTA, and its predecessors, responded with major construction of new lines and facilities, and added services that now consist of three rapid transit lines, a light rail line, a major commuter rail system, 155 bus routes and a variety of para-transit services. Today, the MBTA serves an estimated 600,000 passengers per day, and it expects to increase that number considerably in the late 1980s and into the 1990s through the completion of the new Southwest Corridor Project and other projects now under construction or in the planning/design stage.

The greater portion of the MBTA's expansion and improvement of the transportation system has taken place over the last two decades and is projected to continue throughout the remainder of this century. Since 1965, the MBTA has undertaken a $3.7 billion capital improvement program with the assistance of the Commonwealth of Massachusetts and the U.S. Department of Transportation. This improvement program has been realized in such projects as the extension and relocation of the Orange Line rapid transit service from the Haymarket Station in downtown Boston to the Oak Grove Station in Malden to the north, extension of the Red Line rapid transit service from downtown Boston to Braintree in the south, the construction of new bus maintenance facilities, as well as the Red Line Northwest and Southwest Corridor Projects (see Figure 1).

This surge in construction activity has been the result of the MBTA's efforts to respond to area public transportation needs that have increased considerably in the last twenty years. Fuel shortages in the early 1970s, rising energy costs, urban congestion and increased public concern with environmental issues (specifically, air pollution) were major factors that contributed to a growing recognition by Boston-area residents that public transportation for their daily commute into the city was more practical than by automobile. The MBTA became the principal transportation alternative for thousands of commuters within Boston and its outlying suburbs. Also during this period, plans to expand highway systems in the area came under fire from community groups and local officials who protested the massive land-takings for highway construction within their communities.

In 1970, Governor Sargent responded to these protests by imposing a moratorium on highway construction within the area bounded by Route 128, a highway that rings the Boston metropolitan area. He also created citizen/agency committees to review highway plans and consider other transportation alternatives. These actions resulted in the formation of several key cooperative efforts involving government agencies, community groups and individual citizens that set the planning into motion for MBTA expansion and improvement projects, and also laid the groundwork for successful public participation.

Out of this era, the MBTA's Red Line Northwest Extension and Southwest Corridor Project were born and, subsequently, became the focus for community involvement and sustained cooperative planning between government agencies and citizen groups. The MBTA provided coordination for the development of these projects, not only to address and fulfill the transportation needs of the area, but also to meet the expectations and interests of the project areas' localities and citizens.

Red Line Northwest Extension

Beginning in 1945, many government bodies and agencies studied the viability of, and options for, extending the Red Line rapid transit system beyond its original terminus at Harvard Square in Cambridge. In general terms, studies and plans for the viability of an extension of the Red Line from the Harvard Square Station in a northwesterly direction received the support of the area's political leaders, municipal bodies, community and business groups, and citizens.

During the 1960s alternative routes for the proposed extension from Harvard Square were the foci of numerous studies and public meetings conducted by the MBTA, regional transportation planning agencies, and agencies associated with the city of Cambridge.

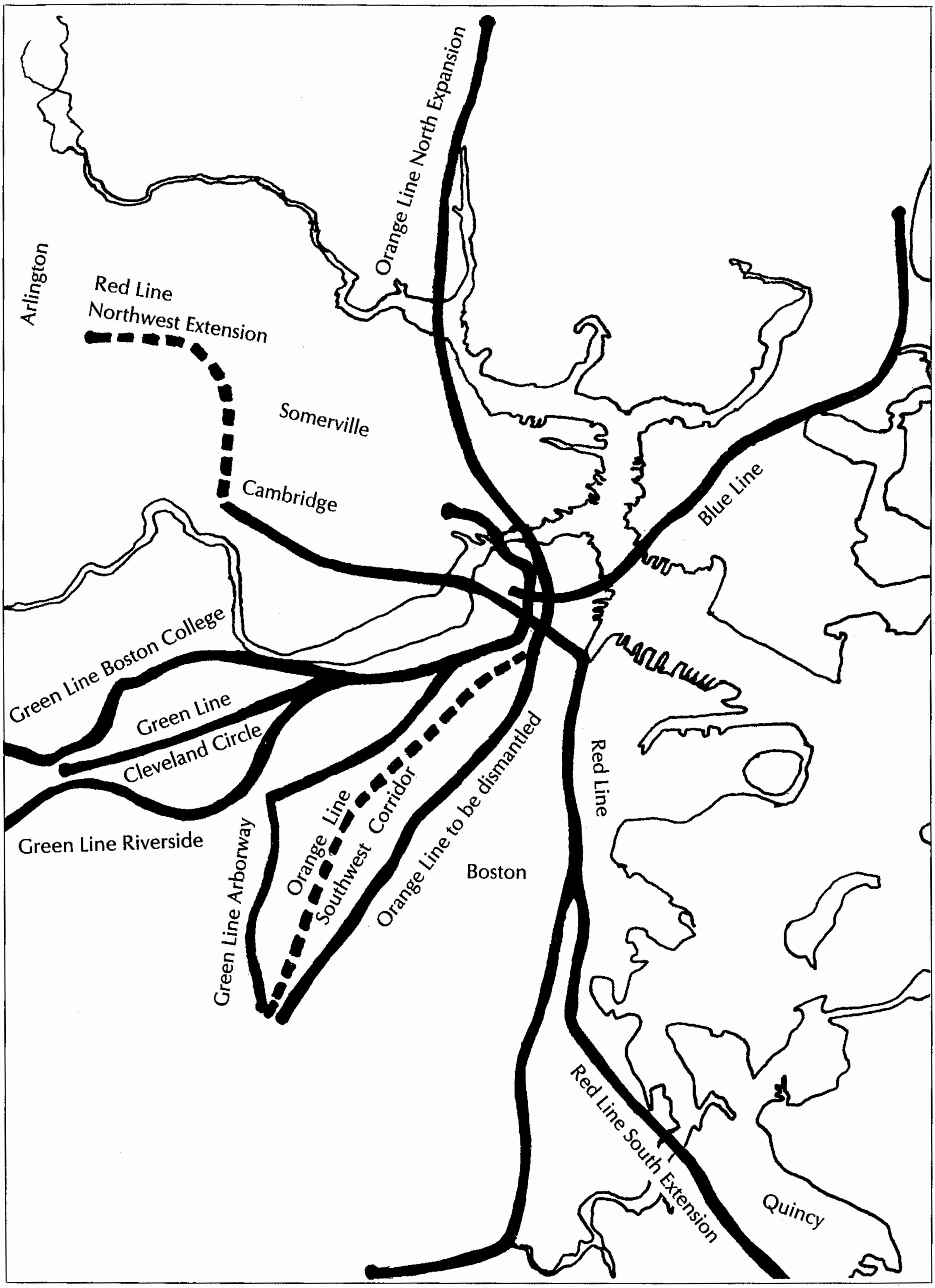

FIGURE 1. The actual routes of the Northwest Extension and Southwest Corridor projects in relation to other parts of the MBTA's rapid transit system.

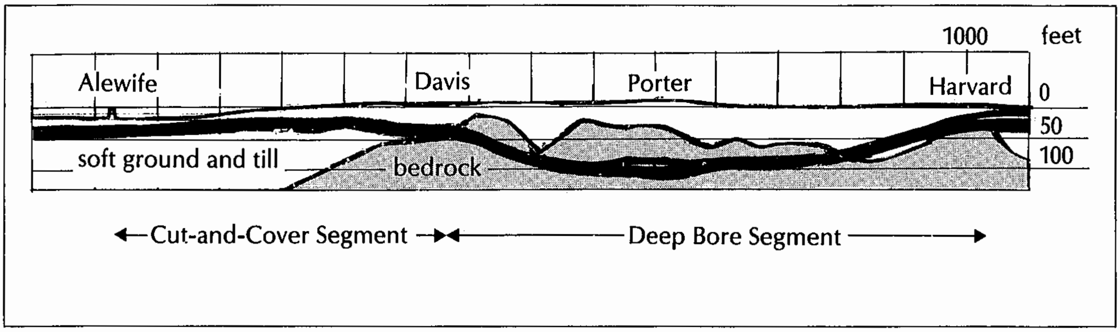

FIGURE 2. The areas where different construction methods finally used for the Northwest Extension are shown. The tunnel entered bedrock about midway to Porter Square and exited it just east of Davis Square. At Harvard and Porter Square stations the track is on two levels. The

This public focus increased during the early 1970s after Governor Francis Sargent declared a moratorium on highway construction within the boundary of Route 128, and formed the Boston Transportation Planning Review to examine current and proposed transportation plans for the Boston metropolitan area. In this anti-highway climate, there was a greater public and political push for mass transit to address the Boston area's transportation problems.

In 1970 a resolution passed by the Cambridge City Council urged the MBTA, the Governor and State Legislature to give high priority to extending the Red Line from Harvard Square to the Northwest as an alternative to a proposed highway (Route 2). The subsequent signing of cooperative agreements between the MBTA and the city of Cambridge in 1970, and the city of Somerville in 1972, resulted in extensive planning efforts that involved large segments of both communities.

Part of the agreement between the MBTA and Cambridge was the eventual creation by the MBTA of a 51-acre park on the site of the former Cambridge City Dump. The MBTA stored excavated materials in the dump during construction and agreed to construct the new park atop the materials when construction had been completed. Another park was also to be constructed along the cut-and-cover tunnels from Davis Square in Somerville to North Cambridge, and improvements were to be made to Russell Field, a recreational area in North Cambridge, as part of the project.

Among the major issues and decisions made during this period was the determination in 1970 of the means of construction for the Red Line extension along Massachusetts Avenue in Cambridge from Harvard Square to Porter Square. Initially, plans called for construction via the cut-and-cover process. Although significant cost savings would have been realized from the use of cut-and-cover, opposition from the Cambridge City Council and the community as a whole favored the deep bore tunneling method (see Figure 2). Representatives of the community and city officials feared the potential for extensive disruption of normal city activities that could result from deep excavation, utility relocation and active construction at the surface of this extremely active business and residential thoroughfare.

Cambridge and Somerville are two of the most densely populated cities in the United States. Construction was planned to pass through and beneath several active retail districts, historic areas, and a major educational and cultural center (Harvard Square). The close proximity of buildings and structures to the construction alignment, a maze of utilities requiring relocation, mixed-faced tunneling conditions, and heavy vehicular and pedestrian traffic throughout the construction area presented some of the many challenges that had to be met in design and construction.

In accordance with Cambridge opposition, deep-bore tunneling methods were used for two segments of the new tunnels and for

Chronology of Red Line Northwest Extension Project

1912 Red Line opens to Harvard Square.

1945 - 1960 Cambridge Planning Board examines routes for an extension of the Red Line beyond Harvard Square. The MBTA begins preliminary engineering studies and considers a variety of extension alternatives. Several other transportation planning groups conduct studies for the extension.

1970 Governor Sargent declares a moratorium on highway construction within the Rte. 128 area and establishes the Boston Transportation Planning Review to reevaluate transportation plans for the Boston metropolitan area.

Cambridge City Council passes resolution urging the MBTA, state and federal agencies to give a high priority to Red Line Extension planning. Council also resolves that extension construction along Massachusetts Ave. in Cambridge must be deep bore as opposed to cut-and-cover.

1973 Congress passes the Federal Interstate Highway Act, enabling the transfer of funds previously earmarked for highway construction to mass transit projects.

Somerville urges the inclusion of Davis Square in the Extension.

1975 - 1977 MBTA undertakes Environmental Impact Study (EIS) to determine feasibility, impact and precise route of the Extension, including routing into Arlington. Final EIS is published.

1976 - 1977 Arlington, through its Board of Selectmen and Town Meeting, officially opposes extension of the Red Line into Arlington if its terminus is to be in Arlington. This opposition results in the terminus of the Extension at Alewife Brook Parkway in North Cambridge.

1976 - 1978 Design (schematic & detailed) process for new stations and tunnels involves extensive community participation.

1977 Urban Mass Transportation Administration approves funding for the Extension to Alewife.

First contract is awarded for the construction of a temporary rapid transit station at Harvard Square during construction.

1978 Urban Mass Transportation Administration awards grants for Arts On The Line program.

1978 - 1982 The MBTA establishes a Community Assistance program to provide the communities affected by Extension construction with information on, and for resolution of, construction-related issues. A variety of programs, including a Business Stimulation program, are developed and implemented.

1983 The MBTA begins operating test trains in new tunnels between Harvard Square Station and a crossover just beyond the Davis Square Station.

1983 - 1985 New Red Line Northwest Extension stations open. Arts On The Line program highlighted with major dedication ceremony.

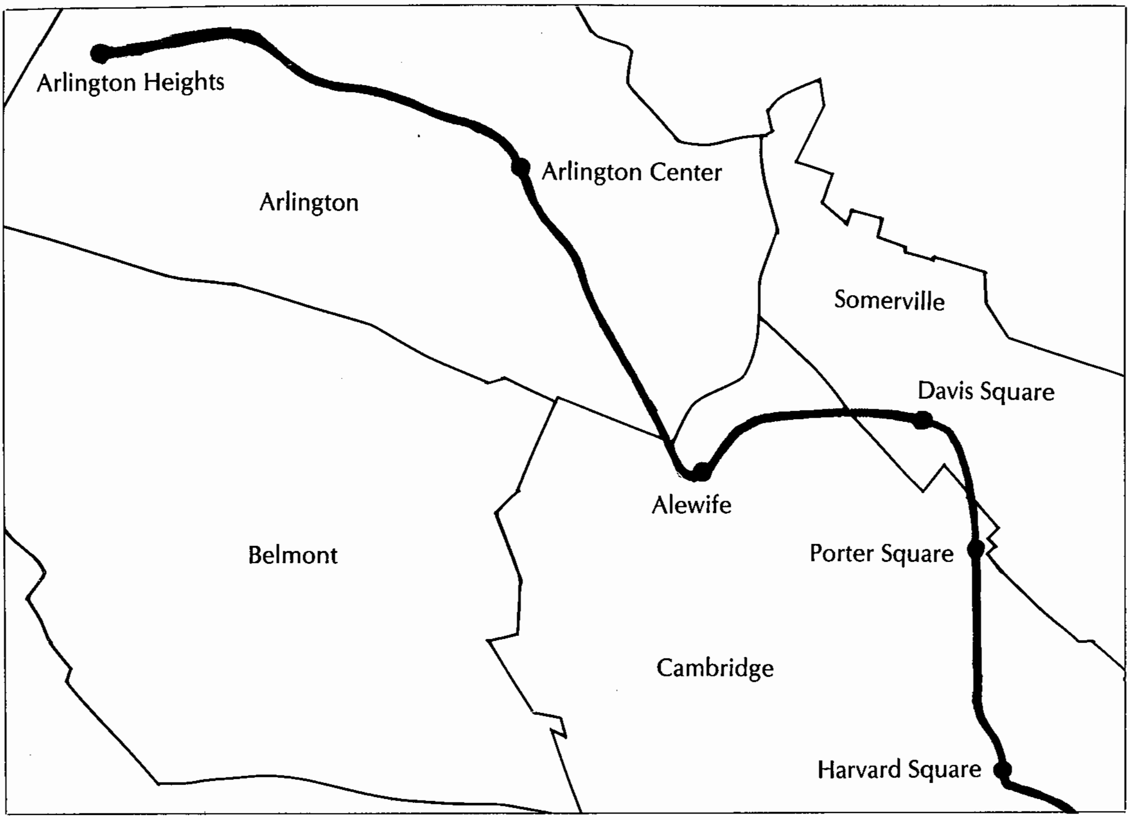

FIGURE 3. The initial route of the proposed Northwest Extension that would have terminated in Arlington Heights.

the Porter Square station. The remaining two tunnel segments and the tail track tunnel were constructed under an abandoned freight cut-off that allowed for the use of cut-and-cover construction methods. The Davis Square and Alewife stations were constructed utilizing the cut-and-cover method.

In fact, in 1973 Somerville requested that the extension be routed through Davis Square in that city so that it might serve that community better. The subsequent decision to extend the alignment of the extension through Davis Square was the result of Somerville's extensive community campaign. Recognizing the transportation and economic benefits of having a rapid transit/bus station at that location, city officials, businesspeople and residents launched a petition and letter-writing campaign to the MBTA and other transportation planning agencies asking for the inclusion of Davis Square in any Red Line extension plan.

Also in that year, the passage of the Federal Interstate Highway Act by the U.S. Congress opened the way for the project through permitting the transfer of highway construction funds to mass transit projects.

Community participation efforts were vital during the Extension's environmental assessment period. This environmental analysis examined the feasibility, impact and precise route of the Extension from Harvard Square in Cambridge to Arlington Heights. More than 110 government agencies, and business and citizen groups participated in more than 650 public meetings during this period, from 1975 to 1977. Consultants to the MBTA conducted the public meetings and compiled the required information for the Extension's three-volume Environmental Impact Statement (EIS). The MBTA instituted a Community Liaison Program that became a vehicle for fostering the participation of, and informing, the public during the environmental analysis.

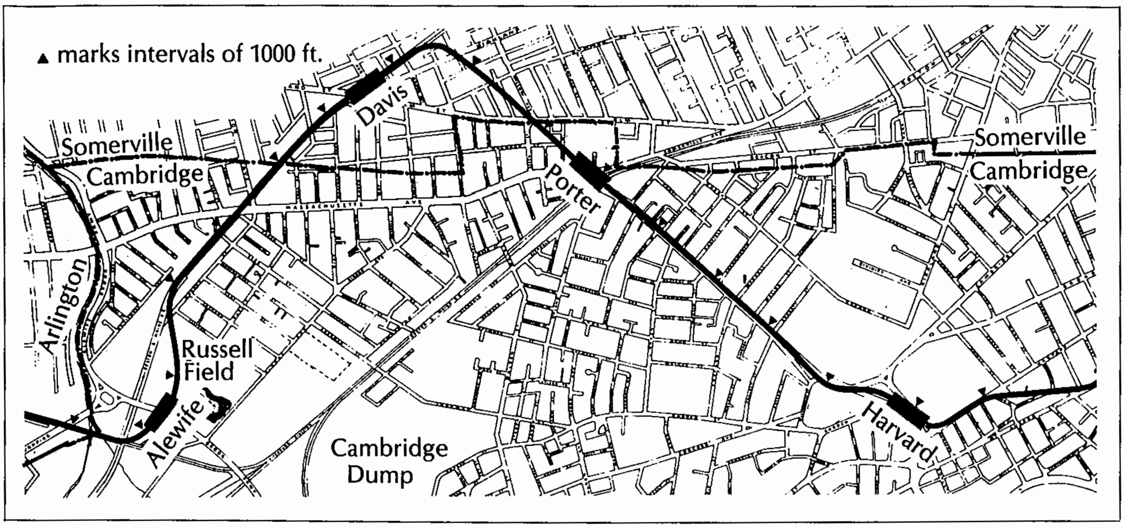

FIGURE 4. The actual route of the Northwest Extension after the town of Arlington rejected its entry into that town. Locations of Russell Field and the Cambridge City Dump are also noted.

An effort was made to involve a broad range of community interests. The development of a newsletter, *The Red Line News,* was part of a public information program that sought to provide the communities with specific information, and the project schedule and progress on an on-going basis. This newsletter was published throughout design and construction until 1981.

The town of Arlington opposed the extension of the Red Line into its boundaries and its termination at Arlington Heights in 1977, despite the fact that the 6.5-mile extension to that point was studied extensively during the EIS period and throughout the planning processes (see Figure 3). The town objected to being the terminus for the extension, citing traffic problems. Arlington also opposed the proposed use of the cut-and-cover construction method, and the multi-phase construction sequence. As a result of Arlington's opposition, the extension was shortened to 3.2 miles and terminated instead at Alewife Brook Parkway in North Cambridge (see Figure 4).

Key components of the Community Liaison Program included the formation of Station Area Transportation Advisory Groups (TAGS). These task force groups were established for each station area to advise the responsible governmental bodies and agencies, and to provide input in the planning process relating to station development and other station alternatives. A Red Line Working Committee (RLWC) was also formed under the auspices of the Central Transportation Planning Staff, the state transportation planning agency. The RLWC was charged with considering and coordinating issues affecting the entire extension project. RLWC members included representatives from the state, regional areas within the state, and business and community groups from all communities along, or in close vicinity to, the proposed terminus of the Northwest Extension. In addition, numerous meetings were held as part of the Community Liaison Program to provide civic organizations and business groups with presentations and information relevant to the extension.

During the extension's schematic and detailed design periods, the MBTA and its consultants continued to involve community groups and individuals as an integral part of station design and tunnel alignment. Six teams of consultants, including one for each of the four stations (Harvard, Porter, Davis and Alewife) and one for each of the two tunnel segments (Harvard to Davis, and Davis to Alewife) conducted numerous public meetings and workshops to obtain community opinion and comment on design alternatives. In addition, a subcontractor to one of the consultants served as the community liaison and provided a major portion of the public information materials, including *The Red Line News.*

By 1978, the MBTA had received full funding for the $574 million Northwest Extension project. As construction activity got underway in Cambridge and Somerville, the MBTA and its consultants intensified efforts to provide the communities with detailed information, and made further efforts to address their concerns relating to initial construction activities.

Among the first of these efforts was the distribution of a project brochure, *Going Underground,* that provided information and graphics relating to the first construction contracts scheduled for award, descriptions of initial construction activities, and a description of the overall project schedule and construction plan. In addition, a 24-hour hotline was established to provide residents and business-people with the opportunity to express their concerns and make inquiries regarding construction activity in their area. The MBTA's engineering consultant assigned a staff member to serve as Construction Information Officer to respond to questions and to address complaints. The MBTA Red Line Construction Project Office also assigned a staff member to coordinate with the consultant and to provide information and liaison services when required.

By late 1978, the MBTA expanded these community participation and information efforts by establishing the Red Line Development Office. This office was to furnish direct community assistance and public information during Red Line construction on a full-time basis. The Development Office staff included:

- a Project Manager with vast community relations experience;
- three Program Development Agents, each possessing backgrounds in community relations and one with extensive experience in the construction industry, including building construction trade union matters; and,
- a Public Information Officer.

The Development Office was responsible for providing construction support and monitoring, coordinating all community participation activities including public meetings, and developing and coordinating all public information programs and materials.

A Property Survey Program and a Construction Damage Review Process were two significant undertakings that resulted from the efforts of the Development Office staff. These programs were developed in response to concerns and complaints from property owners impacted by Red Line construction in the Davis Square area of Somerville and the Porter Square area of Cambridge.

According to contract specifications, property survey documentation was required by the contractor for each MBTA contract within the limits of their contract area. This documentation included color photographs and technical descriptions of the condition of the property prior to construction. However, these specified contract areas did not include numerous properties located directly above the Porter Square to Davis Square tunnel. This tunnel was being excavated by blasting approximately 100-120 feet beneath the surface. In an effort to respond to the anxieties expressed by property owners in this area, the Development Office obtained the approval from the MBTA Board of Directors to offer the supplemental Property Survey Program to serve the property owners within close proximity to the tunnel construction at no cost to the property owner. An engineering consultant was retained to provide the extensive photographic and descriptive documentation. The program was widely publicized in local Somerville and Cambridge newspapers, *The Red Line News,* and through announcements at public meetings. More than 275 property surveys were conducted as a result of this effort. Property owners were supplied with copies of the surveys of their property.

The second program, the Construction Damage Review Process, focused on the allegations of property damage denied by insurance carriers for the MBTA contractors. This program was developed when public outrage was expressed and when an overwhelming number of complaints regarding claims denial procedures by the insurance carriers were received by the MBTA from property owners as well as from the Mayor and other city representatives from Somerville.

The Development Office, in close coordination with the Red Line Northwest Extension's construction staff and the MBTA legal department, developed a process to review and address all claims filed with MBTA contractors. This process included the inspection of alleged damage by the MBTA Damage Review Committee. If the damage was determined by the Committee to be construction related, settlement offers were made to those property owners. The MBTA authorized this expenditure of MBTA funds with the stipulation that all settlement costs would be borne by the contractors and/or their insurance carriers.

An engineering consultant was retained by the MBTA to furnish the technical expertise for damage evaluation, and a team of qualified MBTA staff was assigned to implement the process. An engineering consultant from Somerville's Community Development Office was also secured to represent that community's interests through an agreement with the MBTA, thus ensuring formal city representation as part of the review process. Almost 200 claims were reviewed, and approximately 37% were determined by the committee to be construction related in whole or in part. More than 50 settlement offers were made as a result of the program. This program resulted in greater public credibility that the MBTA was concerned about their interests.

Another successful Development Office program was the Public Blasting Information and Assistance Program. Prior to the commencement of drilling and blasting to excavate the deep-bore tunnels between Porter and Davis Squares, the Development Office initiated informational programs and activities to help ease the anxieties of residents and businesses in proximity to the tunnel areas. These efforts were in response to the many concerns expressed by property owners at Davis Square TAGS meetings and in telephone conversations with the Development Office staff.

Components of the program included the publishing of information regarding blasting in *The Red Line News,* and the posting of informational notices, *Construction Notes for Sidewalk Supers,* at relevant construction sites. These notices provided a step-by-step description of the procedure used for drilling and blasting. Eventually, these notices were posted at additional sites to inform interested pedestrians of all aspects of construction activities. Program Development Agents from the Development Office staff also visited residents in the neighborhoods where blasting was to occur in order to provide direct information and answer questions. Moreover, blasting demonstrations were scheduled and held at sites where the activity was already underway so that residents would have the opportunity to see blasting in use firsthand and relieve any apprehensions when it did occur in their areas.

Another construction assistance program, the Business Stimulation Program, required extensive planning and coordination on part of the Development Office. In 1978, merchants from Harvard Square, along Massachusetts Avenue and in Porter Square in Cambridge (and, eventually, merchants from Davis Square in Somerville) formed an organization, Merchants On The Line (MOTL). This organization was formed out of their apprehension and concerns that heavy construction activity in immediate proximity to their business establishments could adversely affect their businesses. Through a series of meetings with representatives of the Development Office and the Cambridge Chamber of Commerce, MOTL sought financial support from the MBTA for a business stimulation program to attract customers to construction areas during the Extension's active construction phase.

The Development Office first responded by providing funding and staff time for a trial promotion that featured media advertising, discount coupons, and signage and entertainment activities in construction areas between Harvard and Porter Squares. As the result of the apparent success of this promotion, and justification by MOTL that a more comprehensive effort was needed, the MBTA Board of Directors voted for the execution of a $100,000 contract with a public relations firm to handle the business stimulation program on an on-going basis.

In concert with MOTL and other representatives from the MBTA, the Development Office selected a public relations firm to perform a wide variety of tasks that encompassed the development and implementation of several large promotions, surveys to determine the nature and degree of construction impact on certain areas, and the development of programs to assist in Red Line Northwest alignment.

The resulting promotions and activities were considered successful by members of MOTL, although a conclusive determination whether the program did increase or otherwise affect business activity in the impacted areas may not be measurable. The program, however, did ensure the establishment of a positive working relationship between the MBTA and the business community along the Northwest Extension, as well as offering additional community service programs to the general public. Among these programs was a Vision Testing Program that provided free eye examinations for the public through a mobile unit that was located in four Northwest Extension retail areas.

Most issues and complaints relating to the Red Line Northwest Extension were addressed and, in a majority of cases, resolved through discussions and agreements between representatives of the MBTA, city governments and citizen/business groups. Many of these efforts at reasonable compromise prevented further litigation and public displays of protest, although all incidents of discontent could not be avoided.

The major incidence of citizen opposition concerned a Cambridge community group that adopted the name Red Line Alert. This group filed a suit in 1979 seeking to stop construction of the extension until a revised EIS could be completed. Red Line Alert charged that the original EIS did not indicate that blasting would be used as a construction method for the Harvard Square to Porter Square tunnel segment. The group averred that the EIS covered only the employment of soft ground tunneling methods. The suit was ultimately heard in the Federal District Court in Boston and ruled in favor of the MBTA. The suit was dismissed on the grounds that the MBTA had taken adequate safeguards to inform the public, mainly through the Public Blasting Information and Assistance Program, of the construction methods to be used along the extension.

One widely acclaimed aspect of the MBTA Red Line Northwest Extension community participation effort was the Arts On The Line Program. Following the establishment in 1977 of a U.S. Department of Transportation policy encouraging the use of funds for the inclusion of art in public transportation systems, the MBTA was awarded a grant to determine an appropriate role for the incorporation of permanent artworks into the new Red Line Northwest Extension stations. The MBTA then executed an agreement with the Cambridge Arts Council to implement this project. The MBTA committed one-half of one percent of each of its station's construction budget to the project, totaling $695,000 for all four new stations. The Cambridge Arts Council raised an additional $70,000 from the National Endowment for the Arts to supplement the art allowances.

The Cambridge Arts Council, after many months of research, developed a nationally replicated artist selection procedure and policy for incorporating artworks into transit stations. The artist selection process featured the participation of community members from each of the four communities surrounding each station. An Arts Committee was established for each station, consisting of an Advisory Group and an Arts Panel. The Advisory Group was made up of residents, businesspeople, city planning representatives, members of the city's historical commission, and representatives of the station's architect and the MBTA. The group's role was to furnish advice and information to the Arts Panel that consisted of artists, curators and/or historians and that had the responsibility of selecting the artworks. The purpose of having the two groups — one representing the community and the other, arts professionals — was to ensure that the artworks selected would best represent the community surrounding each station as well as being of the highest quality.

Community participation and public information also were the goals of a series of temporary arts programs that were part of the Arts On The Line Program. Working in close cooperation with the Development Office, the Cambridge Arts Council provided ample opportunities for children and adults in Extension communities to learn about the construction techniques being used for the extension. One of these efforts was the creation of a series of Construction Display Panels that highlighted the construction and the future of the new stations and tunnels. These four by eight foot, plexiglas-covered panels featured graphics and text describing construction techniques, such as the extensive use of slurry walls in the construction of the Red Line Northwest Extension.

Overall, the community assistance and participation program for the Red Line Northwest Extension demonstrated the success of public participation in the planning, design and construction of a major transportation project. Although this success may not be readily quantified, the attendance and comments of many members of the community at opening ceremonies for the extension's new stations in 1983 and 1984 reflected a sense of community involvement and pride. This sense of pride was even more evident when hundreds of residents, businesspeople, and representatives from the cities of Cambridge and Somerville attended the Celebration and Arts Dedication ceremony held for the Red Line Northwest Extension in May, 1985. Not of little importance, there were no significant delays in the planning, design and construction of this project caused by overt protest or litigation, and the resulting project was best suited to meet the needs of those who would use it.

Southwest Corridor Project

Unlike the Red Line Northwest Extension, the 4.7-mile Southwest Corridor Project is being constructed entirely by the cut-and-cover method of construction in a depressed railroad right-of-way (Penn Central Shoreline) and adjacent land that was cleared for the construction of an interstate highway (I-95 South) during the 1960s. The project extends from downtown Boston in the north through Roxbury to the Forest Hills area of Boston's Jamaica Plain community (see Figure 5). Considered to be the largest single construction project in the history of the city of Boston, the Southwest Corridor Project encompasses an area in which one-quarter of the population of Boston resides, and links downtown Boston with seven of its neighborhoods.

The transportation elements of the project include the relocation of the MBTA's Orange Line rapid transit service into the railroad right-of-way from the present elevated structure along Washington Street in Roxbury and Jamaica Plain. The current elevated structure of the Orange Line was constructed in the early 1900s and is presently in a deteriorated condition. Demolition of the elevated structure is scheduled to follow the completion and opening of the new Orange Line along the Southwest Corridor.

Three railroad tracks that will service MBTA Commuter Rail and Amtrak are also being placed in the right-of-way. Nine new rapid transit stations are planned for the Corridor; three of these stations will also serve as railroad stations. The project also includes the construction or reconstruction of 21 bridges, some of which are major street bridges over the Corridor, and a comprehensive street improvement and reconstruction program in all Southwest Corridor communities.

One particular feature of the Project is the construction of a 50-acre parkland that will be located on the deck over and alongside the Corridor from the Back Bay/South End area of Boston to the neighborhood of Forest Hills. The parkland will be a significant addition to Boston's park system, linking the series of parks created by Frederick Law Olmsted nearly a century ago and known as the Emerald Necklace. This parkland will include a variety of recreational facilities, as well as bicycle and pedestrian paths.

Possibly the most significant aspect of the Southwest Corridor Project plan is the proposed development of land parcels along

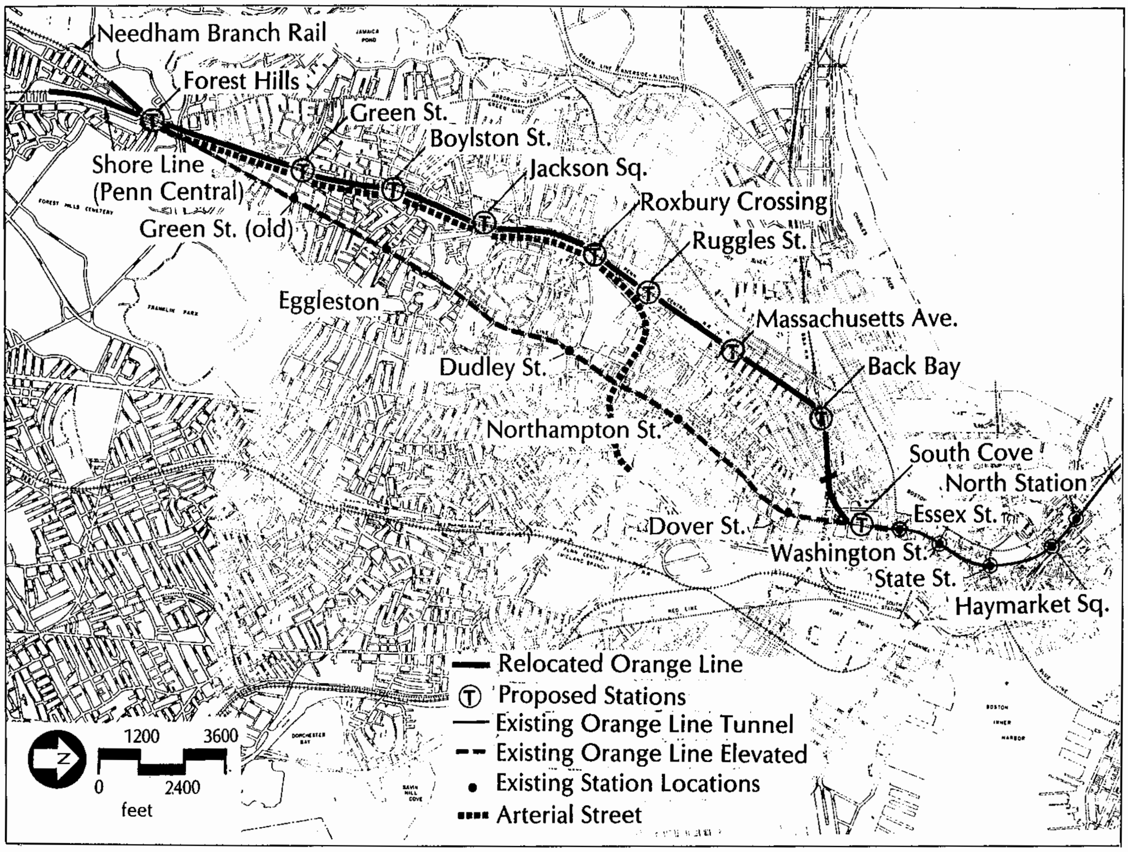

FIGURE 5. The route of the Southwest Corridor for the relocation of the Orange Line rapid transit system.

the Corridor that were cleared for I-95 South, but are not required as part of the transportation improvements. This land includes numerous major parcels that are expected, when developed, to produce an estimated $30 million in annual tax revenue to the city and to provide an additional incentive for the revitalization of many Southwest Corridor neighborhoods.

Like the Red Line Northwest Extension, the Southwest Corridor Project has been highlighted by the cooperative efforts between the MBTA and various city, institutional, community and business organizations and agencies to address and resolve planning, design and construction issues. However, the communities of the Southwest Corridor Project were more enthusiastic in welcoming a transportation plan for their areas than their counterparts in Cambridge, Somerville and Arlington. The Southwest Corridor Project also had the advantage that they were dealing with only one municipal government, that of Boston, instead of three, and that the majority of the construction would not actively take place beneath residences or businesses.

The concept of the Southwest Corridor was a direct response to a proposed highway plan that already had resulted in massive landtakings for the highway construction. The project plan offered a viable alternative to the feared land devastation and negative impact that citizens of neighborhoods along the highway's route saw as the future of the construction of I-95 South. Community and neighborhood groups turned their protest against the highway into active support for the Southwest Corridor concept. Furthermore, they sought to take a participatory role in the formulation and implementation of a plan to ensure that the resulting planning, design and construction would be an open public

Chronology of the Southwest Corridor Project

1948 - 1970 A statewide Master Highway Plan is introduced and implemented by the state Dept. of Public Works and funded by Congress. The plan includes the construction of an eight-lane-wide highway connecting to I-95 South through Boston's Roxbury and Jamaica Plain neighborhoods. Land is cleared for highway construction.

1970 - 1972 Governor Sargent declares a moratorium on highway construction within the Rte. 128 area and establishes the Boston Transportation Planning Review to reevaluate transportation plans for the Boston metropolitan area. The Governor cancels plans for the I-95 extension as a result of the studies.

1973 The Governor appoints a Southwest Corridor Coordinator and establishes a Southwest Corridor Project Office. The Coordinator unites neighborhood and community groups in planning for the Southwest Corridor Project. Congress passes the Federal Interstate Highway Act, enabling the transfer of funds previously earmarked for highway construction to mass transit projects.

1974 Representatives of state, local and federal agencies, neighborhood organizations and community groups sign the Southwest Corridor Memorandum of Agreement, formalizing and guaranteeing participation by the community in the planning and development of the project plan.

1976 - 1978 Environmental studies and hearings are conducted for the project and involve many individuals and groups from communities within the project area. The final Environmental Impact Statement is published following this community involvement process.

1977 Project design and engineering begins and continues. A formalized community participation process is developed and implemented.

1978 Urban Mass Transportation Administration formally announces a $680 million capital grant for the project.

1979 Preliminary contracts for excavation, demolition and utility relocation for project construction awarded and begun.

1981 - 1982 An unexpected shortfall of federal funding results in the Southwest Corridor Project Cost Reduction Effort. The Southwest Corridor Coordination Office is established and conducts community meetings in an effort to redefine project design and costs. Several major construction contracts are awarded that contribute to a favorable resolution of cost reduction issues.

1986 System testing of the new transit and railroad lines is scheduled.

1987 Projected opening of the new relocated Orange Line and commuter rail service.

1987 - 1988 Demolition of the old elevated Orange Line.

process and that the project would have their best interests and desires in mind.

This citizen involvement in the Southwest Corridor Project dates back to the 1960s when residents and groups organized demonstrations and various other forms of public protest in opposition to the demolition in their neighborhoods for the planned construction of I-95 South. Community groups joined together to form the Coalition to Stop I-95.

During the early 1970s, a number of events, highlighted by considerable participation by community representatives, resulted in the cancellation of the highway plan in favor of a transportation plan that featured rapid transit and railroad improvements, as well as an improved local and arterial street system. By executive order, Governor Francis Sargent in 1970 stopped construction of the highway and began a reevaluation of transportation plans for the Boston metropolitan region, including the Southwest Corridor. Many public hearings were conducted by the Boston Transportation Planning Review. The resulting recommendations led to the Governor's decision in 1972 to support the transit/railroad plan. The subsequent appointment of a Southwest Corridor Development Coordinator by the Governor, with the concurrence of the Mayor of Boston, in 1973 further served to unite groups and public agencies in the development of the Corridor plan. As had happened with the Northwest Extension, the Corridor project received its primary boost in 1973 when Congress responded to nationwide resistance to highway construction by passing the Federal Highway Act, authorizing urban areas to transfer highway funds to other transportation projects. Governor Michael S. Dukakis formally canceled the I-95 highway plan in 1975 and funds were transferred to the Southwest Corridor Project.

One important event in the history of community participation in the Southwest Corridor Project was the signing in 1974 of a "Memorandum of Agreement" by the MBTA and other state, local and federal agencies, as well as representatives of community groups and neighborhood organizations. This agreement represented a solid commitment to community participation in the planning, design and construction of the project, requiring ten percent of the planning and five percent of the basic design contracts be designated for community participation and related technical assistance. The agreement further assured that complete, comprehensive and cooperative planning among agencies and community representatives would continue throughout the development and implementation of the Southwest Corridor plan.

This commitment to community participation set the tone for the project's environmental review period from 1976 to 1978. The Southwest Corridor Development Coordinator and Project Office conducted numerous corridor-wide public meetings and legally required public hearings to discuss a broad range of issues relating to the project during the preparation of the project's Environmental Impact Statement. A Southwest Corridor Project Working Committee was established to discuss corridor-wide issues. Individual neighborhood committees were also formed to deal with specific neighborhood-related issues. A number of decisions were made during this period, among them right-of-way alignment, and the location of tracks and station sites.

As the project moved into its engineering and design stage, a formalized structure for community participation began to take shape. Different community groups, many of whom were part of the Coalition to Stop I-95, formed the Southwest Corridor Coalition, and played an integral role in assisting the MBTA's Southwest Corridor Project Office in selecting consultants for design and engineering.

These consultants included more than thirty firms, each with expertise in the various disciplines required to provide the Southwest Corridor Project with engineering, station architecture, traffic analysis, landscape architecture, land development planning and community participation coordination. Five consultants were selected to coordinate activities among the consultants.

In 1977, the structured process for project community participation was delineated by the community liaison consultant and the various committees and task forces. They began meeting to discuss and make recommendations to the MBTA and its consultants on a variety of planning and design issues.

An important component of this process was the assignment of three Section Planners (the project was broken down into three sections — Section I, Back Bay/South End of Boston; Section II, Roxbury; and Section III, Jamaica Plain) to serve as the primary contact between the project and each of the communities in each section. These individuals were, and continue to be, responsible for coordinating all community participation activities in conjunction with the MBTA's appropriate Project Office. Their responsibilities include developing and scheduling meetings, maintaining mailing lists, meeting informally with representatives of the community and businesspeople, and providing liaison services within their section whenever necessary. As the project moved into its construction phase, these Section Planners became responsible for furnishing construction activity information to the community, and receiving complaints relating to construction activity and informing the appropriate MBTA Coordination staff about these complaints. The Section Planners also play an important role in the coordination of meetings and the dissemination of information about the Corridor Land Development Process.

The various groups and task forces that comprise the Southwest Corridor Project's Community Participation Organization structure are:

- the Project Working Committee, which serves as a forum for the discussion of issues relating to the entire Corridor
- three Neighborhood Committees, one for each section, that provide section-wide review and discussion of design and construction issues relating to the section as well as some discussion of system-wide issues
- eight Station Area Task Forces, one for each station with the exception of the South Cove Station, that review station design and issues affecting the areas around each station, including landscape, parkland design and land development

Additional groups were formed during the project's construction phase:

- three Construction Task Forces, one for each section, to address complaints directly to the contractors' representatives who were required to be in attendance, and to discuss various issues relating to construction activity in each section
- a Parkland Management Advisory Committee, to review and receive citizen comments on issues relating to the Southwest Corridor Parkland Management process.

By late 1977, many of these groups were meeting frequently and working in close cooperation with representatives of the MBTA's Project Design staff, and engineering and architectural consultants. These groups made recommendations that were adopted as part of the Project's design. Their influence at the design stage ranged from system-wide items such as overall provisions for security in Corridor stations to section-wide issues such as the location and design of ventilation stacks, street alignments and tunnel decks, etc., to specific station design issues. An important part of the community participation process during the design period concerned Corridor parkland issues. Recognition of the needs and desires of residents and community groups as to what would be or not be part of the parkland areas at each station and neighborhood area were considered by MBTA project staff to be essential to the success of the parkland design.

Through planning, design and construction phases, the MBTA and its consultants offered an array of public information materials and implemented public awareness programs to foster participation. Among the published materials was *The Southwest Corridor News,* a tabloid format newsletter with a circulation of 12,000. *The Southwest Corridor News* continues to be distributed on an ongoing basis. Public notices and especially-written, illustrated explanations of station design processes, termed *SATF Notebooks,* were distributed to provide even more comprehensive project schedules and related information.

An important community involvement effort, the Southwest Corridor Educational Training Program, created opportunities for young residents (ages 16-21) of corridor communities to receive training in engineering, architecture, landscape architecture and planning. A total of 132 students received classroom instruction and placement with engineering and architectural firms through the program between 1978 and 1982. Considered a highlight of the project's community outreach efforts, a current version of the program is being offered to a group of approximately 20 students on a one-year basis, with funding provided by the Urban Mass Transportation Administration (UMTA).

Construction of the project commenced in 1979 and increased the requirements for public information efforts and community participation activities. These requirements became even more important in 1981, when the MBTA was advised by UMTA that no additional funds would be made available for the project budget beyond the $783 million that had already been committed and approved. An $81 million shortfall had been projected by the MBTA at that time.

The MBTA responded by establishing the Southwest Corridor Coordination Office team and immediately began identifying design changes that represented potential cost-saving reductions. The Coordination team was similar to, and composed of many of the same individuals in, the Red Line Northwest Extension Development Office. The Southwest Corridor Coordination Office was given the responsibilities of coordinating activities and scheduling community meetings that were necessary for the presentation of proposed cost reduction candidates in line and station contracts to the communities, and responsibility for developing a consensus satisfactory to all involved.

The project cost savings study began in late 1981 and continued through the spring of 1982 when it was finally determined that as a direct result of an extremely favorable bid climate, bids lower than anticipated were received on three sizable construction contracts. Based on this fortunate occurrence, it was determined that the Southwest Corridor project could be built within budget and substantially in conformance with the original design with minor exceptions.

However, in order to achieve this positive outcome, the process required a large-scale cooperative effort between representatives of the MBTA Coordination Office and the Southwest Corridor Project Office, MBTA consultants, and many members of the various community task forces and organizations. A corridor-wide meeting held in Roxbury in late 1981 attracted more than 200 people who expressed anger over the announced anticipated shortfall. Other neighborhood and station area task force meetings were also heavily attended by community residents and officials who strongly opposed any cutbacks in their neighborhood station's design.

Although the process resulted in minor changes to most of the design plans, such as station finishes for the Back Bay and Ruggles Street stations, the outcome for the Forest Hills station in Jamaica Plain required a drastic station redesign. However, this redesign was not entirely due to the cost reduction process.

A community of very active political forces with strong opposition to the proposed highway plan, the residents of Jamaica Plain were always, and continue to be, heavily involved, and community meetings in Jamaica Plain have always attracted substantial attendance. This section in Jamaica Plain was the focus of considerable community activity during the cost reduction process. At the Forest Hills Station Area Task Force meetings about cost reductions, opponents — including influential community political figures — of a proposed parking garage in the original design produced strong arguments that commuters from outside of the Forest Hills area would benefit most if the garage were constructed. In the end, they were successful in persuading the community to abandon plans for the parking garage. The resulting design modification also had a positive effect on the MBTA's overall success in reducing the cost of the project.

The Southwest Corridor Coordination Office remained active beyond the cost reduction process, assuming many of the responsibilities related to construction support and monitoring. Among its assigned tasks were:

- to respond to all citizen, business, and city, state and federal agency complaints or requests for information or assistance;
- to monitor and measure noise, vibration and dust levels for all project construction contracts;
- to investigate and respond to all public complaints of contract violations or deviations by project contractors;
- to monitor changes and adjustments in designs or contracts that might have an impact on communities;
- to assume direction of the activities of the three Section Planners;
- to monitor the project's Hotline calls;
- to schedule and conduct all community meetings and related activities;
- to serve as the project public information contact, responsible for producing *The Southwest Corridor News,* press releases and other public notices; and,
- to establish, manage and coordinate the Southwest Corridor Damage Review Process for all construction contracts.

The Damage Review Process was introduced in the Southwest Corridor when construction activity in Boston's densely populated Back Bay/South End area resulted in allegations of property damage and complaints from property owners that claims were being ignored or unduly delayed by contractors and their insurers.

The Corridor review process was very similar to that of the Northwest Extension project. Following the submittal of extensive justification for the request for the review process by the Southwest Corridor Coordination Office, approval was granted by the MBTA and funds were released for the Southwest Corridor Project Damage Review Process. An engineering consultant was selected and retained, and an experienced and qualified Damage Review team was recruited to evaluate claims.

As of the beginning of October, 1985, almost 100 claims have been addressed by the process, and determinations have been made and settlement offers rendered to many of those property owners. As in the Northwest project, the most significant result of this process has been greater community credibility of the MBTA, improved community relations and an expedited method for resolving allegations of property damage.

Active participation has continued throughout the project construction. The Coordination Office staff maintains a close working relationship with citizens and community groups. Construction task force meetings are held regularly in each section in order to provide public arenas for the discussion of issues and resolution of complaints relating to construction activity. In some cases, residents in corridor neighborhoods have raised questions and requested additional design changes. Some adjustments in street design have been made as a result of this participation. In other cases, public meetings were held to consider such proposed changes only to result in the design remaining substantially the same.

As the progress of construction moves toward completion, citizen and community group participation continues and, indeed, expands its issues. The project is beginning to open to community participation the process for the development of land parcels along the corridor. Dating back to the early planning process for the project in the 1970s, a plan for potential uses of the land along the corridor cleared for I-95 was developed and recommendations were made. Potential uses for the available land parcels were described in an MBTA brochure, *The Southwest Corridor Development Plan,* in 1979. This brochure was widely distributed and presented the guidelines and criteria for future implementation of the plan.

After having completed the planning steps required for the implementation of the development process, the MBTA has been holding neighborhood public meetings to elicit response to the plan. Developers' kits for the larger parcels of land are being prepared, and the details of the plan for the use of retail space in new Corridor stations are being finalized. The implementation of the development process during the next few years will present opportunities for citizens and community groups to take an active role in determining the characteristics of their neighborhoods.

Community participation also has been, and will continue to be, critical to the acceptance of a plan to offer replacement service for the neighborhoods immediately adjacent to the existing elevated Orange Line structure between the MBTA's Dudley and South Cove Stations in downtown Boston. Following the completion of the project and the opening of the new Orange Line, the old elevated structure along Washington Street will be removed, leaving a transportation service gap for the neighborhoods in that immediate area. As required by the project's EIS, a Replacement Transit Improvement Study has been underway since 1977, and has identified a variety of service alternatives such as light rail, trolleys and buses. Representatives of public agencies and the affected communities have participated in the study and planning process since its inception through a series of informational meetings, including Project Working Committee, Zone, Neighborhood and Project Coordinating meetings. These meetings will eventually focus on developing a community consensus on service alternatives.

Citizens and neighborhood groups of the Southwest Corridor Project will also continue to be involved in the project as the MBTA prepares for the opening of the new Orange Line. Construction of the new parkland areas, in particular, will be the focus of planned community meetings. Future meetings will also discuss the testing of the new rail lines and the need for community attention to, and involvement in, safety issues during testing.

Southwest Corridor communities, through neighborhood crime watch groups, are being asked to cooperate with the MBTA for the protection and security of the newly-constructed facilities in an effort to reduce vandalism and damage. A variety of activities, although presently in the initial planning stages, are being considered so that as many members of the community as possible will be involved in the opening of the new Southwest Corridor Project Orange Line transit service and stations in 1987.

Benefits

The two projects provided a variety of short-term benefits in addition to the permanent long-term assets of improved public transportation, associated development opportunities and a climate of sound working methods with the public and public credibility. More than 2,000 construction and 40,000 service vendor related jobs were created through the Red Line Northwest Extension's 33 construction contracts. The Southwest Corridor Project, through its 44 construction contracts, has been projected to create approximately 37,000 construction and construction-related jobs.

Despite the immediate and lasting benefits of the projects, the increased attention and demands by citizen and community groups in public works construction programs required extensive community relations efforts by the MBTA and other state and federal agencies that performed key functions in the planning of the projects. Representatives of the various agencies were required to be well prepared and to furnish public opportunities for citizens, community groups and municipal agencies to comment on proposals, and, in some cases, to respond to opposition of proposed plans.

Summary

For both projects, public participation programs have consisted of a planned format for informational, issue-oriented and complaint (related to construction activity) meetings; traditional public information items including press releases, newsletters and public notices; and standard methods of addressing requests for information, concerns and complaints through correspondence and telephone conversations. Each of the projects also had 24-hour hotlines available, with the hotline number widely publicized, for matters of immediate concern.

These programs were provided by the MBTA through engineering and public relations consultants. In addition, an MBTA Construction Community Relations Team was assigned to each project to monitor construction activity and attempt to resolve any issues or complaints relating to construction as promptly and efficiently as possible. These MBTA teams, the Red Line Northwest Extension Development Office and the Southwest Corridor Project Coordination Office, were unique in terms of MBTA history. For the first time, the MBTA supplied full-time and experienced staff, which in cooperation with the MBTA Project Design and Construction Office staffs and consultants, had direct responsibility to address issues affecting the communities in areas impacted by project construction on a daily basis.

These teams coordinated and directed most of the consultants' public relations activities, and supplied the resources for the development of resolutions of design and construction issues and crises. Many of these issues were unforeseen during the projects' planning period. Some of these issues included public anxiety and concern over the utilization of blasting in Red Line Northwest construction; access to, and stimulation of, businesses in heavily-impacted construction areas for both projects; traffic detours and transit service changes in Southwest Corridor construction activity; a project-wide cost savings effort for the Southwest Corridor Project; and resolution of alleged property damage due to contractors' construction activity in both projects.

Although there are historic, geographic, demographic and economic factors as well as design and construction methods that differ between the two projects, they do share a common feature of being shaped and implemented through public participation. The MBTA, by supplying opportunities to the communities in its construction project areas, has been successful in balancing community needs with its own goal of project schedule adherence within allocated budgets.

Recommendations

The citizens of metropolitan Boston have exercised public influence to a remarkable degree and played an important role in the shaping and construction of these two large public works projects. Through their participation and active involvement, they have gained new and improved public transportation services that not only serve their needs, but also represent a real and enduring source of community pride.

However, a critical point should be remembered in the planning, design and construction of any public works project. Namely that it is a *public* works project — a project built by a public institution to meet current and future public needs. A key part of the success of a public works project is that it meets public needs, and in order to meet those needs and define concerns, it is vital that the public participate in the project and be well informed of its course. Built on the experience of the MBTA in the Northwest Extension and Southwest Corridor, some basic recommendations for any public participation program can be made:

1. Attend to all federal, state and local requirements for public participation, hearings and information.
2. Plan for public participation in all phases of the project, almost from the conception of the project and on.
3. Develop formal means beyond minimum legal requirements for public participation in all phases through an office with trained staff to coordinate public participation efforts.
4. Ensure that the community, the public agency and its consultants know how the varying means of participation, and its hierarchy, if any, work and that these means are accessible.
5. Develop a timely and regular informational program detailing all phases of the project, their effects and means of participation and redress.
6. Maintain the flexibility to analyze and react to current situations that might require greater public participation (for example, more public outcry for a greater role in decision-making), that might require a greater amount of information, or that might require additional programs or changes in existing ones.

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Controlling the Wind Climate Around Buildings

The wind environment may affect buildings and their surroundings. Engineers and architects must bear in mind that the wind influences both operating costs for buildings and the environmental quality of built areas.

EDWARD ARENS & JON PETERKA

IN DESIGNING BUILDINGS, civil engineers and architects should be aware of environmental wind effects and their control. A knowledge of the causes of wind, influences of topography and ground cover on local wind, and principal features of airflow around buildings is recommended. Designers should study windspeed distributions in the climatological record and use such knowledge to estimate the eventual windfield in the built environment. In this way they may ensure optimum living conditions in the area outside the building and optimum efficiency in operating the building.

Wind: Its Causes and Nature

The sun heats the earth unequally, generating pressure gradients that drive global, or synoptic, wind circulation. The pattern of wind circulation changes as the sun moves north and south with the seasons, and is affected by the position of mountain ranges and large bodies of water on the earth's surface. Temperate regions experience a number of typical wind patterns at any location during a season. These patterns are caused as air masses of different origin — such as maritime, continental, tropical or polar — are drawn over the region. The air masses and fronts that separate them will frequently incorporate such local wind phenomena as thunderstorms or tornadoes. The wind climate of a region may be predicted in terms of the probabilities with which these typical wind patterns occur. For example, average windspeeds in the continental United States tend to be stronger in the colder seasons when the frontal zone separating temperate and polar air masses moves southward from the Arctic.

In addition to synoptic winds caused by large scale weather patterns, there are predictable *local winds* that are produced by the particular features of a given terrain. In many coastal areas, the differential heating of land and water causes sea and land breezes. Figure 1 shows the pressure distribution and flow that cause daytime sea and night land breezes. The sea breeze tends to move inshore around midday as the land warms and causes the air above it to expand.

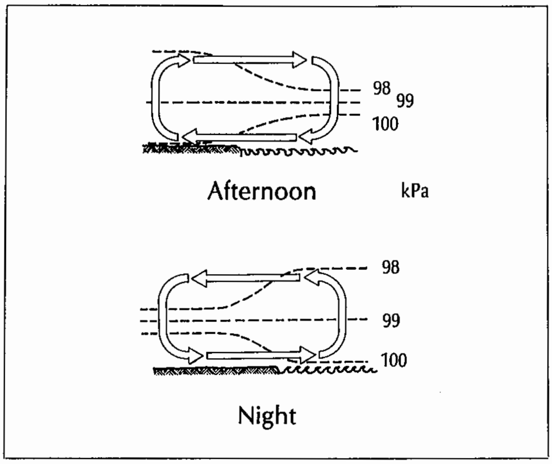

FIGURE 1. The pressure distribution and flow of daytime sea and nighttime land breezes.

Frictional resistance of the earth's surface often forces the incoming sea air to dam up. The air flow then forms a small scale front that progresses inland throughout the afternoon. In places where the temperature difference between land and water is small, the sea breeze layer will be shallow and wind velocities will be weak. Tall buildings along a waterfront can block such a breeze entirely. On the other hand, when the sea and land temperature difference is great, the sea breeze layer will be deeper and velocities much stronger. The San Francisco sea breeze is over 200 m deep, predictably exceeding 10 m/sec in the city throughout summer afternoons, and extending inland 60 km. At night this wind flow is reversed, but velocities seldom exceed 2 m/sec.

The radiant heating or cooling of inclined surfaces causes *slope winds*, another form of local wind. Such radiant heating and cooling produces temperature differences between the air above the slope surface and air at the same level some distance from the slope. Heated air will rise from the surface of hillsides during the day and cooled air will descend, or drain down, at night (see Figure 2). Daytime measurements on slopes surrounding the Inn Valley, Austria, found upward velocities parallel to the slope at 2-4 m/sec; at night there were somewhat lower downward velocities. Wind layer depth was 100-200 m.[1]

When slopes are arranged into a valley system, a combination of slope winds and temperature differences between the valley and the plain can form *valley winds*. These winds are generally stronger than slope winds; their wind velocities can reach up to 5 m/sec. The strongest valley winds are most commonly found in U-shaped valleys that are lined by high ridges. These valleys also open onto a broad plain that is considerably warmer or cooler than the head of the valley. Orientation of valleys with respect to the sun also affects wind velocity. Valleys that have a north-south orientation tend to have stronger daytime breezes due to their increased exposure to the sun.

Wind Over the Earth's Surface

The wind flowing along large-scale pressure gradients above the frictional influences of the earth's surface is known as *gradient wind*. At the lowest layers next to the surface, the gradient wind velocity is zero. The zone of velocity change from zero at the bottom to gradient wind velocity at the top is known as the earth's boundary layer. The depth of the boundary layer and the shape of the velocity

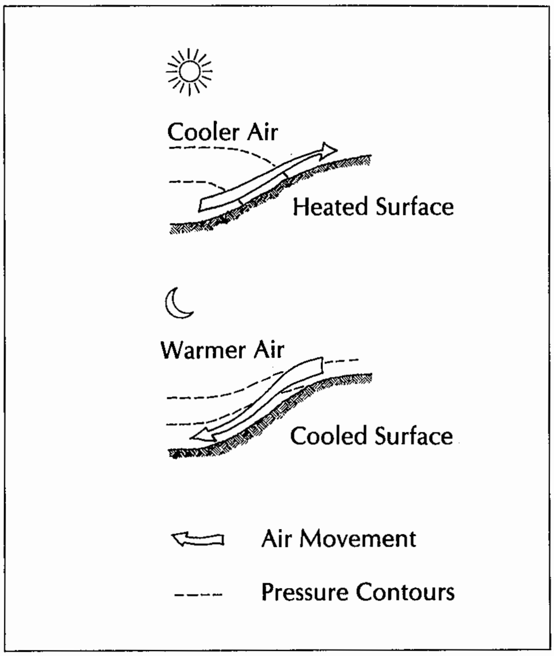

FIGURE 2. Daytime and nighttime flow of slope winds.

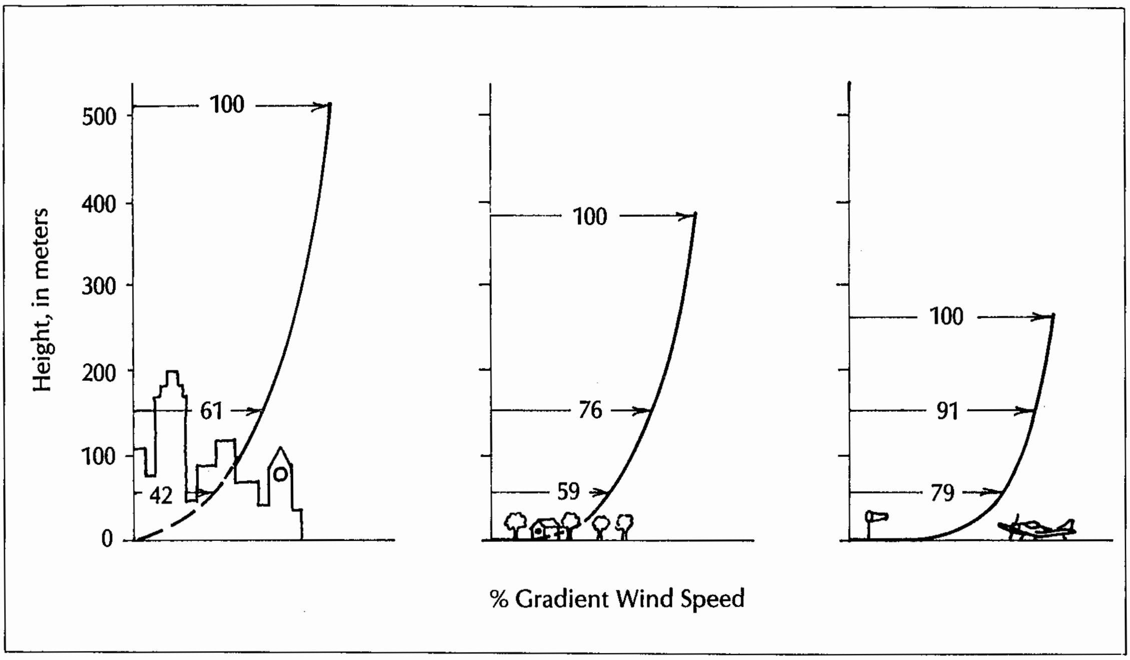

FIGURE 3. Boundary layers for neutral stability conditions from rough to smooth terrains.

profile within it depend on the roughness of the earth's terrain, and on the thermal stability of the atmosphere.

Figure 3 shows three boundary layers for neutral stability (strong wind) conditions. A rough urban surface causes a deeper boundary layer and lower velocity values at any given level within the boundary layer. In smooth terrain, such as at airport weather stations, the wind velocity at the standard anemometer height of 30 feet (10 m) is greater than in rougher terrains. This measured wind is also greater than the wind at pedestrian level at ground level in any terrain.

The profiles of these curves are commonly described as either logarithmic or exponential. In the region of constant shear, typically 100 to 300 m above the top of the roughness, the logarithmic law is correct:

$$U_z = \frac{U_*}{0.4} \log\left(\frac{z}{z_o}\right) \tag{1}$$

where U_z is the velocity at height z; U_* is the friction velocity (a measure of shear); and z_o is the roughness length (a measure of the roughness size). z_o is constant for a given terrain, and U_* is constant across any given profile. Typical values of z_o are given in Table 1 on the next page.[2]

In structural engineering the boundary layer up to the gradient height is often approximated with a power law with a constant exponent α. The relationship between the velocities at any two heights in the boundary layer is given by:

$$\frac{U_{z1}}{U_{z2}} = \left(\frac{z_1}{z_2}\right)^{\alpha} \tag{2}$$

Values of α are also given in Table 1. Both representations of the mean velocity profile are commonly used by meteorologists, engineers and architects.

There are five different terrain categories — I = open water; II = open rural terrain; III = suburbs at considerable distance from towns with widely spaced buildings; IV = towns, densely built-up suburbs, rough or wooded terrain; and, V = centers of large cities — that are shown in Table 1. The boundary layer profiles predicted for these terrain categories will apply only if there is sufficient upwind distance of the terrain type for the develop-

TABLE 1

Surface Roughness Lengths & Power Law Exponents for Various Categories of Terrain

Terrain Category	Open Water I	Open Terrain II	Suburbs III	Towns IV	City Center V
z_o, in meters	0.005	0.07	0.30	1.00	2.50
α	0.10	0.14	0.20	0.25	0.35

ment of the particular boundary layer. The boundary layer above any local terrain will extend upward for a height approximately one percent of the distance to a change of terrain roughness upwind. Above that, there may be a remnant of the boundary layer persisting from the more distant terrain roughness type.[2]

These profiles apply to neutral atmospheres, such as those that occur during strong winds and during periods when the surface is not strongly heating or cooling the atmosphere. During strong heating from below, as for example on a sunny day with light winds, the atmosphere becomes unstable, bringing the gradient wind momentum downward. As a result, the surface wind will be stronger than it would be for a neutral atmosphere with the same gradient wind. Conversely, during night cooling of the ground and lower layers of air, the atmosphere becomes stable, and surface winds will be lower for a given wind than they would be in neutral or unstable atmospheres. This results in a predictable variation in daily wind speeds. Figure 4 gives a typical example of the daily course of wind over flat terrain.[1] Note that the wind at 70 m (210 feet) decreases somewhat in the morning as its momentum is absorbed in accelerating the lower layers of air.

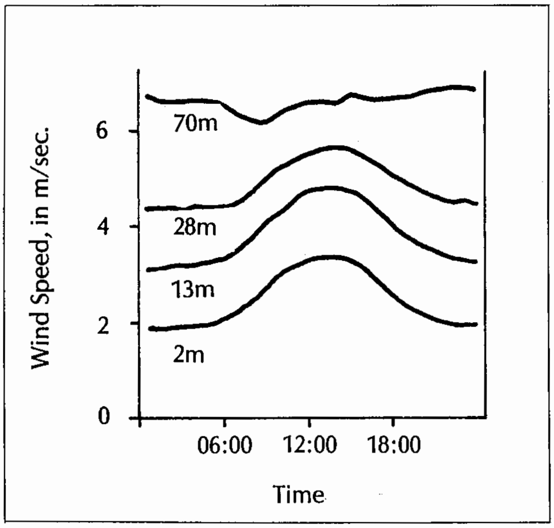

FIGURE 4. Typical daily course of wind over flat terrain.

Local topography has a pronounced effect on surface winds. Wind flow conforms to terrain, changing its strength, steadiness and direction as it passes over uneven ground. Figure 5 shows the velocity profiles of wind approaching a hill or ridge, at the crest and on its leeward side. There is strong wind acceleration near the surface at the top

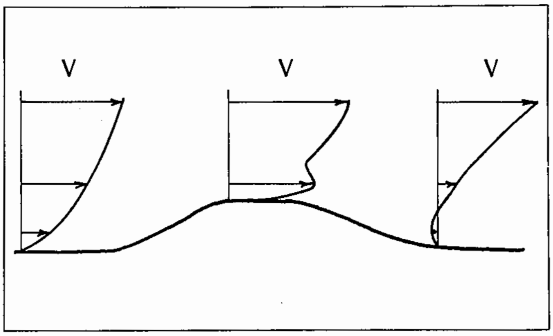

FIGURE 5. Wind velocity profiles to windward, on top of and to leeward of a hill or ridge.

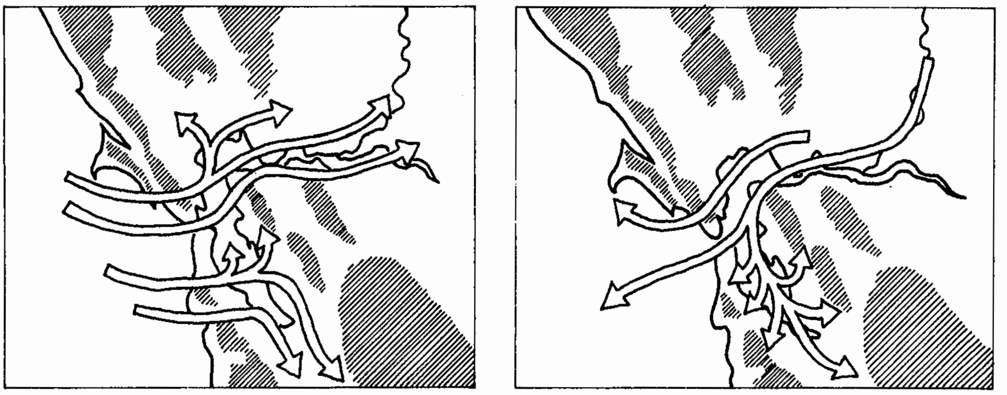

FIGURE 6. Typical surface wind flow patterns in the San Francisco Bay region.

of the hill, and also a wind flow reversal due to an eddy at low levels along the leeward side. The wind acceleration on the windward side of hills and ridges is fairly predictable, but the extent of shelter in the lee is highly variable, depending on the roughness of the hill and the stability of the atmosphere.

In addition, wind may be extensively channeled by regional topography. Figure 6 shows two typical wind flow patterns identified in the San Francisco Bay area.[3] High ground is noted in grey. Local areas of wind turning in excess of 90° to the gradient wind may be noted. This type of channeling occurs primarily when the atmosphere is stable, and the flows depicted extend upward roughly to the height of the surrounding terrain. Similar flow turning and channeling has been observed in street canyons.

Tall vegetation may reduce ground level wind substantially. Trees are very effective at absorbing wind energy rather than deflecting it (as do solid obstructions such as terrain and buildings). Two major categories of wind-reducing vegetation are a surrounding forest and an isolated windbreak. The effects of both of these forms of wind reduction have been studied extensively by agricultural and forestry researchers. Within a forest, the velocity is minimal near the center of mass of the foliage in the crown (approximately 0.75 times the height); in the absence of underbrush there is a small velocity increase among the tree stems. The shape of the wind profile in the forest is contingent on the type of the trees in the forest, their spacing and openings in the crown, and the distance from the edge of the stand from which ground level wind can penetrate. Figure 7(a) compares wind velocity profiles in a ponderosa pine stand to those profiles in the open,[4] and 7(b) shows the influence of foliage from seasonal wind measurements in a deciduous oak-beech forest.[1]

Figure 8(a) shows a cross section of the airflow near a screen of 50% porosity. Figure 8(b) shows the effect of varying porosity in shelter at ground level downwind.[1] A medium porosity of 40 to 50% has been found to provide the maximum distance of wind-sheltered area. A solid barrier will provide a greater wind reduction over a very limited distance downwind of the barrier, but beyond this distance (roughly three heights) it has less effect than screens of either open or medium porosity.

Additional belts downwind of each other have been found to have a slightly decreasing effect, presumably due to the increased turbulence in the lee of the first belts. Similarly, the sheltered zone leeward of a wide shelterbelt or forest is less extensive

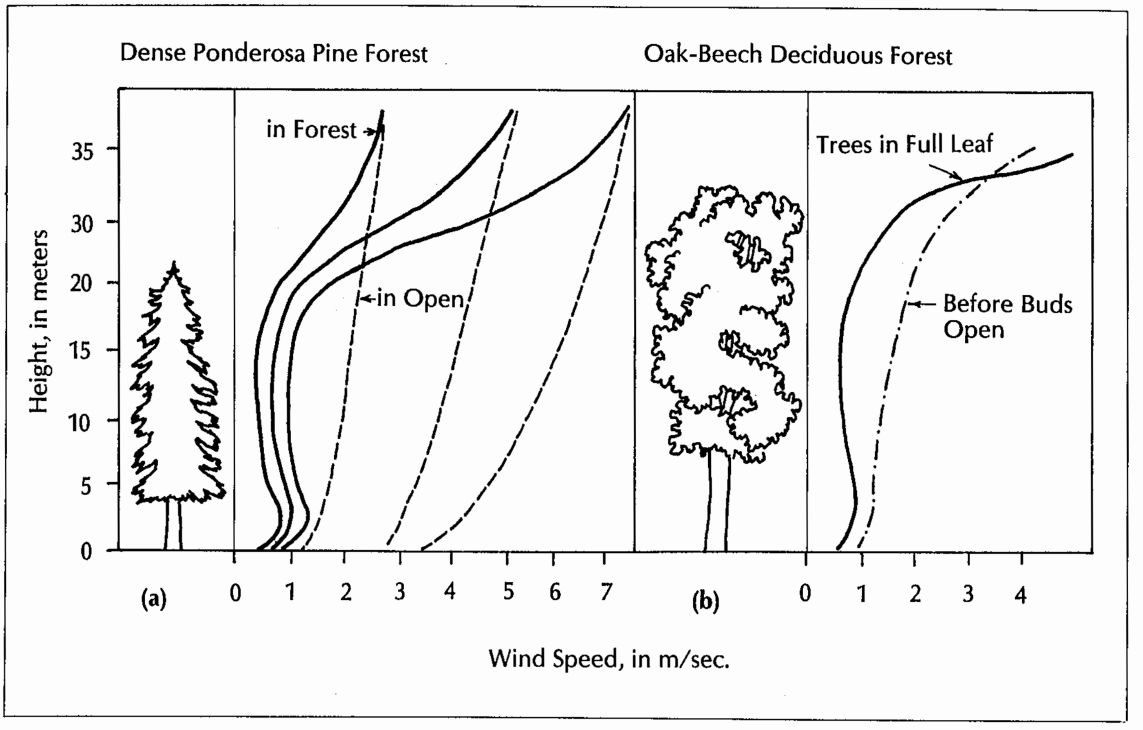

FIGURE 7. A comparison of wind velocity profiles at three wind strengths: (a) in a ponderosa pine forest vs. in the open; and, (b) a comparison of the average wind speeds between leafed and leafless forests.

than that behind a single permeable windbreak.

Wind Flow Around Buildings

The wind in urban areas is generally lower than in aerodynamically smoother rural areas (see Figure 3 on page 45.), but the local wind flows at pedestrian level around individual buildings are extremely variable, and may be much higher in these places than those in flat rural areas. This is because tall buildings may act as scoops that bring down high velocity air from aloft. Figure 9 shows the principal flow patterns around a building exposed to the wind.

Strong flows are found in the windward vortex, in which the direction at the surface is reversed from wind direction aloft; at the windward corners of the building; and in any passages or openings leading from the relatively high pressure zone on the windward side to the low pressure zone in the lee. The zone in the lee of the building has low wind velocity, often with the airflow going in the opposite direction from the approach wind. Similar flow patterns, known as "lee rollers," typically can be seen in street canyons when the wind crosses the street from the side.

While it is not possible to accurately predict the windfield within complicated building clusters without tests, estimates can be made for the surface wind environment for certain simple isolated buildings, and for some specific building clusters that have been previously studied. For an isolated rectangular building, the approximate maximum mean winds at the corners of the building may be anywhere from 0.8 to 1.0 times the mean velocity approaching the building at its top. Researchers at building research stations in the United Kingdom, France, and the Netherlands have studied other building shapes and typical building clusters and produced illustrations of commonly occurring wind phenomena, with generalized quantifications where possible.[5,6,7,8] For complicated geometries, it is difficult to make generalizations, and the only

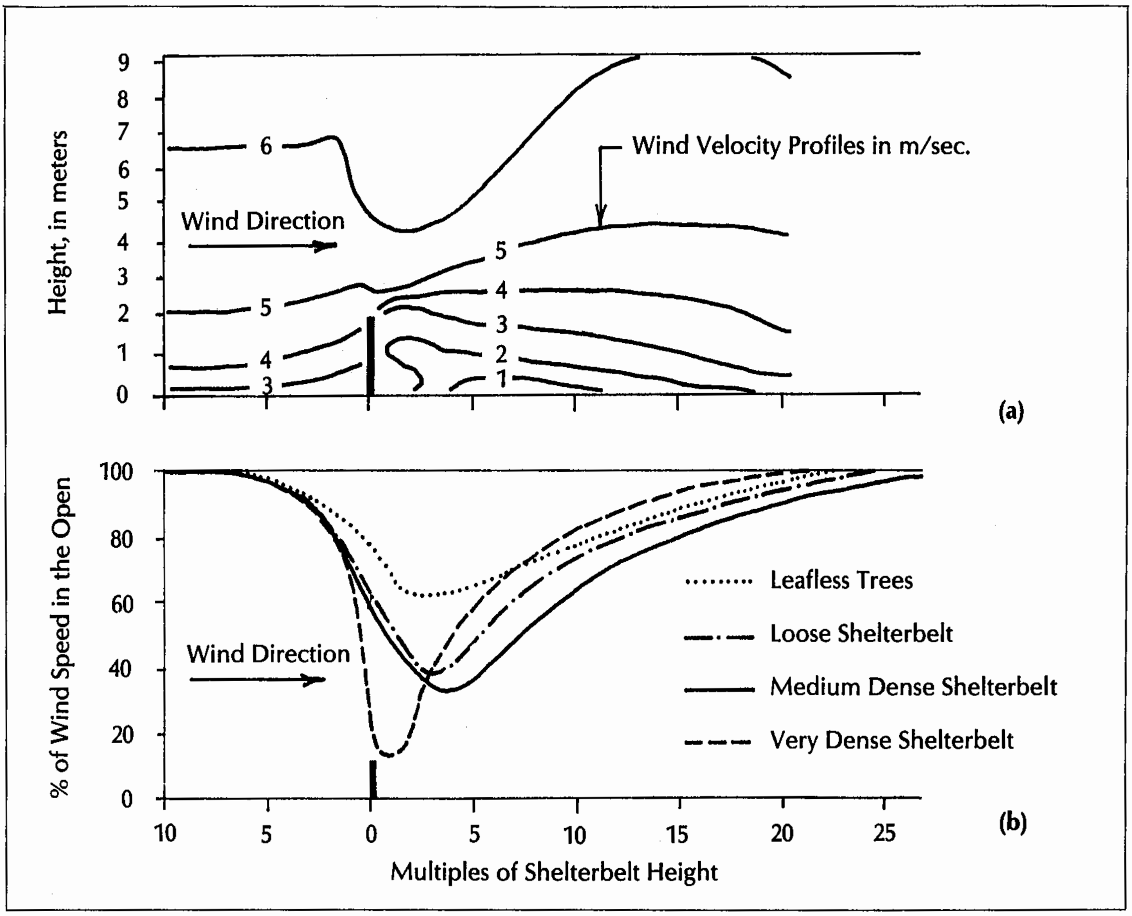

FIGURE 8. Wind velocity profiles around: (a) a shelterbelt of 50% porosity; and, (b) porosity vs. downwind shelter effect.

recourse at present is to use wind tunnel tests. The wind in built-up environments may be controlled at several scales, from the design of the surrounding buildings to devices specifically employed to provide local shelter.[9] Several factors should be considered in urban building design:

1. Large slab buildings should not be oriented in a direction normal to the prevailing wind to avoid downwash on the windward face. Circular and polygonal towers tend to have advantageous wind climates at ground level because of reduced downwash.

2. Tall buildings benefit from significant horizontal projections to break up downward-directed winds. From the point of view of wind control, the "ziggurat" or

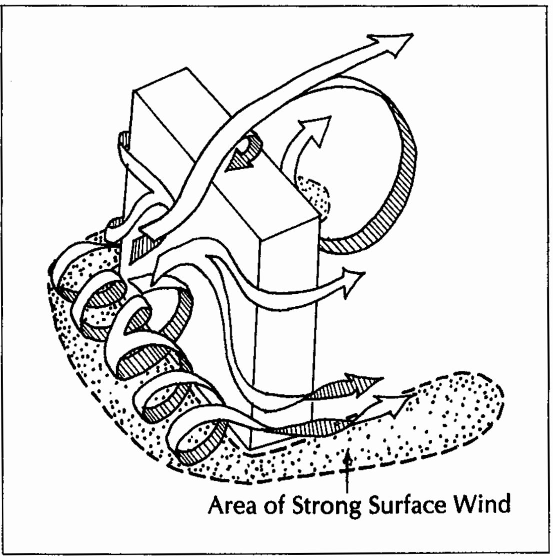

FIGURE 9. Principal wind flow patterns around a building exposed to the wind.

"wedding cake" designs of the 1930s through 1950s were better than the sheer slabs of the last two decades.

3. Large buildings placed at an angle to each other can form a funnel. This funnel can then accelerate the wind in the gap between the buildings. This effect, known as a *venturi,* will occur when buildings are over five stories high, have a combined length of over 300 feet, and have open areas in front of and behind the gap. Similar acceleration will occur when wide buildings overlap relative to the wind, so that the high pressure on the face of one building is channeled laterally to the low pressure area behind the other.

4. Important plazas, pedestrian thoroughfares, and building entrances should not be planned on the windward side or corners of tall slab buildings, since these areas are downdraft regions and exhibit accelerated corner flows. Well-known examples of wind-plagued plazas and entrances include the U.N. building in New York City and the John Hancock and Prudential buildings in Boston.

5. Openings through buildings near the ground, especially openings facing the prevailing wind, will experience strong winds unless revolving doors are used to prevent flow though the openings. The Earth Sciences Building at M.I.T., with its main entrances off a tunnel through the building at ground level, proved inaccessible in windy weather and required extensive ground level modification.

6. Vegetation and mechanical windbreaks may be used to absorb horizontal wind energy in pedestrian areas. There are a large number of windbreaks available for use in urban surroundings.[10] Such barriers are usually not effective at protecting large areas from the downdraft, or vertical, winds common in the vicinity of tall buildings.

There are also situations where it is desirable to encourage wind flow in cities. City planners in hot climates have investigated building spacing to maximize the natural ventilation available to the buildings,[11] and ventilation is also encouraged in areas near pollution sources such as highways or factories.

Wind Issues In Design

Natural Ventilation is the intentional displacement of air in buildings through windows, doors, ventilators or other devices under the occupants' control.[12] It is used to remove heat generated in buildings and to provide air movement to cool the occupants by convection. The airflow is induced by wind forces and thermal forces. Wind produces positive pressures on the windward face of the building and negative pressures on the leeward face. The building shape controls the pressures on the other faces. The pressure differences drive air through the building as estimated by the following formula:

$$Q = CAV \qquad (3)$$

where Q is volumetric airflow, A is the free area of inlet or outlet openings, V is the wind velocity, and C is the effectiveness of the opening, depending on its shape and orientation relative to the wind. Common values range from 0.25 to 0.60.

The thermal buoyancy caused by temperature differences between the building interior and exterior produces the additional airflow:

$$Q = CA[h(T_i - T_o)]^{1/2} \qquad (4)$$

where h is the difference in height between inlet and outlet, and C ranges between 0.09 and 0.12, depending on effectiveness of the opening, when Q is in m^3/sec and T in °C. Increasing the height and area of opening increases the airflow. Inlet and outlet areas should be nearly equal.

Some general rules for designing for natural ventilation are:[12]

1. Interior-exterior airflow systems should be designed to work regardless of wind direction. This may require using backup fans to counteract unfavorable windflow.

2. Openings cannot be obstructed by surrounding buildings, trees, etc. In such

cases, the initial velocities used for airflow calculation should be reduced to represent the velocity at the openings.

3. Openings are usually most effective when one or both are positioned low to move air through the occupied zone of the interior.

The placement of trees and shrubs can funnel and direct airflow around and through buildings.[13,14] Hedges and trees placed close to buildings can be used to create high and low pressure zones to force greater ventilation through building openings. Although there is little real data available for predicting natural ventilation, approximations and estimates can be obtained using rudimentary wind tunnel techniques.

Infiltration is the uncontrolled displacement of air through unintentional gaps in the building envelope. In cold weather, infiltrative air exchange accounts for roughly one-third of residential heating requirements. It is a function of exterior wind, and is most simply predicted by the crack method:[12]

$$Q = CA(\Delta P)^n \tag{5}$$

where C is a flow coefficient (the volumetric flow rate per unit length of crack) per unit pressure difference. ΔP is the interior-exterior pressure difference, and n is the flow exponent, with a usual value for building cracks of 0.65. Infiltration is roughly proportional to wind velocity when wind forces exceed thermal buoyancy forces. Infiltration can also be predicted with more sophisticated models that use as variables an empirically-determined whole building leakage area, the wind velocity and the temperature difference.[15] Trees and fences surrounding buildings have been shown to reduce wind pressures on buildings and significantly reduce infiltration rates.[16]

Mechanical Systems Efficiency. Wind influences the energy requirements of mechanical systems by causing the recycling of exhaust air from cooling towers, and by reducing the thermal efficiency of cooling equipment and heat pumps. There does not appear to be much published literature on the magnitude of wind-induced mechanical inefficiencies although these inefficiencies can be serious. There are highrise buildings in San Francisco topped with cooling towers that have been reported to lose 70% of their cooling capability during the daily sea breeze. The problems are usually associated with the design of the architectural enclosure surrounding the cooling tower. Such enclosures can encourage the wind to circulate within them, trapping the moisture laden exhaust air and returning it to the cooling tower supply. However, wind will also reduce the design efficiency of unenclosed open-sided cooling towers by disturbing the flow of cooling water within the tower. Effective enclosures should both reduce the wind within the cooling tower and prevent a flow pattern around the tower that returns the exhaust to the tower. This may be done by providing the enclosure with localized openings.

Wind pressures also affect mechanical systems at their inlets and exhausts by affecting fan power requirements and the balance of HVAC (heating, ventilating and air conditioning) systems. In addition, mechanical systems must respond to the wind flow patterns around buildings to avoid the reentry of exhausted pollutants into the building. This affects duct runs, vent positions, exhaust stack height, and stack exit velocity. Chapter 14 of the *ASHRAE Handbook of Fundamentals* discusses these issues in depth.[12]

Pollution Around Buildings. Pollutants emitted in the vicinity of buildings from traffic, parking garage ventilation exhausts, and building exhausts will be dispersed in patterns determined by the wind. Dispersal in the wake of single buildings has received fairly systematic study.[17,18] Although there have been numerous field and wind tunnel studies of dispersal from specific exhausts in specific built-up urban environments, such studies are difficult to generalize because of the variability of building configurations. Street canyons and courtyards sunk into a reasonably uniform rooftop line yield a typical airflow pattern under the influence of wind or of differential heating in the sunlight, as shown in Figure 10. Note that a south wind

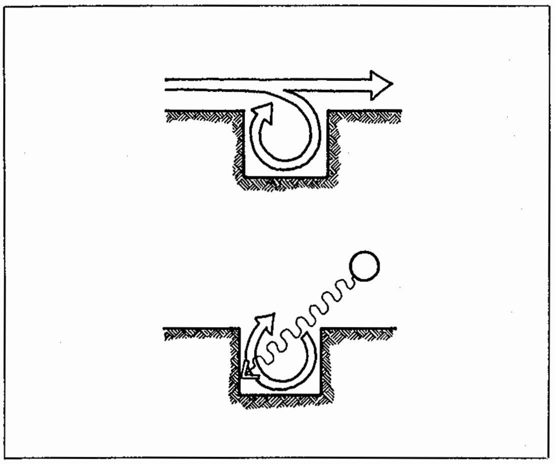

FIGURE 10. Typical airflow patterns in street canyons and courtyards under the influence of wind or differential heating by the sun.

will tend to suppress the roller set up by solar convection.

Using a model of an urban area, Figure 11 shows the wind influence on pollutant concentrations in some typical blocks.[19] This model shows that higher pollutant concentrations are experienced on the upwind side of the street.

Pedestrian Comfort. Strong winds around buildings may cause discomfort and even danger to pedestrians. People become discouraged with chronically windy open spaces, and by avoiding them they at least defeat the purpose of the open space, and at worst cause economic hardship to surrounding businesses. Pedestrian winds have been studied widely in recent years.[8,20] Figure 12

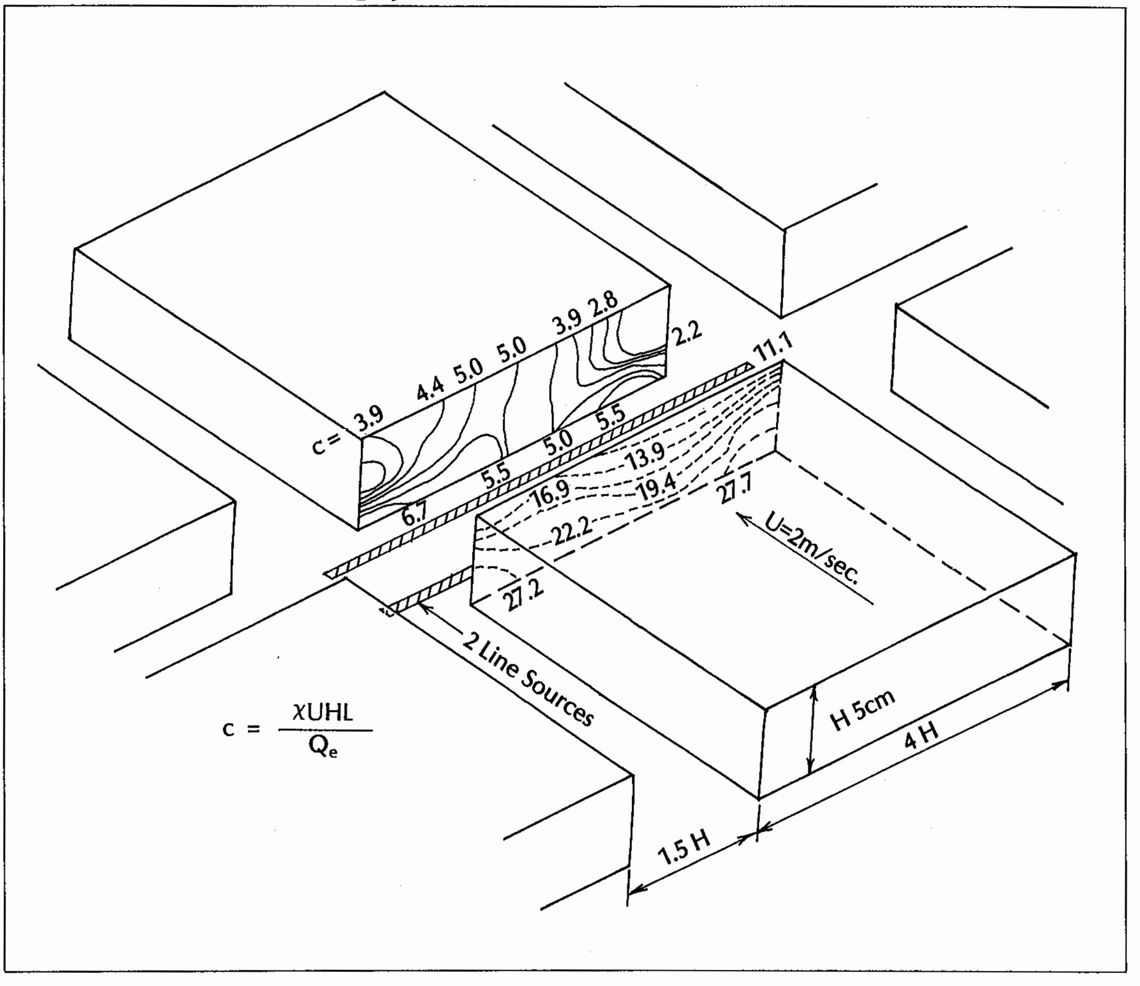

FIGURE 11. A model of wind influence on pollutant concentrations in some typical urban blocks.

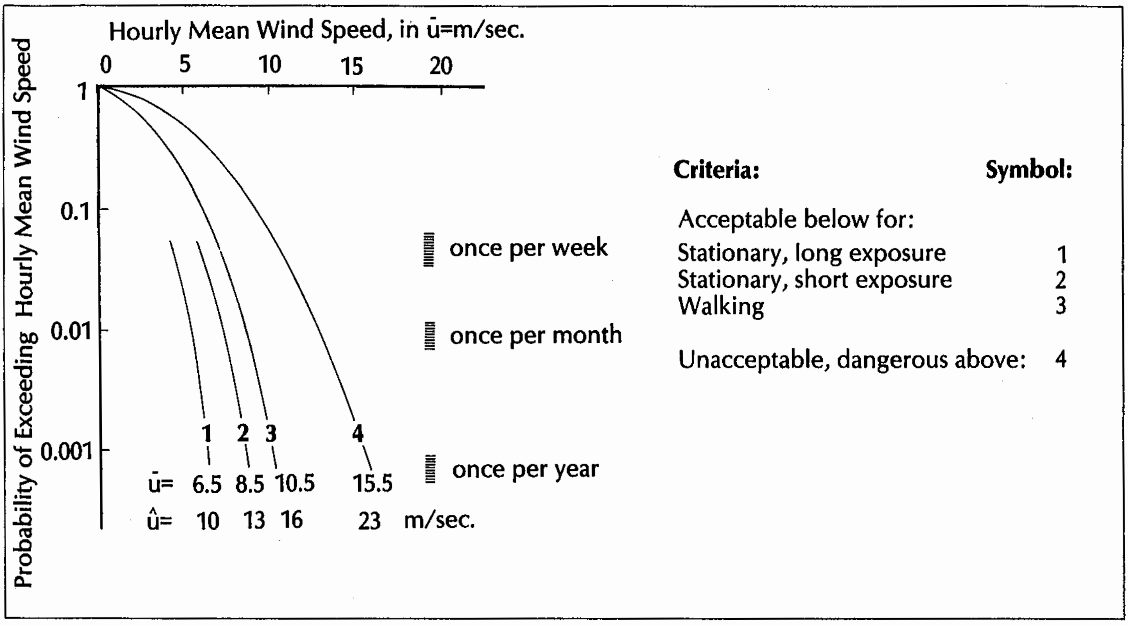

FIGURE 12. Acceptability criteria for pedestrian winds. The boldface numbers correspond to the symbols for acceptability criteria.

shows some pedestrian wind level acceptability criteria.[21] These criteria have been compared to the results of other researchers and been found to be consistent worldwide.[22] In the figure, $\bar{u}$ is the peak annual hourly mean, and $\hat{u}$ is the peak annual gust of a few seconds' duration.

Designers must evaluate the windiness of a site. For aerodynamically simple projects, it is possible to estimate windiness using previous experience. If this is not possible, a wind tunnel test of a model of the project is the only currently practical alternative. The velocity patterns obtained within the model are used to adjust the directional windspeed distributions from the most appropriate nearby weather station to obtain the wind climate on site. This information, when compared to the criteria shown in Figure 12, determines whether the site will have an acceptable outdoor wind environment.

Particle Transport. Wind may also influence a project by drifting particles of sand, soil or snow across circulation areas. There are even cases where winds generated around the base of tall beachfront hotels have scoured the beach away into the ocean. These problems may be controlled in the design of the buildings themselves, or by localized devices to trap particles.

Shelterbelts and artificial screens are commonly used to control snow and sand drifting (see Figure 8 on page 49). The optimum porosity for snow fences has been found to be around 50%, with no significant difference between vertical and horizontal slatting. There is no aerodynamic advantage to tilting the fence either into or away from the wind. Since there is considerable lateral transport around the ends of the fences, their length should be at least 30 times their height, and in staggered configurations. They should overlap by a length of at least 8 fence heights. Catchment efficiency of fences can be greatly increased by placement before a lee slope, or directly downwind of a rising slope.

Wind Records and Their Sources

Meteorological records are necessary to determine the local wind climate. Both the original data and their various summaries are kept at the National Climate Center (NCC) in Asheville, NC. Because most practitioners do not have the time or expertise to reduce the original data, summaries are useful.[23] The military SMOS and RUSSWO summaries are most comprehensive and are available for locations worldwide.[24] The *Airport Climatological Summary* provides useful information on wind frequency as a function of magnitude and direction.[25] Other summaries list extreme winds (fastest mile per hour) and other climatological variables. Most local libraries carry some of the climatological summaries. Copies are available from NCC at nominal cost.

Translation of meteorological conditions from an airport measurement site to a local site some distance away can be simple or quite involved. For example, wind speeds near the surface at a local site may differ from those at the nearest weather station due to different terrain roughness or other factors. In some cases, it may be desirable to monitor the wind over periods as short as a few days in order to make hour-by-hour comparisons with weather station values. In important projects, or where the climate changes rapidly over short distances, it is advisable to retain a consulting meteorologist.

Model Simulation

Modeling of wind effects on buildings and of wind flow and dispersion about buildings has been performed for more than two decades using boundary-layer wind tunnels. Comprehensive reviews of the techniques and similarity requirements are available.[26,27,28] In most cases, the modeling of atmospheric boundary layer winds requires the use of a wind tunnel in which the mean-velocity and turbulence characteristics of the wind flow are reproduced to scale. In other cases, particularly for dispersion problems, the thermal stability of the atmosphere should also be modeled. Within the wind tunnel, a model of the building or site requiring investigation must be constructed to a scale compatible with the modeled atmospheric flow. Instruments are placed in the model in order to obtain the information required — for example, in studies of pedestrian comfort, the magnitude of the horizontal wind and its fluctuations over time are typically measured by hot wire sensors at various ground level locations in the model. A model instrumented with pressure sensors to determine wind loads on a structure can also be scanned with a hot wire probe to determine pedestrian comfort in plazas or other areas around the building. In the model, the influence of surrounding buildings or topography should be included since they may have a major influence in the character of the wind flow at a particular point.

Conclusions

The influences of wind loads on building frames and cladding have been a traditional concern of engineers. Building designers have in recent years become markedly more aware of such influences, and there has been fairly widespread activity aimed at improving our ability to predict them in design. This increased awareness may seen in the construction of numerous boundary-layer wind tunnels in universities, research laboratories, and private consulting firms. Wind testing has become so sufficiently commonplace that it is used by architects and planners as well as engineers, with the result that influential early design decisions are now informed by wind considerations.

For the control of pedestrian-level winds, several cities have adopted codes requiring the testing of proposed building projects for their eventual wind climate. Researchers have developed fairly consistent acceptability criteria for wind effects on people, although there is still considerable room for improvement in this area.

Energy conservation concerns have prompted much recent research on natural ventilation, infiltration and mechanical system performance. Air pollution regulation has also fostered work on pollutant dispersion in the vicinity of buildings. As a result, a variety of new prediction methods have been developed for use by building designers.

Continued improvement is needed in estimating local climate statistics, and in the computer modeling of both the air flow itself and its influences on the built environment.

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The following symbols are used in this article:

- A = free area of inlet or outlet openings
- C = factor for the effectiveness of the opening
- c = mean concentration coefficient
- H = building height
- h = difference in height between inlet and outlet openings
- L = reference length
- n = flow exponent
- Q = volumetric air flow
- Q_* = pollutant emission rate
- T = temperature
- U_* = friction velocity
- U_z = velocity at height z
- V = wind velocity
- z = height above ground surface
- z_o = roughness length
- ΔP = internal-external pressure difference
- α = power law exponent
- χ = mean concentration

Subscripts

- i = inside
- o = outside

Immersed Tube Tunnels: Concept, Design & Construction

Offering significant engineering and cost advantages, the use of immersed tubes for tunnel construction is growing. Major questions today involve where and how to use the immersed tube concept.

THOMAS R. KUESEL

IMMERSED TUBE is the designation for tunnels composed of prefabricated sections that are placed in a trench that has been dredged in a river or bay bottom. The sections are usually constructed at some distance from the tunnel location and made watertight with temporary bulkheads. They are then floated into position over the trench, and are lowered into place and joined together underwater. The temporary bulkheads are removed, and the trench is backfilled with earth to protect the tubes.

Immersed tubes have been widely used for highway and rail crossings of soft-bottomed, shallow estuaries and tidal rivers. They have occasionally been adapted to sites with irregular hard rock bottoms, and to sites exposed to ocean wave and storm conditions. In a few cases, they have been used for water supply, and in one case to transport liquefied natural gas.

Immersed tubes have been designed to accommodate both ground shaking and fault displacement resulting from earthquakes. Over many years of service, they have proven to be generally more watertight than other forms of tunnels. For example, the San Francisco Trans-Bay Tube is so watertight that a fire hose needs to be brought in occasionally to spray the concrete-lined inspection gallery in order to keep the dust level down.

Historical Perspective

The first use in the United States of immersed tube tunnel construction methods — setting long prefabricated elements onto a prepared bed in a subaqueous trench — was for a water tunnel crossing the Shirley Gut in Boston Harbor in 1896. The first transportation tunnel constructed by immersed tube methods in the United States was the Michigan Central Railroad Tunnel under the Detroit River, completed in 1906 under the direction of William Wilgus. Another early immersed tube was the 4-track Harlem River crossing of the New York Subway, completed in 1914, presently part of the IRT Lexington Avenue line.

The first highway immersed tube in the United States was a concrete tube section, the Posey Tube between Oakland and Alameda, California, completed in 1928. In 1930, the Detroit-Windsor tunnel between Michigan and Canada was completed. This tunnel marked the first use of welded steel shell construction for immersed tubes, and signalled more widespread use of similar construction methods for tunnels, including:

- The Baytown Tunnel under the Houston Ship Channel in Texas
- Three tunnels under the Elizabeth River between Norfolk and Portsmouth, Virginia
- Two parallel tunnels under Hampton Roads in Virginia
- Two tunnels in tandem on the Outer Chesapeake Bay Crossing in Virginia
- The Baltimore Harbor and Fort McHenry Tunnels in Baltimore
- A single 2-track tube used for the Chicago River crossing of the State Street subway in Chicago
- The Orange Line Charles River crossing in Boston, comprising two 2-track transit tubes
- The 4-track 63rd Street transit and rail tunnel in New York City
- The Trans-Bay Tube of the BART system in San Francisco
- The Cove Point Tunnel for unloading tankers at a marine terminal in Maryland
- The Washington Channel crossing on the WMATA Yellow Line in Washington, DC

Although there has been much discussion of concrete box section tubes in the United States, no project using this alternative has been realized here since the Posey Tube, primarily owing to economic constraints of building such a tunnel. The Deas Island Tunnel near Vancouver and the Lafontaine Tunnel at Boucherville, near Montreal, provide two Canadian examples of concrete tube construction.

Advantages & Disadvantages

For underwater tunnels, the immersed tube concept offers several advantages compared to mined or shield-driven tunnels:

1. The tunnel has the minimum possible depth. For an approach gradient fixed by operating criteria, this usually means minimum tunnel length.
2. Almost all of the construction is accomplished above ground in normal working conditions. This promotes better quality of construction, particularly greater control of water leakage.
3. Most of the construction is similar to ship or building construction, and can utilize readily available labor skills. Relatively small amounts of special labor are required to control the placing and joining operations.

A primary disadvantage of immersed tube construction is the potential for disruption of existing facilities if the trench must be extended past the shore lines. Also, special equipment is required to construct a level foundation for the tubes, and to place and join the tube sections. The disposal of dredge spoil material excavated from the trench may create serious environmental problems.

Configurations

Figure 1 shows representative immersed tube cross-section configurations. Circular sections are structurally efficient in resisting water pressure, which is the principal design load. Rectangular sections can frequently be made shallower than circular sections, reducing the tunnel depth. For highway tunnels, spaces for ventilation ducts must generally be provided above, below or between the roadway compartments. All sections must provide space for ballast to be added to overcome buoyancy in order to sink the tubes and hold them in place in the trench.

The typical steel shell section has evolved in the United States to combine the structural efficiency of a circular ring section with the economy of shipyard construction. This type of tube can conveniently accommodate a two-

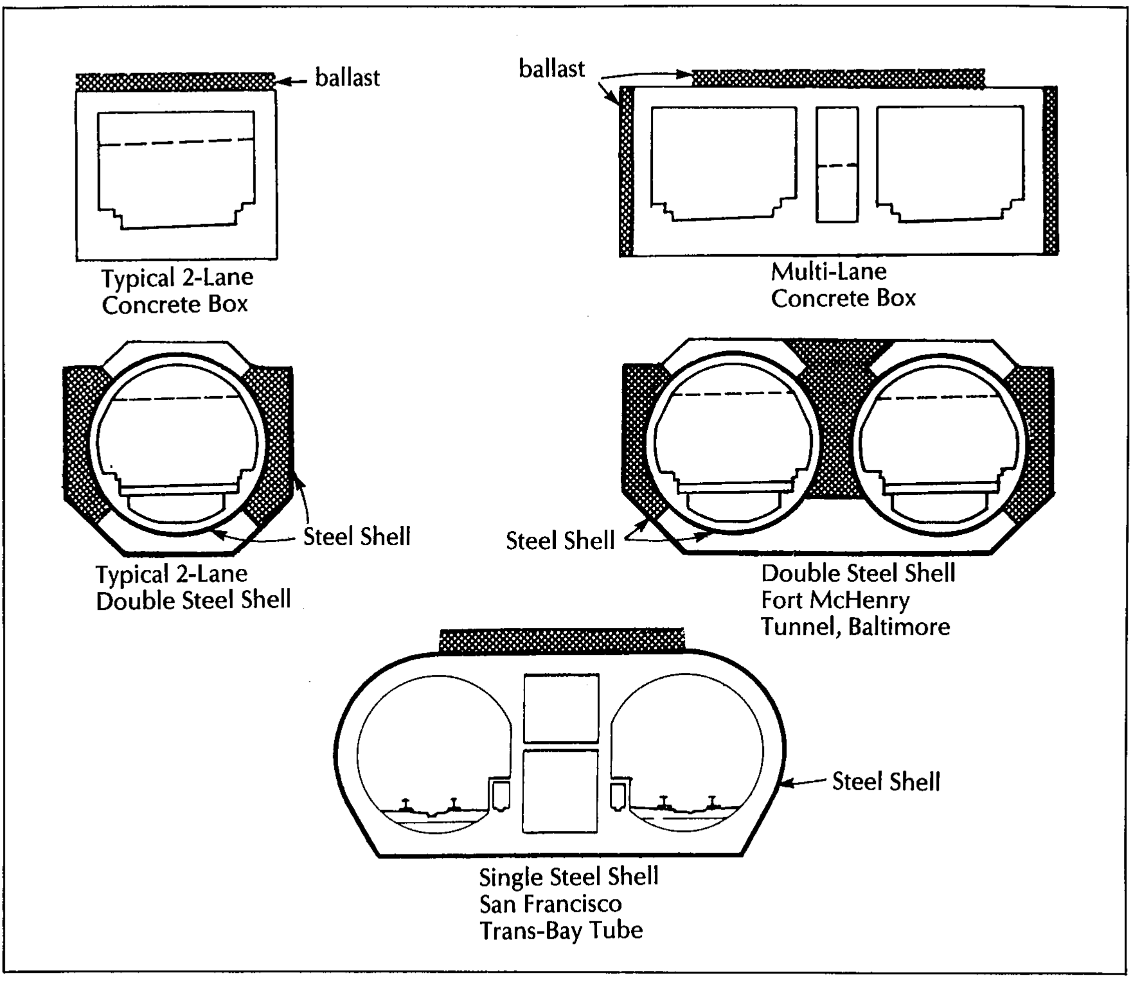

FIGURE 1. Representative immersed tube cross section configurations.

lane roadway with a fresh air duct at the bottom and an exhaust air duct at the top. Twin circles can afford sufficient room for four-lane roadways. Double steel shell sections are most common; however, single shell elements have been used. A single steel shell twin-track rapid transit tunnel is represented by the section of the San Francisco Trans-Bay Tube in Figure 1.

Ventilation

While ventilation is a consideration for all tunnels, it has special significance for immersed tubes in that it may govern the configuration of the cross section. For highway tunnels, ventilation requirements are of primary importance, especially for long tunnels. The two design requirements for ventilation systems are the dilution of exhaust gases and the control of smoke during a fire. Figure 2 shows some typical ventilation arrangements. A longitudinal ventilation system has fans mounted directly in the roadway compartment above the vehicle clearance line. This type of system is suited to tunnels with one-way traffic in each roadway compartment. However, the quality of the air decreases progressively toward the exit portal because the polluted air is not removed from the roadway compartment. In past U.S. practice, longitudinal ventilation has been limited to rural tunnels with light traffic or to relatively short tunnels (up to 1,000 feet). Longitudinal ventilation has been used for much longer one-way tunnels in Europe and Japan, and is currently being considered for

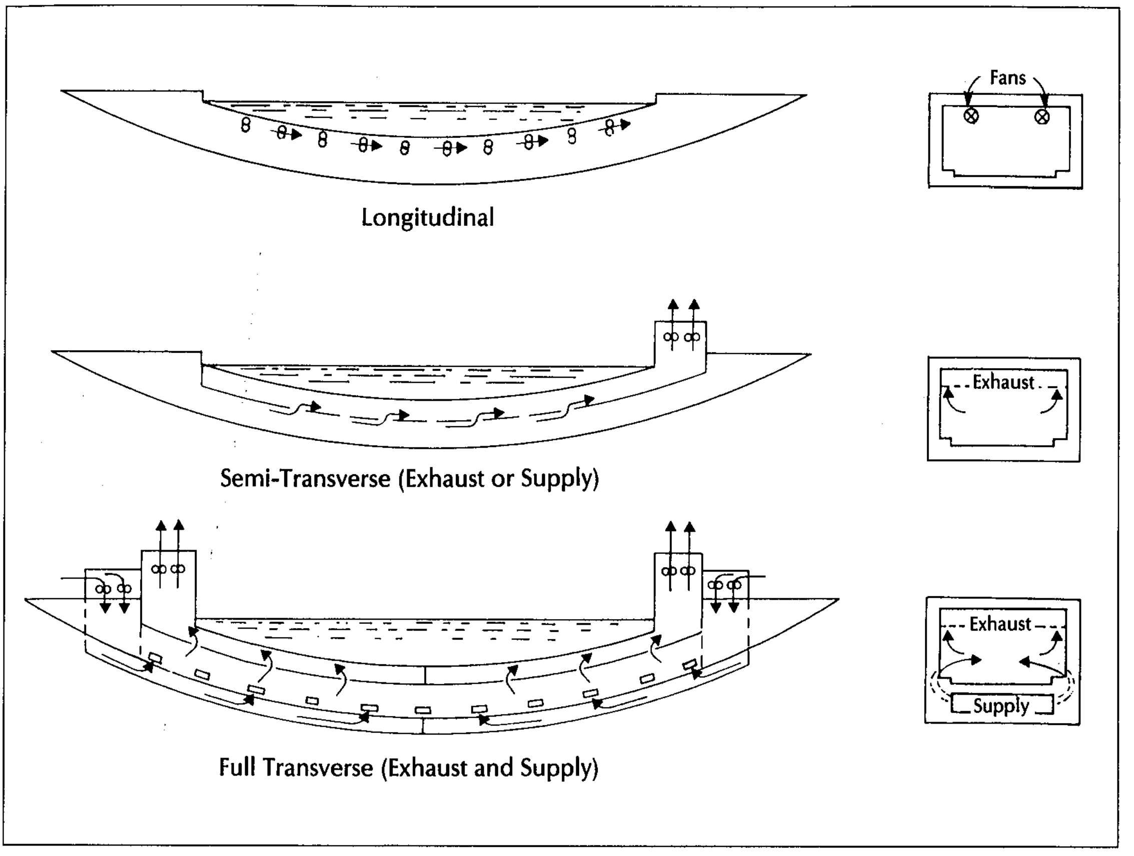

FIGURE 2. Different types of tunnel ventilation systems.

two U.S. mountain tunnels about 4,000 feet long.

Semi-transverse ventilation systems provide a single ventilation duct separate from the roadway compartment, for either supply of fresh air or exhaust of contaminated air. A supply system provides better air quality in normal operations, but an exhaust system provides better control of smoke. These systems have been used in the U.S. for tunnels up to 3,000 feet long.

For very long or heavily congested tunnels, a full transverse ventilation system is preferred, with separate supply and exhaust ducts. This provides the best quality of control of both exhaust emissions and smoke.

Figure 3 shows the relation between the length of ventilated tunnel and area required for roadway and sidewalk compartments and for ventilation ducts. This figure is based upon data from completed projects. Ventilation considerations may be the primary factor controlling the selection of the cross-section configuration for long tunnels.

Construction Methods

The two general construction methods employed for immersed tubes are the concrete box and steel shell systems shown in Figure 1. Most concrete box sections have been rectangular, which are well suited to wide tunnels under relatively narrow and shallow waterways. Concrete box sections depend for watertightness on very careful quality control of the concrete and frequently involve prestressing.

The steel shell system uses a circular steel shell plate as both a primary structural member and as a watertight membrane. The structural concrete lining contributes to the structural strength and provides weight to counteract buoyancy. The double shell system provides a circular structural steel ring and an octagonal steel form plate, and has evolved in

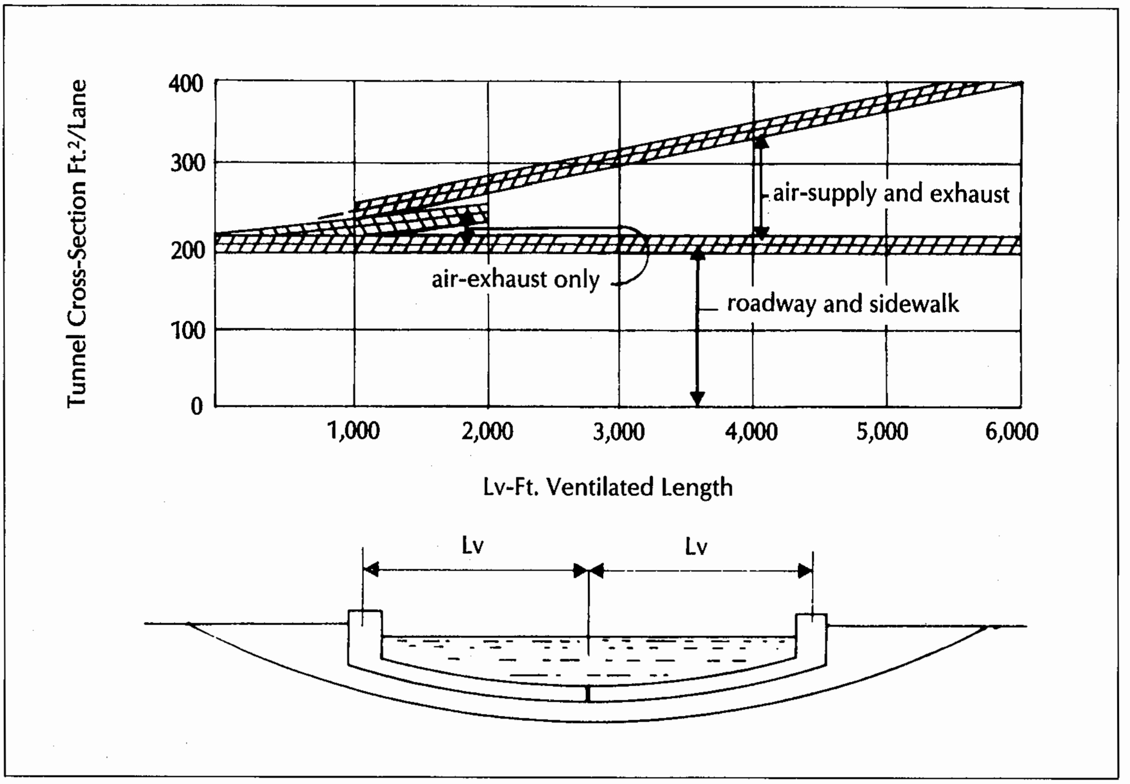

FIGURE 3. Tunnel ventilation requirements.

the United States as an efficient form for shipyard construction. The internal structural steel ring is protected by the exterior ballast concrete. Single shell construction, as used for the San Francisco Trans-Bay Tube, minimizes the amount of steel required, but the exposed steel shell must be protected against corrosion.

Trench Profile

Most immersed tube tunnels have been constructed in soft soils and have been completely buried beneath the existing bottom of the watercourses. However, there are cases where trenches have been successfully blasted into rock, and cases where parts of the tunnel have projected above the existing bottom. Protection must be provided against scour by river and tidal currents, and to distribute concentrated loads or shocks that might arise from sinking ships or dragging anchors.

The buoyant weight of the tube and backfill is not greatly different from that of the original soil. As a result, foundation settlement is usually not a problem for immersed tube tunnels. The tube sections are relatively flexible in a vertical plane, and can accommodate considerable differential settlement without distress. Very soft soils may have to be removed by dredging and replaced with more suitable materials.

Foundations & Backfill

Figure 4 shows a typical trench cross-section. The rough dredged trench must be leveled to provide a uniform foundation for the tubes. After the tube section is placed and joined to previously placed sections, a special locking fill is added on both sides to hold the tube in place. This locking fill should be composed of angular crushed rock, so that the particles interlock to resist movement. Rounded river gravels are more suitable for foundation courses, since they can be readily screeded off to form a level bed. The tube is then covered over with ordinary backfill, which usually consists of material excavated from the trench. A protective course of gravel or heavy

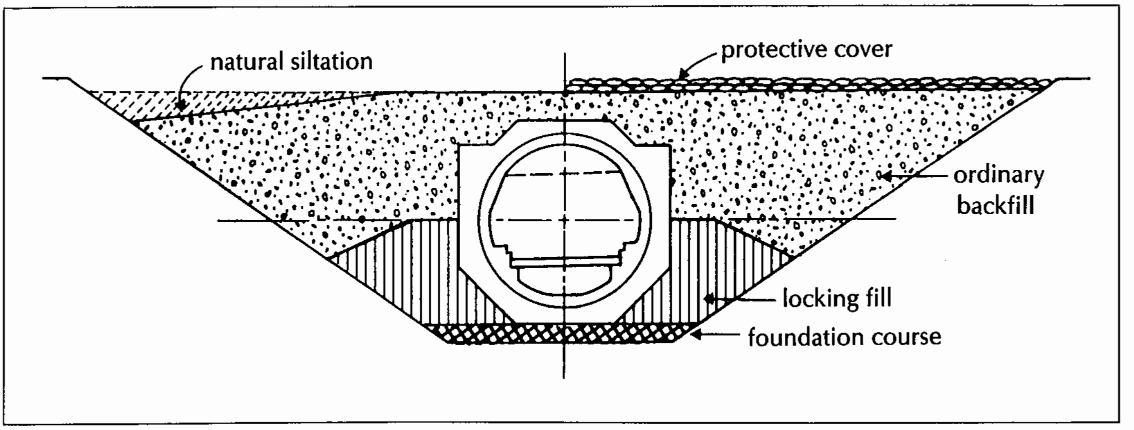

FIGURE 4. A cross section of a typical immersed tube trench.

stones may be added if required by hydraulic conditions or by possible exposure to dragging anchors or occasional special loads.

Dredging

The side slopes of the dredged trench are determined by the nature of the bottom soils. The bottom of the trench should be kept clear of material that may slough off the trench slopes, or drift in on bottom currents. These conditions usually require clean-up dredging just prior to placing the foundation course.

In the United States, concern for environmental pollution has made disposal of dredged materials a serious problem. At present, it is frequently necessary to construct a diked containment facility to prevent the soft, contaminated bottom soils from spilling out into the watercourse.

Foundation Alternatives

The most common foundation system in the United States is the screeded bed. This system requires a special construction rig for striking off a smooth plane at the desired profile. This is generally accomplished by suspending a heavy screed bar from a carriage that rides on rails set parallel to the trench profile and supported on a pair of barges. Figure 5 portrays the screed rig operation for the BART Trans-Bay Tube. The gravel is fed to a group of hopper bins supported by a carriage that rides on rails on the floating screed rig, which is ballasted so that the rails are parallel to the desired trench grade. The gravel is fed down three pipes to a spreader box, which is open on the bottom only. As the carriage travels along the rails above, the box releases gravel into the trench, and the edge of the box screeds off a level bed. Screeded beds have been constructed to a width of 180 feet, with a surface accuracy of ±2 inches.

The pumped sand foundation has been widely used in Europe. It requires setting the tube section on temporary foundation pads and adjusting its location with jacks. Sand is then pumped in beneath the tube to form a bed. This system also requires special equipment to place the sand uniformly and to verify that the space has been filled. The Japanese have developed a system involving injecting cement grout beneath the tube from the inside, working through holes in the floor. This system is capable of producing a superior foundation, but requires great care to seal up the large number of holes in the floor.

Tube Fabrication

Steel shell sections have generally been fabricated on existing ship-launching ways in shipyards. Occasionally, new shipway facilities have been especially constructed for tube fabrication. The character of steel fabrication work required is similar to that required for ship construction. Double steel shell sections are particularly well suited to shipyard construction. The fabricating facility may be located at a great distance from the tunnel site. Steel tube sections have been towed through the open ocean for distances up to

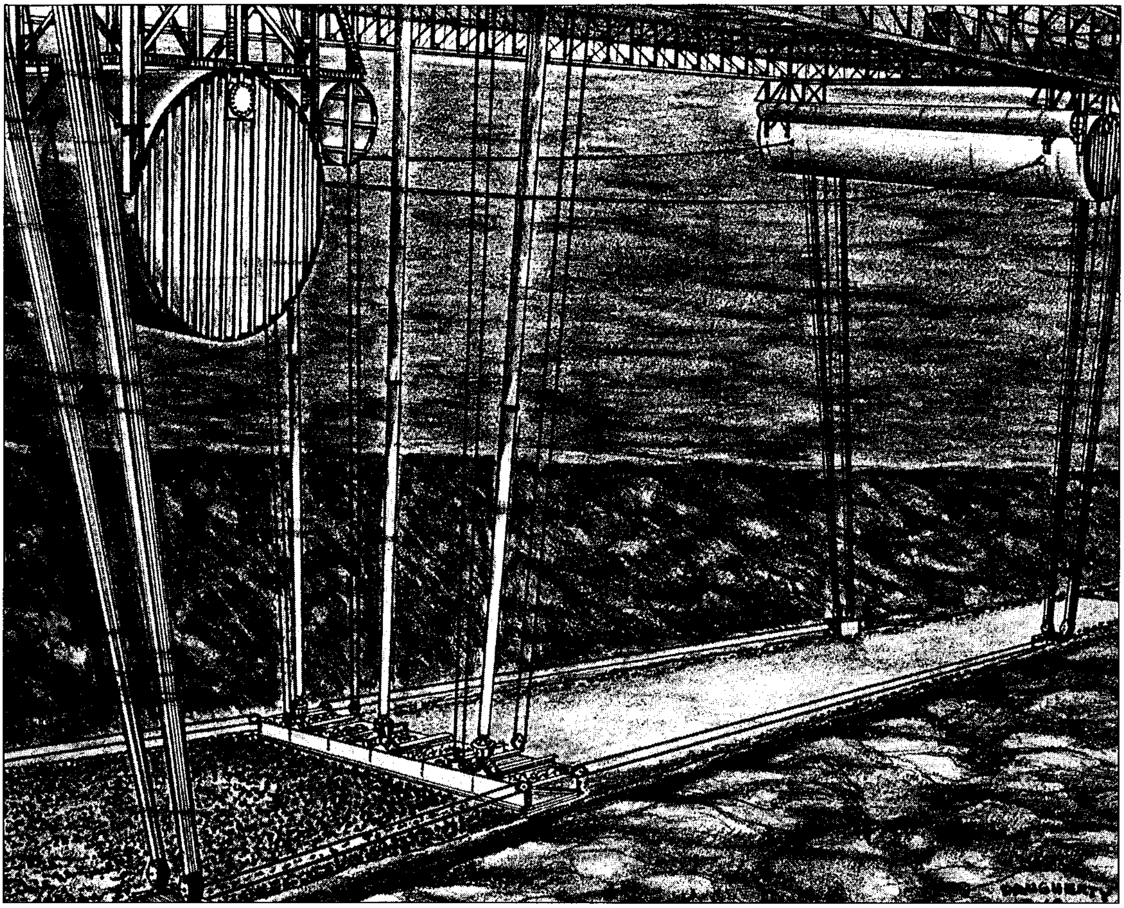

FIGURE 5. The screed rig operation for the Trans-Bay Tube Tunnel.

1,500 miles. An outfitting facility, at which most of the concrete lining and ballast for sinking are added, should be provided. This facility is usually close to the tunnel site, but in one case it was actually 400 miles away.

Although concrete box sections may theoretically be constructed in existing drydocks or graving docks, in practice such facilities have rarely been available for the long duration required for their use in tunnel construction. Therefore, concrete box tubes generally require a construction basin specifically dedicated to their fabrication. The basin usually must be located fairly close to the tunnel site because of the difficulty of maneuvering the large, heavy sections (weighing up to 35,000 tons). Transportation of the sections from the basin to the tunnel site may require dredging to secure adequate depth for flotation. Special control of concrete materials and their placement is necessary to control the development of shrinkage cracking. If the box section is not prestressed, membrane waterproofing is usually required to assure watertightness.

Records of projects worldwide indicate that the total construction time has generally been one to two years longer for concrete box tunnels than for steel shell tunnels.

Joint Connections

In early U.S. immersed tube tunnels, connections between tubes were made with the tremie concrete joint (see Figure 6). This system permits tubes to be positioned independently, so that tolerances in tube fabrication do not result in alignment errors. More recent tunnels have used rubber gasket joints for temporary connections. These joints are made more quickly and are less costly than

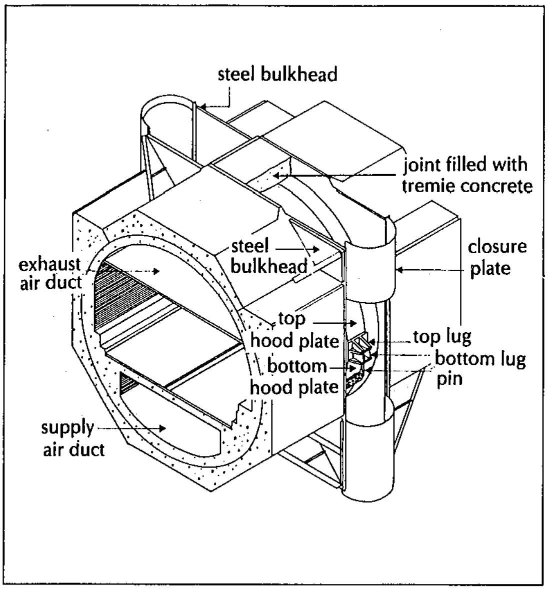

FIGURE 6. Tremie concrete joint.

the tremie joint, but require great accuracy in fabrication in order to assure that the ends of adjacent tubes are exactly square to the tube axis and parallel to each other.

For the rubber gasket joint, temporary closure is made by means of couplers mounted on the ends of the tube sections, similar to those used to couple railroad cars. The operation of the couplers is remotely controlled from a surface vessel. The general position of the tube is established from survey towers projecting above the surface and the precise relative location of the sections to be joined is determined by electronic sonar methods. A diver is generally sent down shortly before the closure for a visual inspection to confirm the absence of obstructions, but the actual closure operations are all accomplished by remotely controlled equipment (see Figure 7).

In both methods, after the temporary seal between prefabricated tunnel sections is made, the interior bulkheads are removed and a permanent seal and structural connection between the tubes is made by welding a closure plate from the inside.

Ventilation

For highway tunnels, as the length between ventilation buildings grows beyond 6,000 to 7,000 feet, both the construction cost and the operation cost of ventilation systems become oppressive. The longest existing ventilated length in the United States is about 7,300 feet for congested tunnels in urban areas. For rural tunnels with light traffic, ventilation of 10,000-foot lengths is practical to a high quality standard. With lower ventilation standards, several European and Japanese mountain highway tunnels have been stretched to 13,000 to 14,000 feet between ventilation shafts. The Mont Blanc Tunnel through the Alps achieves an extraordinary length of 38,000 feet between ventilation buildings by devoting 40 percent of the tunnel cross section to ventilation ducts and by limiting the permitted volume of truck traffic to approximately 100 trucks per hour (sum of both directions).

For electric railway tunnels, ventilation is much less serious and essentially places no limit on tunnel length. For rail tunnels using coal- or diesel-fired locomotives, the ventilation problem is intermediate. The Rogers Pass Tunnel in Canada is designed with a rather elaborate ventilation system for diesel operation with a maximum ventilated length of 27,500 feet.

Geotechnical Conditions

Exceptionally soft soils may make it difficult and costly to keep the trench open long enough to place the foundation course and tube sections. Isolated pockets of soft materials may be dredged out and replaced. Short stretches of rock may be blasted out for the trench, but this work is slow and costly. If there is a general condition of a rock bottom, immersed tubes should be laid on the bottom and mounded over for protection (if navigation depth clearances will permit this).

Tides & Currents

The current should preferably not exceed a velocity of 3 feet per second for a minimum duration of two hours to permit maneuvering the tubes into position over the trench and lowering them onto the foundation bed. Somewhat higher currents are not an absolute bar, but indicate a need to investigate the hydraulic drag forces that will be exerted on the tube section and the placing equipment,

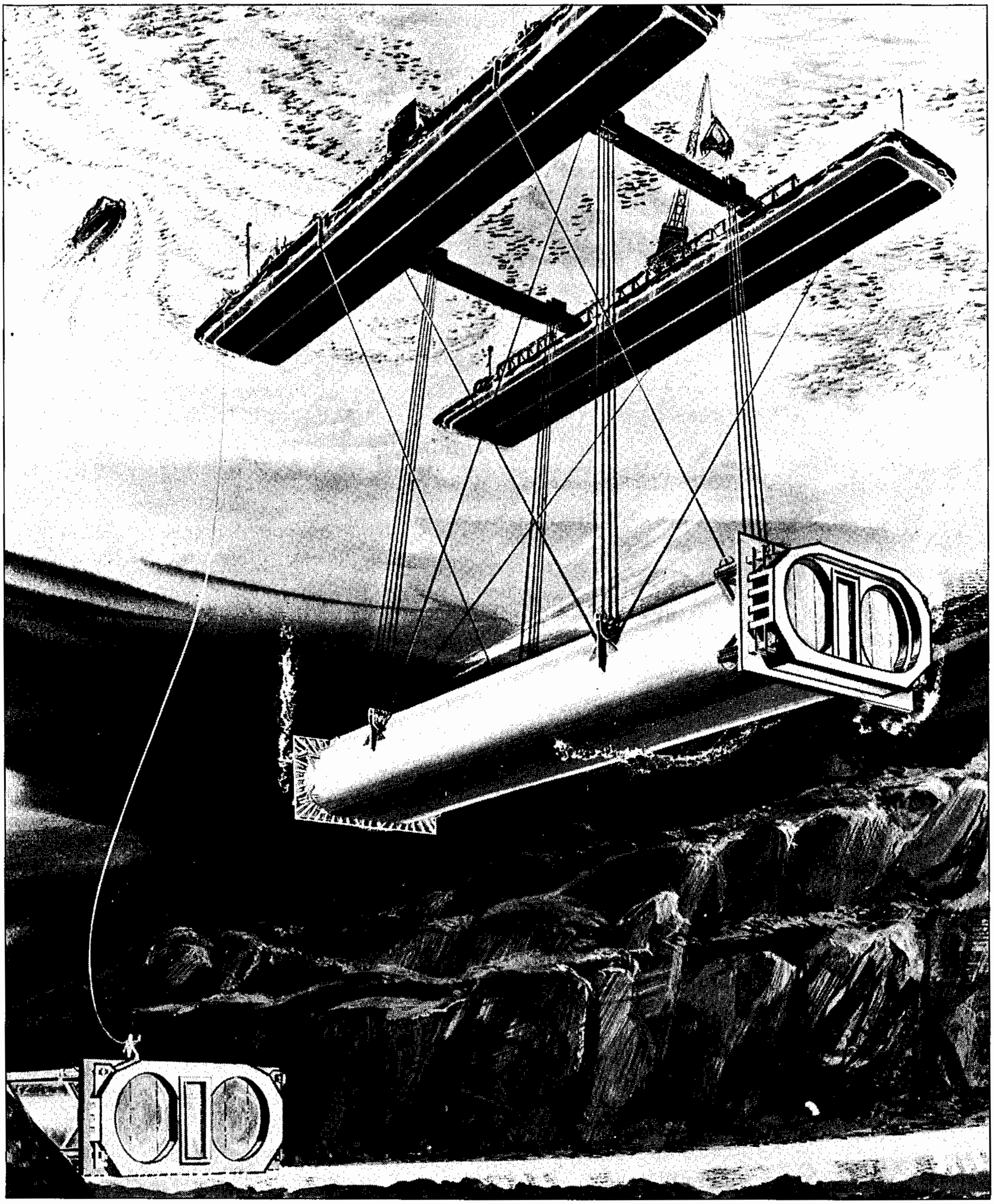

FIGURE 7. Divers inspect the area for obstructions prior to closure operations.

the forces on anchor cables, and the ability to develop reliable anchorage in the bottom soils to resist these cable forces.

Salinity & Siltation

The density of the water in the bottom of the trench at the time of tube placement, and uncertainty regarding the value of this density, are important constraints on the amount of ballast required. Supplemental external sinking blocks and water ballast in internal tanks may be used to overcome

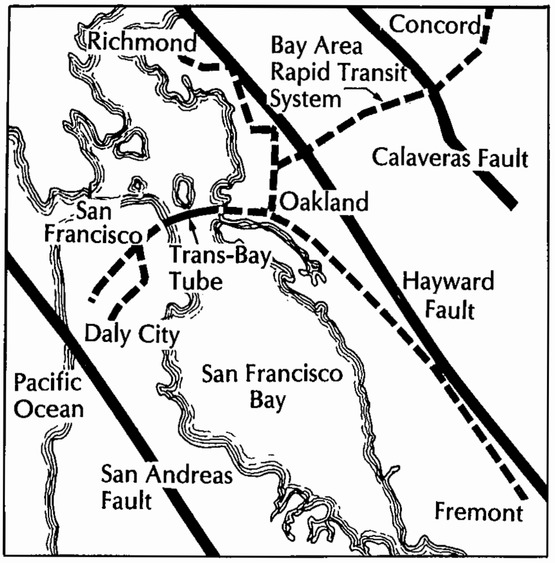

FIGURE 8. The location of the Trans-Bay Tube Tunnel.

excess buoyancy during sinking. Generally, a specific gravity of 1.0 to 1.1 for the water in the trench can be handled. Heavy infusions of silt deposited on every tidal cycle may cause serious problems with placing and stabilizing the foundation course and the tube sections.

Fabrication Facilities

The number and size of shipways in the United States have limited the length of steel shell sections that can be fabricated to about 375 feet. However, there is no reason why sections 500 feet long could not be handled if facilities for fabricating them are available.

The construction basin for concrete box sections is generally custom-built for each project, so there are no special constraints on the size of the concrete sections. The availability of waterfront property for use as a construction basin, and the requirements for environmental and other regulatory permits for its use, may impose serious constraints on concrete box construction.

Water Depth

The deepest immersed tube tunnels in the United States have a maximum trench depth of about 135 feet below normal water level. Designs were prepared for an immersed tube tunnel for the English Channel in a depth of about 200 feet of water. The hydrostatic pressures at 300-foot depth would not impose unmanageable structural problems, but would require further development of joint details and a high grade of quality control in waterproofing. More important than hydrostatic pressure, the length of approach tunnels necessary to reach that depth at an acceptable profile gradient would be very great, so that the economic feasibility of an immersed tube tunnel at 300-foot depth would probably be controlled by the approaches rather than by the actual depth of the tunnel.

The problem of length of approach tunnels leads to the suggestion of founding the tunnel on top of a rock dike established on the bay bottom, in order to raise the tunnel profile line and shorten the approaches. This solution has been proposed for several deep-water crossings, but has yet to be implemented.

San Francisco Trans-Bay Tube

The San Francisco Trans-Bay Tube Tunnel carries two tracks of the Bay Area Rapid Transit (BART) System between San Francisco and Oakland (see Figure 8).[1] The tunnel has a length of 19,113 feet, composed of 57 tube sections, between ventilation buildings. It is by far the longest immersed tube tunnel in the world, and the first to be designed to resist the effects of a major earthquake. It passes beneath the San Francisco-Oakland Bay Bridge and is located to permit future construction of a parallel bridge. The alignment has two horizontal curves, with radii of 8,000 feet and 12,000 feet.

From the San Francisco shore, the tunnel profile descends at a 4% gradient to pass beneath the West Bay with a minimum cover of 5 feet below existing bay bottom (see Figure 9). For a short stretch across a narrow, deep natural trench, the top of the tube is exposed above the bottom and is covered with a rock fill blanket as a protection against scour. The profile rises to pass over a buried rock ridge, descends to pass beneath the Oakland shipping channel, and rises past this onto the Oakland shore. Seven vertical changes in grade are required. The lowest point of the tube trench is 135 feet below low-water level.

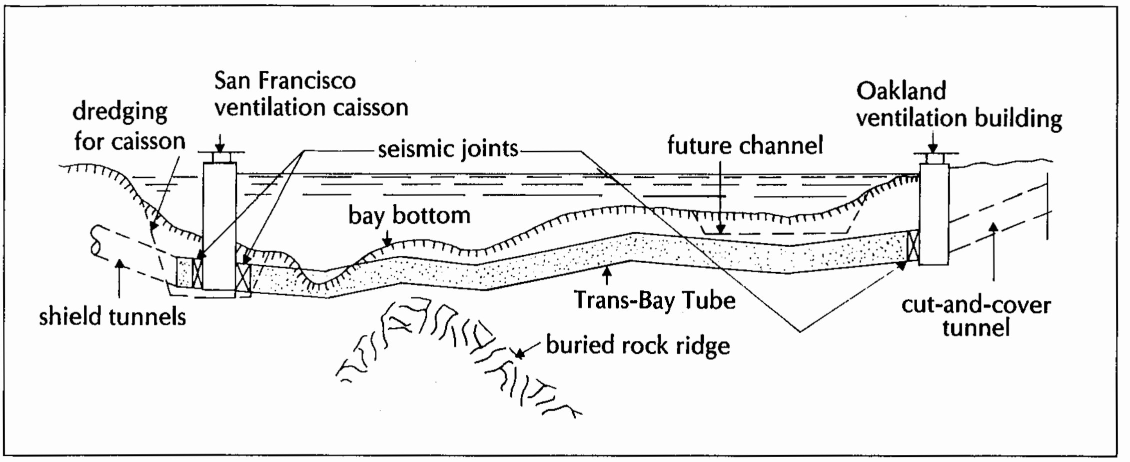

FIGURE 9. A profile of the Trans-Bay Tube Tunnel.

The general geologic conditions of the site are shown in Figure 10. Bedrock is generally at great depth beneath the bay, but a rock ridge rises to about 50 feet below the bay bottom near Yerba Buena Island. The West Bay basin is largely filled with a soft silty clay. The East Bay basin soils are mixed sands and clays.

The tunnel lies between the San Andreas Fault, which passes beneath the ocean west of San Francisco, and the Hayward Fault, which runs through the hills east of Oakland. Both of these faults have produced major earthquakes in the past 100 years. They serve to isolate the intervening block, including the bay and Trans-Bay Tube, in a seismically quiet zone, and no evidence of direct faulting beneath the bay could be found. Review of the geological conditions indicated that the possibility of direct fault displacement through the tube was so remote as to be negligible, but that the soil surrounding the tube would be subject to severe shaking. The intensity and duration of shaking were established for design on the basis of records of previous earthquakes in California.

After the tube alignment was set, the first important question to be decided was how deep the tube had to be buried. This question devolved into two further questions:

- Would the bay mud fail in shear (a mud slip) during the design earthquake, and if so, to what depth?

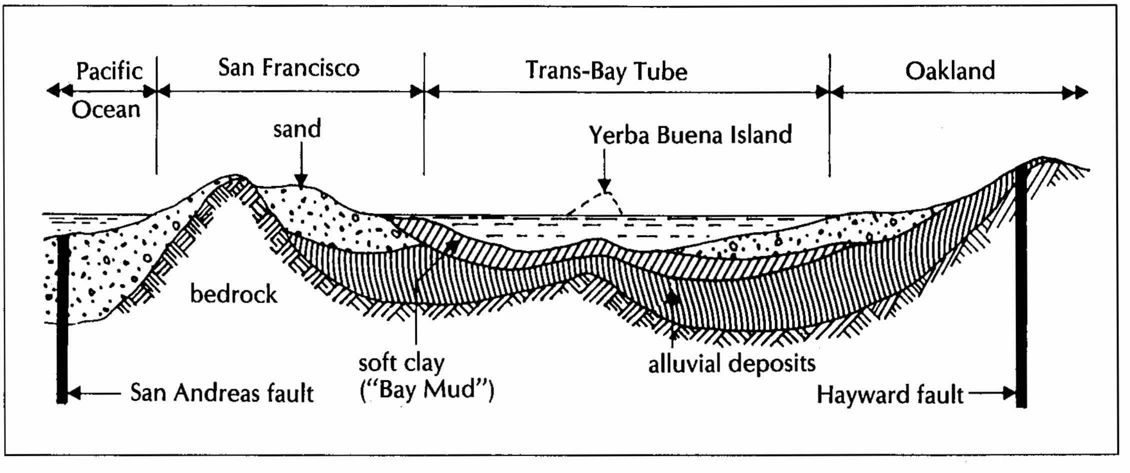

FIGURE 10. The geology of the Trans-Bay Tube Tunnel site.

• Could any of the bay bottom soils be liquefied during the design earthquake?

Although the samples of bay mud directly at the bottom were very weak, the rigidity increased rapidly with depth. From this analysis of bay bottom soils it was determined that if mud slips occurred (they had been reported in the 1906 San Francisco earthquake), they would be very shallow phenomena at this site, and could not extend deep enough to endanger the tube.

To investigate liquefaction potential, samples of representative soils were subjected to special dynamic laboratory tests. These tests demonstrated that it was possible to produce liquefaction, but that this would require either much larger vibrations or a much longer duration of shaking than would be expected during the design earthquake. Based upon these analyses, it was concluded that there was an ample margin of safety against either mud slips or liquefaction, and therefore no need to bury the tube deeper than the minimum depth profile. The minimum depth was determined generally by keeping the top of the tube structure about 5 feet below the natural bay bottom.

Preliminary estimates indicated that each concrete box section might be about $1 million less expensive than a steel shell section. However, it was judged to be very difficult to devise a fixed joint between the concrete tube sections that would remain reliably watertight when subject to earthquake vibrations. The alternative of providing a watertight flexible joint between each pair of tube sections was very costly, and was deemed inferior to the fixed, ductile welded steel joint. It was thus concluded that the steel shell design would provide a more ductile structure, better able to absorb the earthquake vibrations.

On the San Francisco shoreline, the tube alignment passes beneath the Ferry Building, an historic structure that had to be preserved. The San Francisco ventilation building was established in a caisson that was floated into place in an enlarged basin at the end of the dredged trench for the tube, 400 feet offshore (see Figure 9). The basin was backfilled with a special clay fill to create an impervious plug, through which the approach tunnels were driven by shield methods into the caisson. The caisson is protected against ship collisions by a wharf structure that completely surrounds it.

On the Oakland shore, the ventilation building is located on shore within the port facilities. Cofferdam construction was used for the ventilation building. The approach tunnels were constructed using cut-and-cover methods.

Because the center of mass of the San Francisco caisson is considerably above that of the tube structure, it will develop a rocking motion with respect to the tube sections under the vibration of an earthquake. In addition, the earthquake waves imposed on the tube will cause a longitudinal displacement between the end of the tube and the caisson. These combined actions require provisions for longitudinal, transverse, and vertical motions at the joint between the caisson and the tube, and some freedom of rotation about all three axes.

The principle of the seismic joint developed for the Trans-Bay Tube is shown in Figure 11.[2] It consists of two sections which together form a universal joint. The first section is a telescoping sleeve concentric with the tube shell, which permits longitudinal motion and rotation about vertical and transverse axes. The second section is a vertical plane along the outside of the caisson. This part of the joint permits vertical and transverse motion, and rotation about a longitudinal axis. The joints are sealed with neoprene gaskets sliding on Teflon-coated steel plates that are compressed by a series of short wire ropes.

Two such joints were provided on both sides of the caisson, and a third joint at the junction of the tube and the Oakland ventilation building, which is solidly anchored in firm ground.

After investigating several alternatives, the designers settled on the tunnel section shown in Figure 12. This is a single shell steel tube design, with separate compartments for each trackway and a central compartment divided into an upper emergency exhaust ventilation duct and a lower inspection and

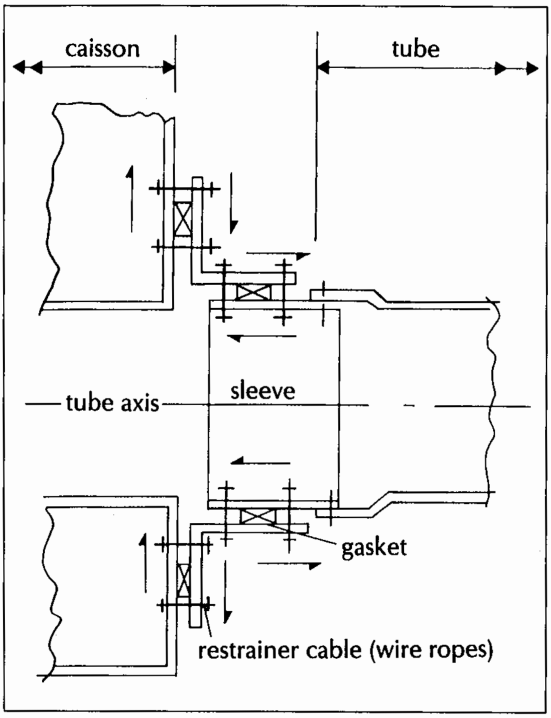

FIGURE 11. Conceptual design of sliding seismic joint used in the Trans-Bay Tube Tunnel.

utility gallery. The basic binocular shape is efficient for resistance to the earth and water pressures at a depth of 135 feet. The flat bottom is adapted to fit the screeded bed foundation, and the inward sloping sides minimize the trench width. The top ballast box permits the use of economical stone ballast.

Because of the presence of large stray electric currents resulting from operation of the direct-current traction power system, a cathodic protection system was provided for the steel shell. This system uses sacrificial anodes located on the bottom of the bay and connected to the steel shell through cables.

Figure 13 shows typical sections for dredging and backfill. Although the profile was kept as shallow as possible, the irregular configuration of the bay bottom combined with the maximum operating gradient for the trains resulted in trench depths of up to 70 feet. In these locations, the backfill was placed only to a height of 5 feet above the top of the tube structure, and the remainder of the trench was left open, to be filled by natural

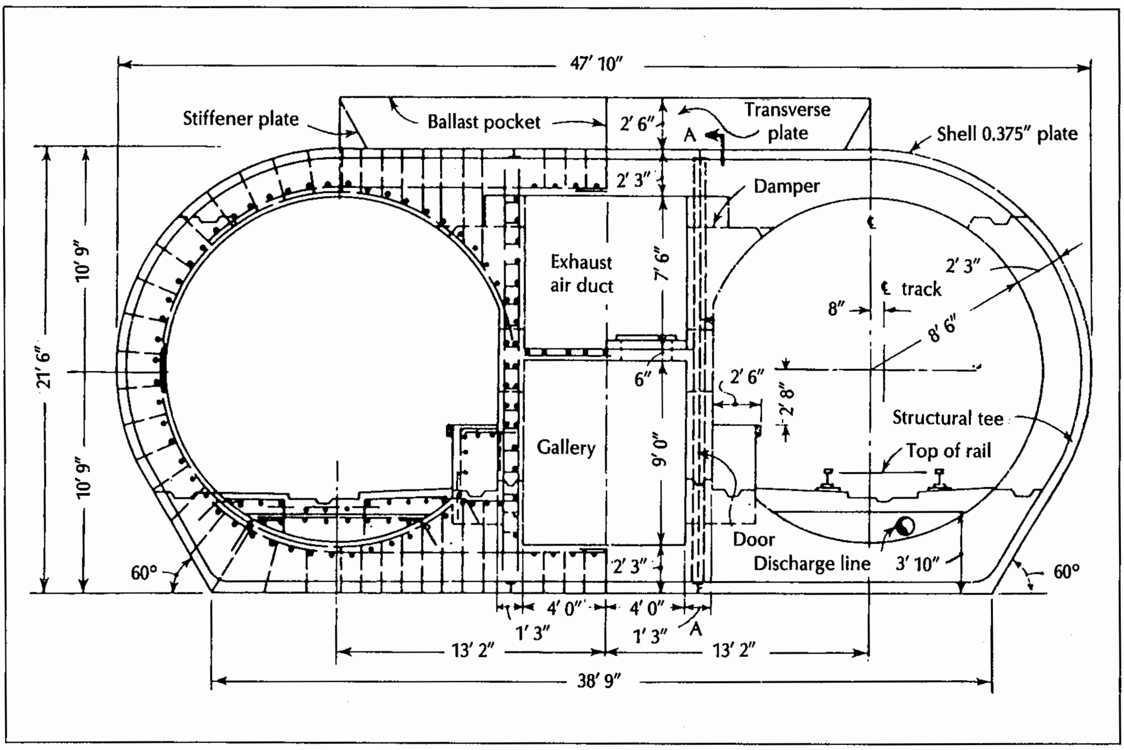

FIGURE 12. A cross section of the Trans-Bay Tube Tunnel.

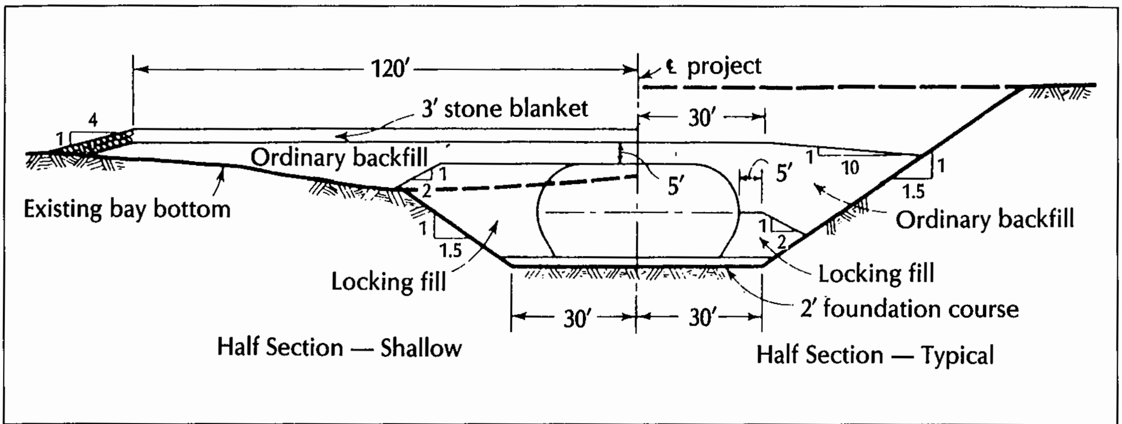

FIGURE 13. Dredging and backfill for the Trans-Bay Tube Tunnel.

siltation. At the other extreme, the top of the tube structure was exposed at or above the natural bay bottom in some locations. A blanket of stone was placed as protection against scour in these locations.

Rounded river gravel was used for the foundation course in order to facilitate the screeding operation. The locking fill was crushed rock, and the ordinary backfill was sand.

At the time of construction of the Trans-Bay Tube, the Port of Oakland was planning a major redevelopment of the Oakland Mole as a port facility. It was arranged that as part of the Trans-Bay Tube project, a dike would be constructed to enclose 140 acres, within which all of the dredged material except for the soft bay mud would be disposed. The total excavated volume was 5,600,000 cubic yards of which about 3,900,000 cubic yards was placed on the Oakland Mole. The remainder was barged out to sea and dumped at a location where prevailing currents would disperse it offshore.

The final design of the Trans-Bay Tube was started in May 1964. Construction for the principal contract, covering all structural work for the 57 tube sections and the San Francisco ventilation caisson, was started in April 1966 and completed in September 1969. Separate contracts for the Oakland ventilation building and for all electrical and mechanical installations followed, and were completed by December 1970. The total construction cost of all of this work was $110 million.

Second Hampton Roads Tunnel

One of the major harbors of the eastern United States is Hampton Roads, an estuary in southeastern Virginia. Because of the very heavy shipping traffic and the presence of extensive U.S. Navy facilities, the use of a bridge to cross this estuary has long been prohibited. In 1957, the first bridge-tunnel crossing in the world was completed between Hampton and Norfolk. This crossing covers a length of 3.5 miles, including a 7,200-foot two-lane immersed tube tunnel, two portal islands constructed in shallow water, and two trestle bridges connecting the islands to the shore at each end.

By 1970 traffic had grown to such an extent that a second parallel crossing was required. The layout of the combined twin bridge-tunnel facility is shown in Figure 14. The tunnels provide a clear navigation channel 4,500 feet wide by 50 feet deep, but at the deepest point the water depth is 70 feet and the trench reaches 120 feet below sea level. The total length of the precast tube sections is 6,898 feet, and the length between portals is 7,315 feet.[3]

The entire site is underlain with alluvial sediments that extend to a depth of over 1,000 feet. An organic silty clay is found in the trench bottom for a substantial length of the tunnel. This clay lies beneath the entire South Portal Island to a depth of 90 feet. The remaining soils are reasonably firm and offered no design or construction problems.

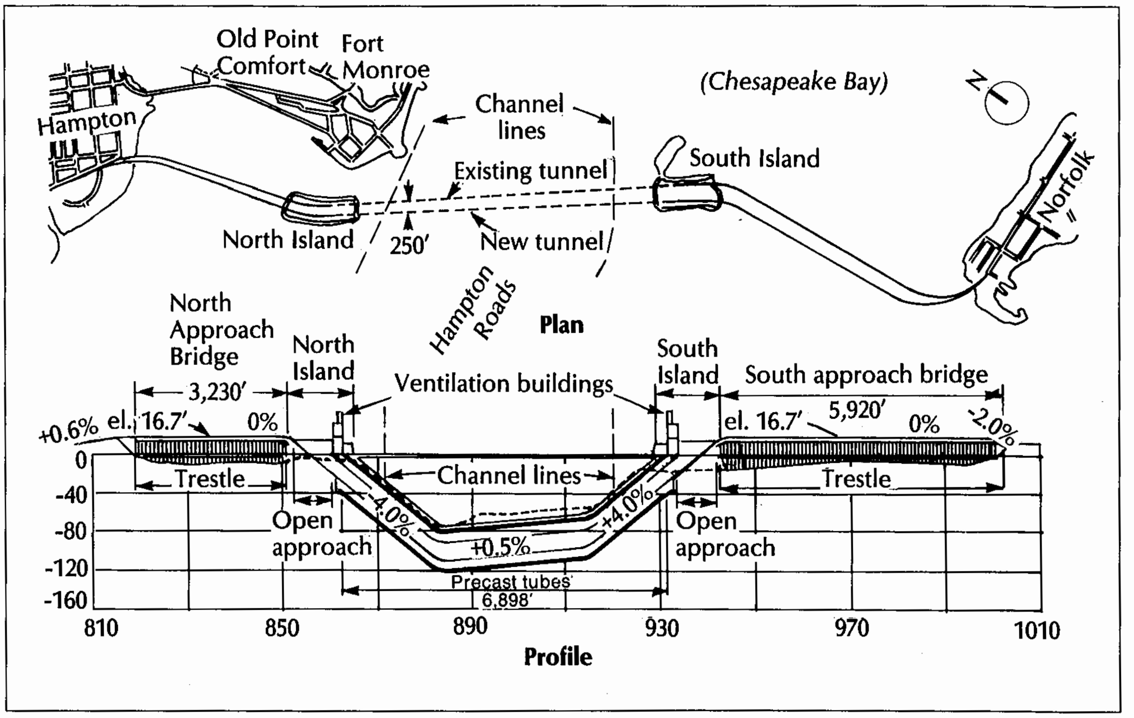

FIGURE 14. The bridge-tunnel layout for the Hampton Roads project.

The most important design question for this project involved the enlargement of the existing South Portal Island in order to accommodate the new tunnel. The original island had been constructed by dredging out all of the soft clay and replacing it with sand fill. Three options were considered for the construction of the new South Portal Island, as shown in Figure 15.

The first option, using a sheet pile cofferdam, would have minimized the extent of the island enlargement, but would have produced unacceptable disturbance to the existing tunnel. The second option for the South Portal Island followed the method used for the original tunnel — removal of all the soft clay and replacement with sand. Concern for stability of the dredged slope in the soft clay, and for lateral movement of the existing structure, would have required a spacing of 500 feet between tunnel centerlines. This layout would have required dredging and disposing of one million cubic yards of unsuitable material. Environmental restrictions would have made this option difficult and costly. The third option proved to be both technically sound and economical. This option involved consolidating the soft clays in place, utilizing a system of sand drains and surcharge. A finite element analysis indicated that at a spacing of 250 feet between tunnels, the settlements at the existing tunnel would be of the order of 0.5 inch and would cause no damage. This prediction was confirmed by monitoring observations during construction.

Hydraulic sand fill was the most appropriate material for the island and surcharge. However, environmental restrictions prohibited discharging hydraulic fill in the open water, so the entire site had to be enclosed with a rock dike before fill placement could begin. The soft clay was too weak to support the full height of the island plus the surcharge, so a series of berms was established to provide adequate safety against deep-seated slides during construction. All of this work resulted in enlarging the South Island from its original 3.5 acres to 14 acres.

When the island had been built up to about 12 feet above water level, 6,000 sand drains were installed by the jet boring process, and the surcharge was then built up to a

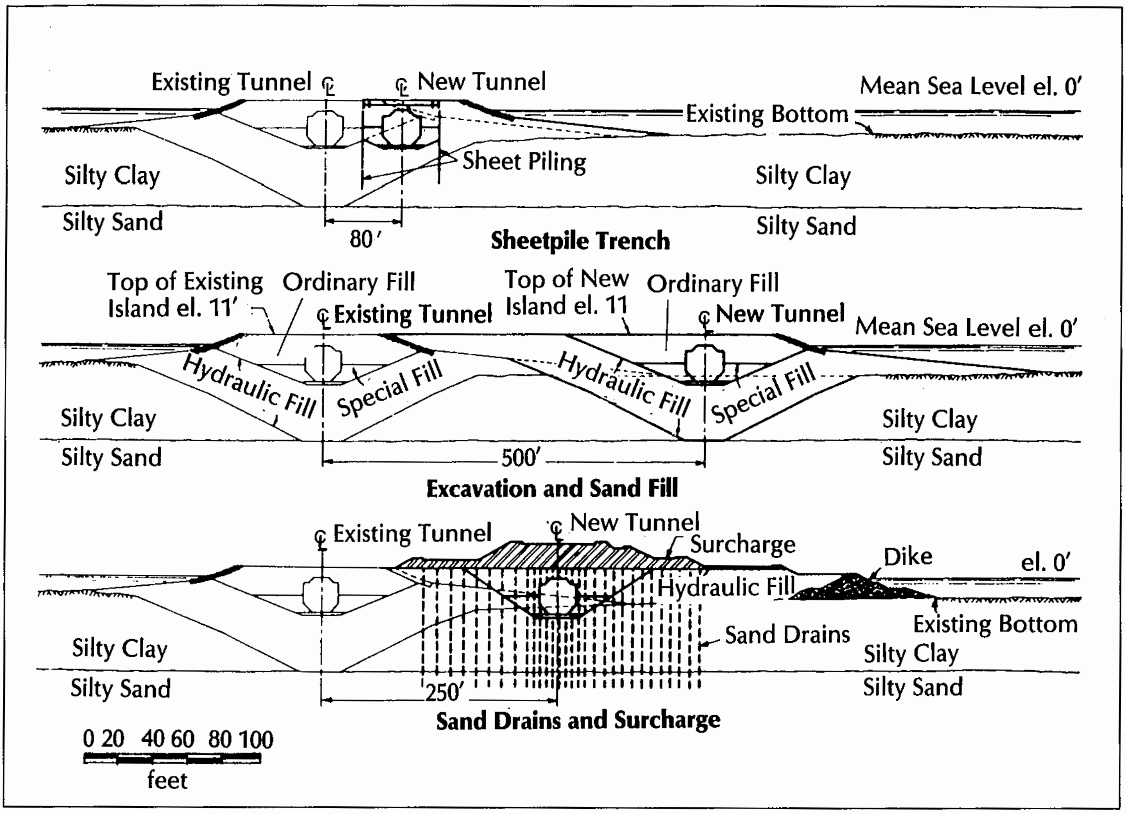

FIGURE 15. South Island design alternatives for the Hampton Roads project.

height of 52 feet above the bay bottom. This surcharge remained in place for a year, during which time it was covered with a sprayed emulsion to keep the loose sand from blowing. The island was heavily instrumented to monitor settling. During the year the surcharge remained in place, the settlement amounted to 13 feet. The surcharge was then removed, and subsequent settlements have been small.

A wide variety of alternative tube cross sections were studied — in rectangular, circular, and octagonal configurations, and using reinforced concrete, prestressed concrete, and composite structural steel and concrete shells (see Figure 16). Owing primarily to the availability of shipyard facilities, the double shell octagonal steel section proved to be most economical and was adopted for design. Twenty-one tube sections, each approximately 350 feet long, were fabricated at Port Deposit, Maryland, approximately 200 miles from the project site. These sections were towed to Norfolk with only sufficient keel concrete to stabilize them, and the interior concrete was placed at an outfitting dock in Norfolk. The tube sections were then placed on a screeded bed foundation.

Figure 17 shows a section through one of the ventilation buildings. The exhaust air is blown out vertically through the roof, and fresh air is drawn through grilles in the side walls into a plenum beneath the roof, from which the supply fans deliver it to the fresh air duct beneath the roadway.

The Hampton Roads area is subject to infrequent but severe hurricanes, during which the water level may rise above the tops of the islands. A portal tide gate is provided at the end of each ventilation building to permit closing off the tunnel in the event of a catastrophic high tide. This gate is a vertically sliding leaf that fits into a slot in the portal structure, and is equipped with rubber gasket seals. The gate can be operated either by

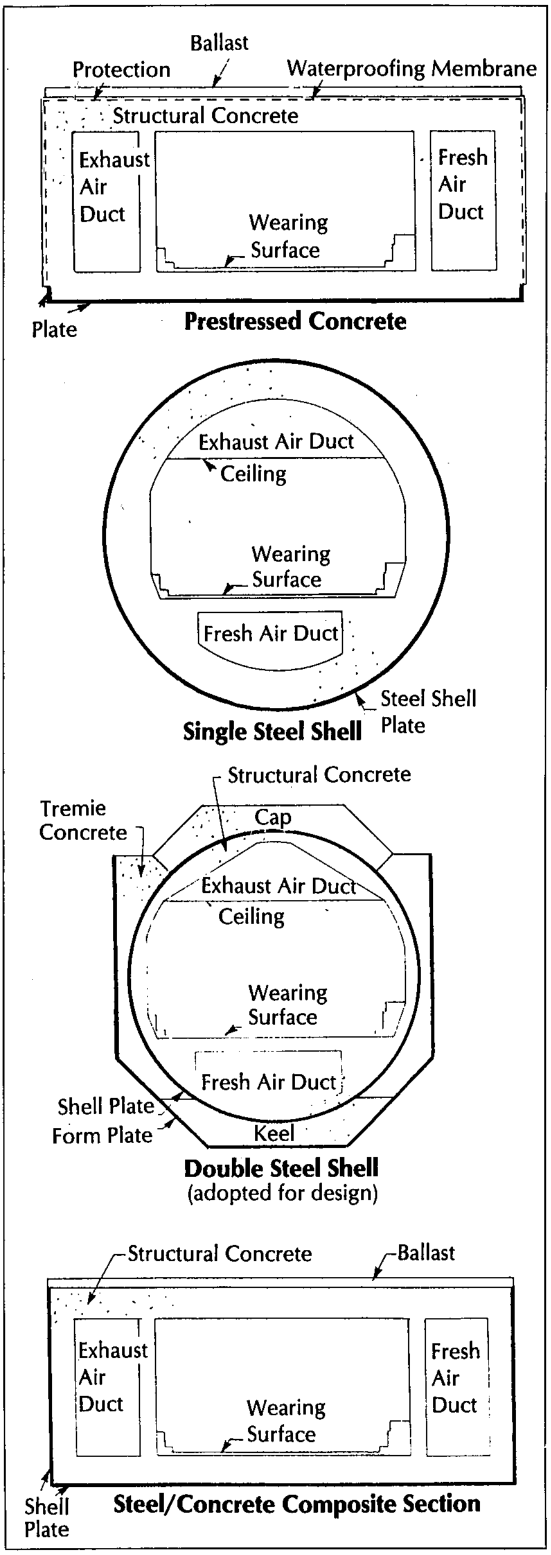

FIGURE 16. Alternative cross sections proposed for the Hampton Roads project.

electric drive, or in emergencies by hand crank.

Design of the Second Hampton Roads Tunnel was started in August 1969. The first construction contract, for the South Portal Island, was begun in July 1970. The project was completed in June 1976, at a total construction cost of $96 million.

Baltimore: Fort McHenry Tunnel

The Fort McHenry Tunnel is the largest highway tunnel project ever undertaken in the United States. The tunnel carries eight lanes of Interstate Highway 95 beneath Baltimore Harbor (see Figure 18). The tunnel project was selected instead of a high-level bridge primarily to reduce the impact on the historic monument of Fort McHenry, which lies immediately to the north of the tunnel. The total length of the tunnel is 7,150 feet between portals, of which 5,370 feet is composed of immersed tube sections.[4] The cross section includes twin double-bore tubes of double shell steel construction, providing room sufficient for four two-lane roadways. A typical double-bore tube section is 82 feet wide by 350 feet long, and displaced 35,000 tons at the time of placement. Sixteen pairs of these tubes make up the immersed tube portion of the tunnel.

Because the shipping channel is close to the eastern shoreline, the project required dredging a trench 1,300 feet long, 300 feet wide, and up to 70 feet deep into the eastern shore. The first four pairs of tubes were placed in this trench to carry the tunnel down to the depth required to pass under the shipping channel (see Figure 19). The perimeter of the trench was lined with bulkhead walls tied back with soil anchors that protected adjacent industrial facilities. In order to minimize the width of the approach trench and its effect on existing facilities, a careful study was made of the space required for placing the twin tubes in a common trench. The southbound tube sections were placed with the conventional twin-hulled placing barge. Because of the confined space, a special arrangement of heavy cranes mounted on narrow barges was devised to place the northbound tube sections

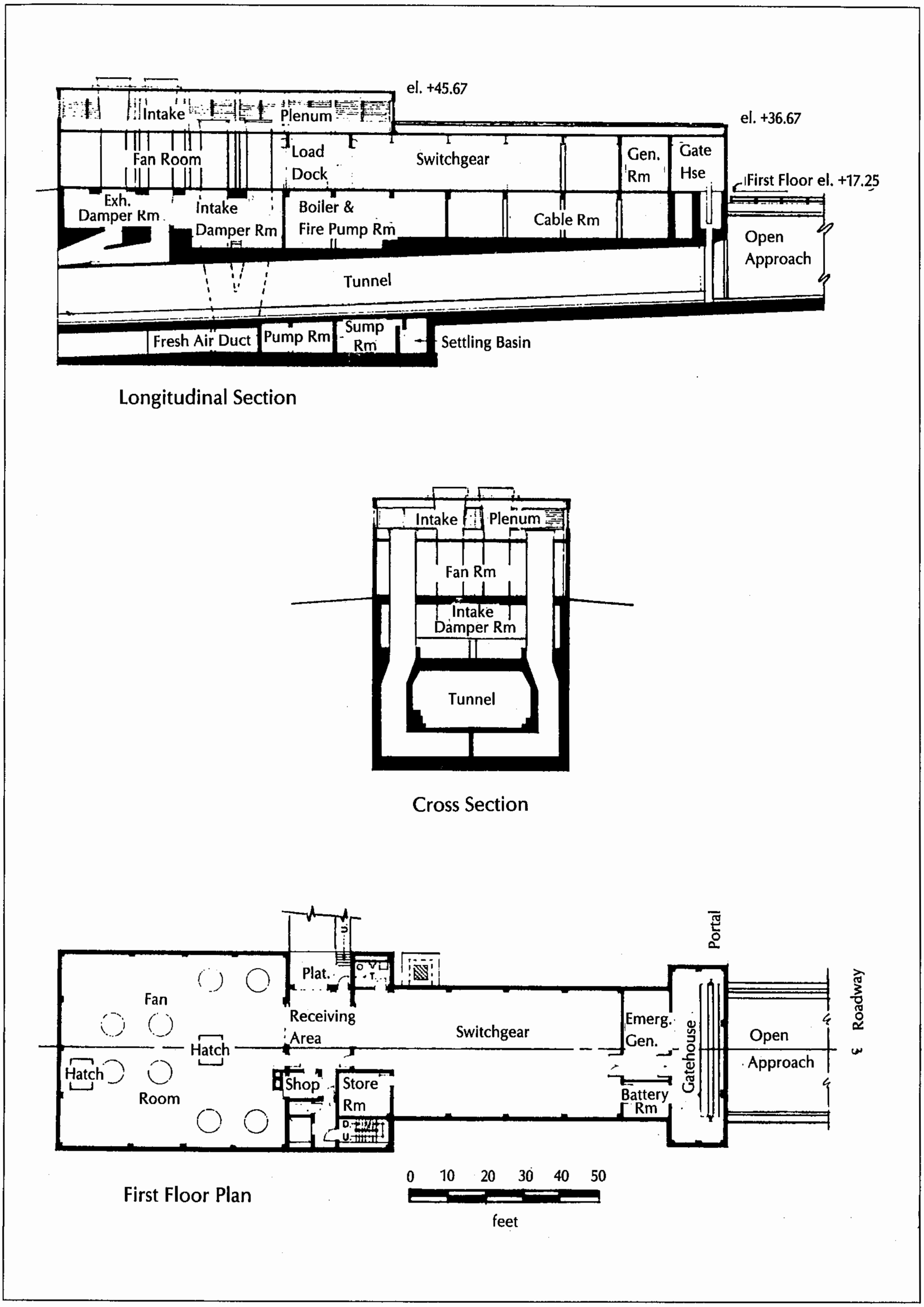

FIGURE 17. Ventilation building for the Hampton Roads project.

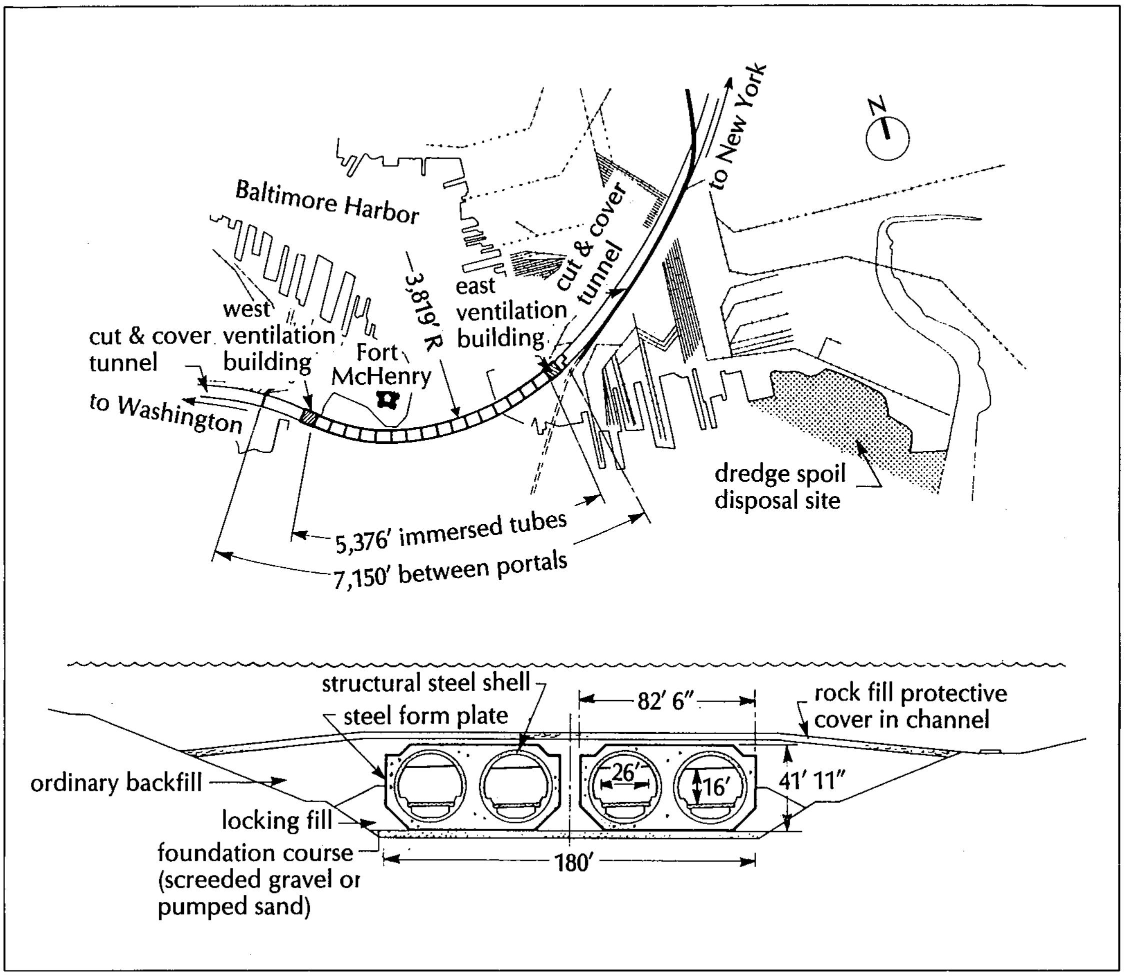

FIGURE 18. Plan and section of the Fort McHenry Tunnel.

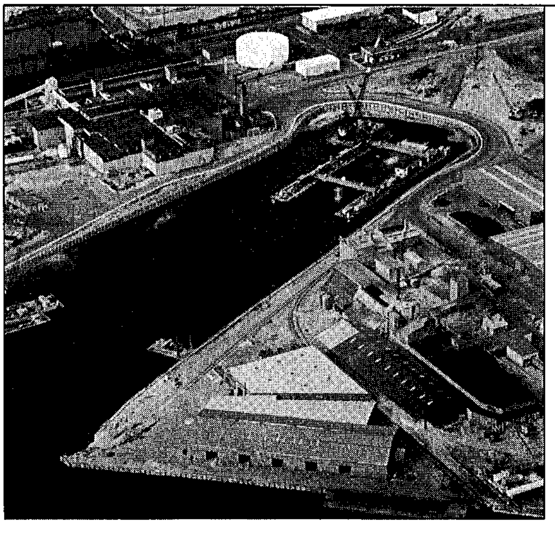

FIGURE 19. The east approach trench for the Fort McHenry Tunnel.

in shallow water at the upper end of the trench (see Figure 20).

The twin-shell tube sections were fabricated in a shipyard about 65 miles from the tunnel site (see Figure 21). One of the most difficult tasks on the project was to move the tubes from the shipyard to the outfitting site. The floating sections had to pass through several existing bridges, with clearances as little as 3 feet in some instances (see Figure 22).

The contract documents provided for alternative foundation construction methods, either the screeded bed or the pumped sand system. The successful bidder selected the screeded bed method.

The project included exceptionally stringent controls on disposal of dredge spoil

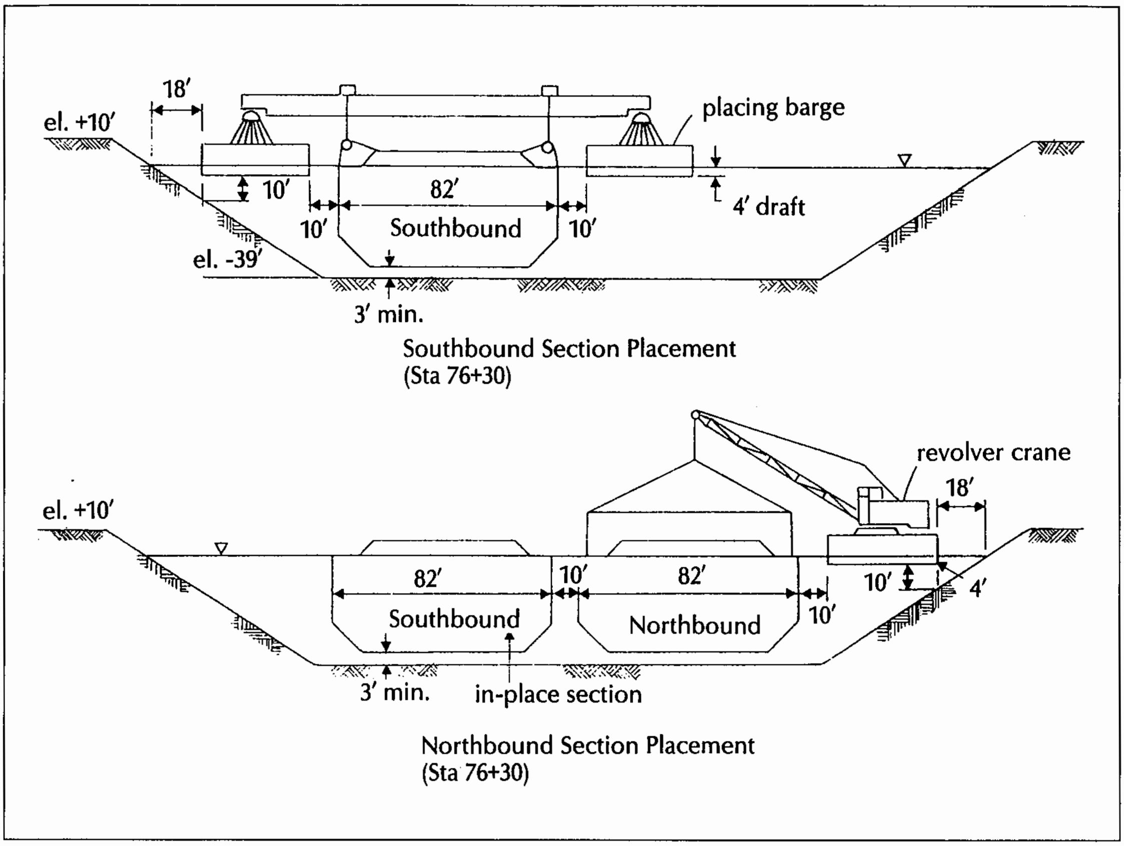

FIGURE 20. Tube placement clearances for the Fort McHenry Tunnel.

material. Before any dredging could be started, a 145-acre dredge spoil containment facility was required. The containment facility was constructed by enclosing a site about 1.5 miles from the tunnel with a cellular steel sheetpile cofferdam 5,500 feet long (see Figure 23). The disposal site was divided into two areas. The first area received all the soft, contaminated muck that comprised the top layer of harbor bottom sediments. The second area received the better grade sands and clays dredged up from the deeper parts of the trench. The second area has been stabilized by natural desiccation and is now being developed for a port facility, while the muck area may eventually be reclaimed as a park.

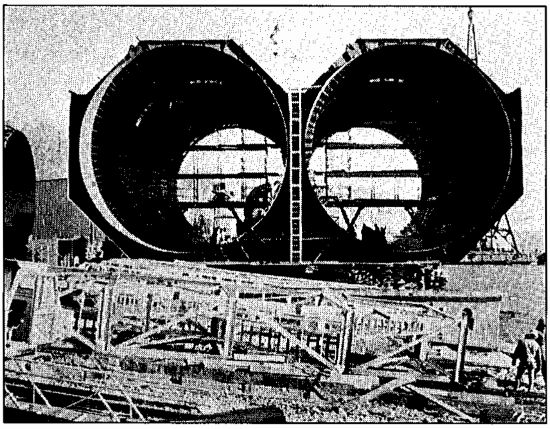

FIGURE 21. Tube fabrication for the Fort McHenry Tunnel.

The effluent from both disposal areas was discharged into a treatment basin where chemical flocculents were added to precipitate suspended solids. The effluent then passed over a wier into a settling basin in which a majority of the suspended material settled out. The final discharge into the harbor was cleaner than the present harbor water.

Design of the project began in September 1978. Construction of the main tunnel contract — covering trench excavation, furnish-

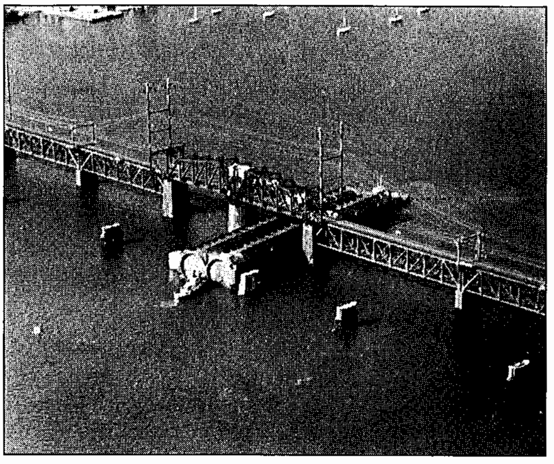

FIGURE 22. Towing a tube section to the outfitting site for the Fort McHenry Tunnel. Bridge clearances were extremely tight.

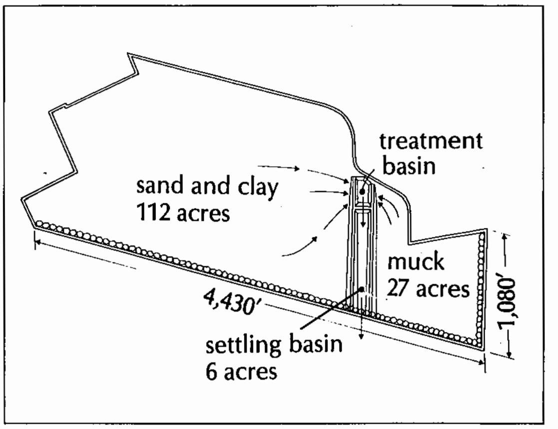

FIGURE 23. The dredge spoil containment facility for the Fort McHenry Tunnel.

ing and installing the 32 prefabricated tube sections, backfill and the dredge disposal facility — was begun in June 1980 and completed in January 1984. The tunnel was opened to traffic in November 1985. The $426 million tube contract was the largest ever awarded for a U.S. transportation project. Including subsequent contracts for cut-and-cover work, open portal approach structures, ventilation buildings, and all operating and finish installations and equipment, the total construction cost was $750 million.

Alternative Concepts

All tunnel projects involve their own special problems, and no two tunnels are exactly alike. There is a wide range of conditions for which immersed tubes have been found suitable. However, immersed tubes are not invariably the best alternative for all underwater tunnels. Alternative concepts are mined and shield driven tunnels.[5] Although their ranges of application overlap, the following general guidelines are helpful in selecting among these alternatives for any specific project:

1. Immersed tubes are especially suited to sites with moderate water depth (100 to 120 feet) underlain by alluvial deposits or marine sediments, with tidal cycles that provide several hours of slack water or modest current to facilitate tube handling and placement.

2. Environmental constraints associated with disposal of large volumes of dredge spoil may preclude immersed tube construction. If an immersed tube is the selected alternative, environmental problems associated with acquisition of a waterfront site for a construction basin may tilt the economic balance away from a concrete tube, towards a steel shell section.

3. The greater ductility of steel compared to concrete makes steel shell sections the favored choice for immersed tubes in seismic areas.

4. Mined tunnels are most economical in a free air construction environment, in dry ground requiring relatively little structural support. If continuous, competent rock is available at a shallow depth beneath the watercourse, a mined rock tunnel may be the preferred alternative. Great depths to sound rock, or extensive water-filled joints, will tilt the balance toward an immersed tube.

5. Shield driven tunnels are best suited to impervious ground. Special measures such as pressurized face machines, compressed air and clay blankets may enable shield tunnels to pass through pervious zones, but if these conditions pervade the site, the cost of a shield-driven tunnel increases sharply. Where existing development makes dredging trenches in from the waterfront objectionable, shield work may

well be appropriate. A number of tunnels have combined immersed tube sections under the water with shield tunnel approaches under the land on either shore.

Summary

Commonly, tunnel site conditions are not uniform over their length, which may range from less than one to several miles. Project site conditions place their own particular imprint on every tunnel project, posing unique challenges to the designers and constructors. The choice of tunnel concept is frequently a compromise amongst conflicting criteria. A single project may well involve a combination of different methods for different sections of the crossing, each method best adapted to the particular conditions of that section. This type of approach may result in a completed project that best meets engineering and cost criteria. Examples of such hybrid tunnel and bridge-tunnel layouts abound and their use is growing.[5] For underwater tunnels, the immersed tube concept, either alone or as a component of a hybrid layout, is well established and merits consideration for many future projects.

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Emerging Biological Treatment Methods: Aerobic and Anaerobic

Researchers have uncovered fundamental concepts of biological waste treatment and engineers are designing systems to make the environment safe now and in the future.

ROSS E. McKINNEY

IN THE FIRST HALF of this century biological wastewater treatment plants were designed on a trial and error basis and emphasized structures and hydraulics. Design engineers knew next to nothing about the biological processes that were the very heart of the biological treatment plants that they were designing. Consequently, some biological treatment plants failed to provide the desired treatment.

Early Studies

Prior to the late 1940s and early 1950s, wastewater treatment design required little knowledge of biological concepts, and sanitary microbiology had no interest in treatment systems. The theory of biological wastewater treatment was limited to the point of non-existence. During this period, both faculty and students at M.I.T. recognized this void in the research and raised more questions than there were answers available. Laboratory experiments were developed to combine basic concepts with potential engineering systems. Although the research involved was still conducted on a trial and error basis, each experiment saw the number of trials producing errors quickly reduced, and each success led to a better understanding of treatment concepts.

One faculty member, C.N. Sawyer was heavily involved in biotreatment research for industrial wastewater treatment at this time. As a chemist, he approached biological treatment from a chemical point of view. He was interested in how much nitrogen and how much phosphorus were required for trickling filters and activated sludge. Sawyer found that sound biological treatment of industrial wastes required specific quantities of nitrogen and phosphorus, and that this treatment produced varying amounts of excess solids at different temperatures.[1,2,3]

At the same time, questions were being raised about the microorganisms that comprise biological treatment systems. Since sanitary bacteriology had limited answers and conventional bacteriology provided even

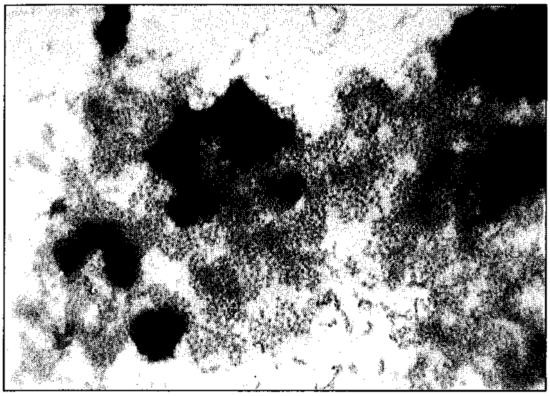

FIGURE 1. Young activated sludge grown on soluble organics showing individual bacteria around edges of dense clumps of bacteria (970 X).

fewer answers, it was necessary to start with aerobic bacteria and build a knowledge base to explain how these bacteria stabilized organic wastes and to discover what were the quantitative relationships exhibited under different environmental conditions. Since bacteria were not the only microorganisms involved in the treatment processes, the study expanded to include fungi, algae, protozoa, crustaceans and nematodes. The problem was defining microbiology under low food conditions. No one appreciated the impact that the specific environment played in the growth of particular microorganisms in mixed cultures.

A.M. Buswell in the early 1920s made extensive microscopic examinations of activated sludge and identified several groups of microorganisms from physical appearances.[4] Filamentous bacteria predominated in this activated sludge: *Crenothrix, Sphaerotilus,* and some *Zooglea ramigera.* In 1935, C.T. Butterfield isolated *Zooglea ramigera* in pure culture and stated that it was the primary floc-forming bacteria in activated sludge.[5] L.A. Allen attempted to evaluate the bacteria in activated sludge.[6] He found that homogenized sludge contained 2.2 billion bacteria per ml, but he was unable to isolate *Zooglea ramigera.* The bacteria he found were classified as *Achromobacter, Chromobacterium* and *Pseudomonas.*

There was little concern about the specific metabolism of zoogleal bacteria making up activated sludge. Researchers assumed that zoogleal bacteria grew in any substrate, since activated sludge was formed in most wastewater. Another assumption was that zoogleal bacteria were able to obtain food more efficiently by absorbing it into the gelatinous matrix surrounding the zoogleal bacteria. Since these assumptions had little impact on design, design engineers accepted them readily.

Floc Formation

In 1950 there were some interesting questions raised at M.I.T. about the role of *Zooglea ramigera* in activated sludge:

- If *Zooglea ramigera* was so important in activated sludge, why was it so difficult to isolate in pure culture?
- If the gelatinous material absorbed food so readily for the zoogleal bacteria, why was the gelatinous matrix impossible to stain with ordinary bacterial stains?
- How could one group of bacteria metabolize so many different types of organic compounds?

In an effort to answer these questions, researchers at M.I.T. employed a technique in which the aeration tank was simulated in pure culture aeration systems with a soluble organic substrate. Their results showed that several bacteria isolated in pure culture were capable of forming floc in the same manner as *Zooglea ramigera.*[7] Further studies revealed that many other common bacteria could be isolated from activated sludge and could form floc similar to the zoogleal bacteria.[8] There was no need for special zoogleal bacteria to produce activated sludge. It soon became apparent that almost any bacteria could be made to flocculate under the proper environmental conditions (see Figure 1). From the design engineering standpoint, this research changed the techniques required for activated sludge development.

Examination of floc indicated that motile bacteria predominated over non-motile bacteria because of their ability to remain dispersed, presenting a greater surface area to mass ratio for more efficient food gathering

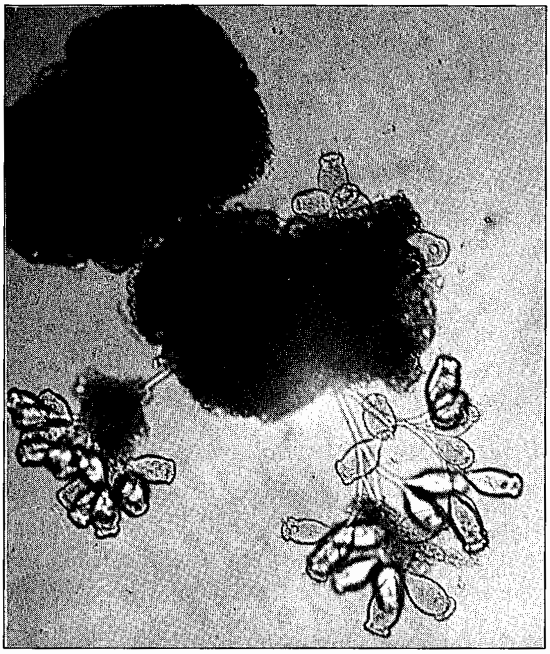

FIGURE 2. Colonies of stalked ciliated protozoa growing on dense clumps of bacteria in activated sludge (430 X).

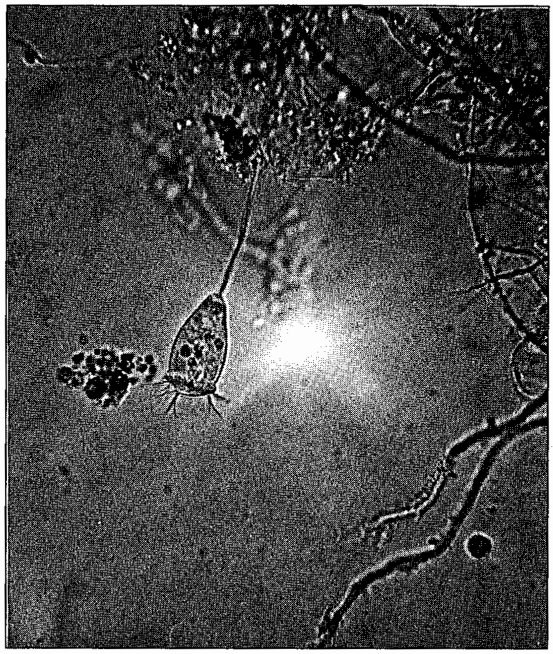

FIGURE 3. Single stalked ciliated protozoa *(Vorticella)*, showing the cilia used for catching dispersed bacteria, aids in the production of highly clarified effluent that is characteristic of a well-operating activated sludge system (970 X).

across the cell wall. As long as food remained unmetabolized, the motile bacteria remained dispersed. Once the food was metabolized, the bacteria could not remain motile and tended to form tiny aggregates under the mixed conditions created by aeration. Repeat feeding of fresh food resulted in the partial dispersion of active bacteria and the accumulation of dead bacteria residues. Examination of the dead bacteria residues indicated that these residues were predominantly polysaccharide materials that appeared similar to the gelatinous material produced by the zoogleal bacteria.

As Buswell had observed many years earlier, activated sludge was a mixture of bacteria and protozoa (see Figure 2). Research on mixtures of protozoa and bacteria confirmed earlier observations that protozoa play a secondary role in activated sludge by clarifying the liquid-dispersed bacteria and by producing additional dead cell mass to accumulate as inert suspended solids in the activated sludge floc (see Figure 3).[9] Thus, it was established that activated sludge floc can be created by all the different species of bacteria and protozoa that are able to grow in the aeration tank. Accumulation of inert suspended solids accompanied by aeration equipment mixing helps provide additional surfaces for flocculation. However, the microbes must have adequate metabolism time for floc formation of value to result.

Organic Metabolism

After having established the formation of activated sludge floc, attention was turned to the metabolism of organic matter by bacteria in the aeration tank. Hoover and Porges, in their 1952 study of activated sludge treatment of dairy waste, indicated that approximately 38% of the skim milk substrate was oxidized in 6 hours.[10] The remainder of the substrate was converted to microbial protoplasm that had an empirical formulation of $C_5H_7O_2N$. Once the skim milk was metabolized, the microbes underwent endogenous respiration with oxidation of the microbial mass produced by synthesis. Hoover and Porges thought that it was possible to have complete oxidation of microbial solids so that no excess activated sludge would have to be removed from the system. However, total oxidation was not possible, since approximately 20% of the cell mass produced by synthesis remained as dead cell mass after endogenous respiration was complete.

Although Hoover and Porges' studies did not result in total oxidation, they stimulated further studies into the metabolism of various organics in order to delineate energy-synthesis relationships. Additional studies at M.I.T. indicated that metabolism could be grouped into major classes of organics such as carbohydrates, proteins, and fatty acids.[11] The resultant substrate energy was deemed critical for determining the synthesis of newly activated sludge. A later study pursued a different approach to data evaluation that permitted delineation of the break between synthesis and endogenous respiration.[12] This study revealed that different classes of organics exhibited different energy-synthesis relationships. It was not until continuously-fed activated sludge systems began to be operated in a completely mixed mode that the problem was found to reside with the batch-fed studies. In the batch-fed studies, the initial high-food concentration resulted in different patterns of metabolism for the major groups of organic compounds. Instead of being metabolized to normal cell protoplasm, carbohydrates were converted to polysaccharide. This slime production resulted in lower oxygen requirements for synthesis and increased dead cell mass accumulation since the microbes could not metabolize the slime. Amino acids and fatty acids furnished better results since, unlike carbohydrates, they could not be processed to slime.

The development of basic energy-synthesis relationships was handicapped by the failure of most investigators to recognize that endogenous respiration occurs at the same time as synthesis and that the two reactions are independent. When completely-mixed activated sludge systems operating on a continuously-fed basis were studied it was then possible to develop a simple evaluation of energy-synthesis and endogenous respiration relationships. Started at M.I.T. back in the 1950s and continued over the past 25 years without major change, these studies revealed that one-third of the energy in the biodegradable organics is oxidized. The energy released from this oxidation is then used to convert the remaining two-thirds of the energy into cell protoplasm which immediately undergoes endogenous respiration at 2%/hr at 20°C, based on the active microbial mass. The development of these fundamental relationships permitted the formulation of design equations for use in field scale designs.[13,14,15]

Field Applications

Design engineers in the 1950s were not thoroughly comfortable with the new ideas generated from the current research. Full scale plants would have to be designed, constructed and operated satisfactorily before they were going to accept the fundamental approach to activated sludge design.

Regulatory engineers did not readily accept the new ideas either. It took special situations to demonstrate that these concepts worked as well in the field as in the laboratory. Initial applications were with industrial wastes that could not be treated economically with conventional design concepts. In the 1950s industries were just beginning to look seriously at wastewater treatment and responded positively to new ideas that promised efficient treatment at relatively low cost.

The first application of basic concepts to engineering design was at a small cotton textile plant located in a residential area of New Jersey.[16] The wastewater from the plant contained highly alkaline, carbohydrate type wastes that were considered unsuitable for treatment with activated sludge. The pH was 11 to 12, indicating caustic alkalinity. Microorganisms in biological wastewater treatment prefer a pH range from 6 to 9 and are killed either by strong acids or caustics. In order to achieve the proper pH, acid is normally added to caustic wastewater in sufficient quantities to drop the pH down to somewhere between 7 and 8. The carbohydrates in these textile wastes were primarily starches that stimulated the growth of filamentous bacteria rather than

FIGURE 4. Filamentous bacteria creating a poorly flocculating activated sludge (100 X).

normal activated sludge bacteria. The filamentous activated sludge produced from carbohydrate wastewater appeared like large balls of cotton fibers and settled very poorly in the final clarifiers (see Figures 4 and 5). Laboratory studies showed that it was possible to treat this wastewater with activated sludge provided that the system was completely mixed. In order to employ the same concepts in the field design as used in the laboratory, the aeration tanks were designed in modular units so that the treatment system shifted as the plant production changed. Since this wastewater was deficient in nitrogen and phosphorus, supplemental N in the form of ammonium salts and P in the form of phosphate salts were added to provide the bacteria with these two essential nutrients. By using complete mixing with extended aeration (24 hours) it was possible to minimize the amounts of N and P supplied.

The high concentration of caustic in the wastewater had to be neutralized initially with sulfuric acid until the bacteria level rose to the levels required for carbohydrate metabolism. One of the primary end products of aerobic metabolism is carbon dioxide. This supply of carbon dioxide can accomplish the necessary neutralization of the incoming caustic as long as the caustic is not added too fast. The mixing of fresh wastewater with the activated sludge was able to neutralize the caustic at the same rate as it was added. Thus, no further injections of sulfuric acid were needed to keep the pH in the aeration tanks at a suitable level.

This plant clearly established the concepts of complete mixing in the field. Later, a process change resulted in a change from alkaline to acidic wastes. There was no change in the waste treatment efficiency of 97 to 98%. However, acid-enzymatic treatment of the cotton cloth proved unsatisfactory and the process was changed back to the normal caustic kiering. Eventually, black sulphur-type dye wastes were added to the treatment process. The success of this plant in treating textile wastes led to the adoption of these concepts for other types of textile waste problems in Pennsylvania. There is one interesting note. A large textile manufacturer requested that a major New York consulting firm examine this new treatment process and evaluate it for use in their own wastewater treatment process. The consulting firm sent a young engineer to examine the process. He took one look at the simple construction and left without even looking at the data. His report indicated that the process had no value and should not be considered. The net result was a more expensive treatment process for

FIGURE 5. Filamentous bacteria are shown congregating with dense bacterial clumps in a poor settling activated sludge (970 X).

the industry.

One of the major problems associated with industrial wastewater was developing a satisfactory technique for evaluating the organic strength of the wastewater. At that time, municipal wastewater treatment plant operators used a test that measured the amount of oxygen the microorganisms utilize in a completely closed system at 20°C over a five-day period under aerobic conditions, designated the BOD5. Since the solubility of oxygen in water is very low, about 9.1 mg/L at 20°C at sea level, the amount of organics must be low to permit the test to be accurately run. However, the amount of oxygen used over a five-day period is not the total oxygen required by the bacteria. The BOD5 test does not measure the theoretical oxygen demand of an organic compound. Industrial engineers have found the BOD5 frustrating to work with in testing industrial wastes. Sometimes it yielded accurate results; at other times it yielded totally inappropriate results. The search for a new test led to the dichromate COD test that furnished the total oxygen demand value in two to three hours. However, the COD test produced total oxidation rather than just microbial oxidation. COD data and BOD5 data were not correlated for many years. C.N. Sawyer and others showed that the problems with using the BOD5 test on industrial wastes were the requirements for nutrients and for a microbial seed that was acclimated to the wastewater being tested. The use of a reasonable population of acclimated bacteria allowed the BOD5 test to be used for evaluating industrial waste and municipal sewage.

The next major opportunity to apply these concepts came with pharmaceutical wastewater produced during the manufacture of penicillin. The process wastewater from the penicillin manufacturing facility had been blamed for creating problems at a new municipal trickling filter plant that serviced the facility. In an effort to alleviate the problems, the industry had constructed its own pretreatment plant for initial treatment of its wastewater prior to discharging into the municipal sewage system. There was concern that residual penicillin would be toxic to the microorganisms in the biological pretreatment plant and that the wastewater was too strong to produce the desired effluent quality. A single-stage, completely-mixed activated sludge plant was constructed and placed into operation with excellent results.[17] The influent BOD5 ranged from 5000-7000 mg/L and the effluent was under 50 mg/L. However, the removal of this organic load from the municipal wastewater treatment plant demonstrated that these industrial wastes had not been the cause of the treatment plant problems.

A third field application demonstration plant was a small chemical plant in Ontario that was faced with having to reduce the phenols in its wastewater. The process wastewater contained approximately 2000-3000 mg/L mixed phenolics with a COD from 6000-8000 mg/L. Research at M.I.T. on microbial metabolism of aromatic compounds had indicated that phenolic compounds could be treated biologically, if the completely-mixed biological reactor did not permit the phenol concentration to rise to the toxic level.[18] The treatment plant demonstrated that it was possible to design a single-stage activated sludge system capable of reducing the phenols in the effluent to under 0.1 mg/L. Official data from the Ontario Water Resources Commission indicated that the system yielded an effluent with only 0.4 mg/L phenol, a 99.99+% reduction. The stability of the system was verified when an accident ran the influent phenolics to 6000 mg/L. At that level, the biological system was definitely overloaded, but it recovered quickly.

These field installations were all concerned with industrial wastewater treatment. Efforts to apply these same principles to municipal wastewater were met with complete opposition from regulatory engineers responsible for approving the design plans and specifications of new treatment plants. The argument was used that industrial wastes were different from domestic wastewater and that, therefore, the treatment concepts were, and had to be, different. These excuses prevailed until the City of Grand Island, NE, needed a new wastewater treatment plant to handle the wastewater from a proposed meat packing plant along with handling municipal wastewater. The problem of handling the combined municipal-industrial wastewater created the opportunity to demonstrate that complete-mixing activated sludge was able to treat municipal wastewater as well as industrial wastewater.[19]

Microbial Metabolism

The success of these industrial wastewater treatment plants stemmed from the research conducted at M.I.T. during the 1950s. One facet of that research dealt with the relationship between the chemical structure of the organic compounds in wastewater and the ability of microbes to metabolize those compounds. There had to be a relatively simple pattern of microbial processing of organics in wastewater. Starting with simple organic compounds, a series of studies were made in the laboratory that demonstrated the common patterns of metabolism for both energy and synthesis.[20,21,22]

The problems with certain industrial wastes and the incomplete metabolism of synthetic detergents provided the opportunity to further apply the fundamentals of microbial metabolism to real world situations. One of the studies determined that bacteria metabolized small, soluble organic molecules first and then metabolized more complex organic molecules. Metabolism of the small molecules always started at the most oxidized chemical group. Carboxyl groups (-COOH) were more reactive than hydroxyl groups (-OH); and hydroxyl groups were more reactive than methyl groups ($-CH_3$). Metabolism of each organic compound followed a simple pattern. Energy was released by the microbial oxidation reactions and then applied to synthesis reactions for the creation of new microbial mass.

Bacteria have the ability to take in organic molecules that have 12 carbon atoms or less without any difficulty. Larger molecules have to be broken down to small molecules before they can assimilated by the bacteria. Many compounds such as starch, cellulose and proteins must be hydrolyzed to simple sugars and amino acids before being metabolized. Large molecules that cannot be hydrolyzed can be metabolized; but the pattern is a little different. In this case, metabolism starts at the most reduced end at a methyl group ($-CH_3$) instead of starting at the most oxidized end of the molecule. The methyl group actually dissolves into the lipids making up part of the cell wall structure. The oxidation reactions begin at the methyl group dissolved in the cell and convert it to a carboxyl group (-COOH) which then fits into the normal pattern inside the cell. The molecule is then broken into units having two carbon atoms each, and the rest of the organic molecule is simply pulled inside the cell.

Examination of the various metabolic reactions with the different microorganisms indicated that they all followed the same general patterns. At first, it appeared that every bacteria and every organic compound followed special metabolic patterns with quite complex routes. Closer examination revealed that there were very few biochemical reactions within the microbial cell. In fact, the same reactions used for breaking organic compounds down for energy could be used for creating new organic compounds for cell mass. The energy levels of the various reactions determined whether the reaction was an oxidation reaction for energy or whether it was a reduction reaction for synthesis. There were only five primary reactions, regardless of the organic matter under metabolization. The primary reactions either added or removed two hydrogen atoms (2H), water (H_2O), carbon-carbon bonds (C-C), ammonia (NH_3) or phosphate (PO_4). Lesser reactions operating at a secondary level included the addition or removal of sulphur (S) as either sulfates ($-SO_4$), or sulfides (-SH) and chloride (Cl). The ability to remove the chloro group (-Cl) from certain organic compounds has proven of value in reducing the toxicity of these synthetic organics. The inherent simplicity of the biochemical reactions in metabolism lessens the problems in determining the biodegradation of new organics that are being synthesized for industrial application. Instead of having to uncover large and complex metabolic patterns, it is only necessary to examine a few series of recurring reactions.

All biochemical reactions are catalyzed by enzymes that are specifically targeted for each reaction. These enzymes have three components: the apoenzyme, the coenzyme and metallic activators. The apoenzymes are large proteins that determine where the reaction will occur. The coenzymes determine the specific chemical reaction that occurs and the metallic activators are important in orienting the enzyme and in electron transfer. The microbes have very few enzymes and must use them repeatedly. For this reason the reactions require both the rapid regeneration of enzymes for reuse and the alteration of enzymes to produce new reactions. The apoenzyme tends to be the part of the enzyme that is changed most often while the coenzymes and the metallic activators often remain the same, since the same basic reaction is performed even though it may be at a new chemical point.

By understanding the basic biochemical reactions the microbes use in synthesis of their protoplasm, it is possible to estimate the potential reactions that the bacteria can bring about in metabolizing industrial organics, both natural and synthetic. Since bacteria synthesize aromatic compounds as part of their proteins, it was only natural to expect that bacteria should have the natural ability to metabolize phenol and phenolic derivatives, even though phenol is toxic and is used as a disinfectant. Even the key ingredient in Orlon, sulfonated acrylonitrile, could be metabolized in the correct environment.

During and after World War II synthetic detergents were produced and used extensively. The most common detergent was an alkyl benzene sulfonate (ABS) made from petroleum residues. Its expanded use after World War II created a serious problem in activated sludge plants and in streams receiving treated effluents. The microbes could not completely degrade the ABS syndet in a well-operating activated sludge plant. The remaining syndet foamed badly and covered the aeration tanks with a foam that was only partially stabilized by the residual proteins in the wastewater. Research at M.I.T. in the 1950s demonstrated that the problem was with the chemical structure of the ABS syndets.[23,24,25,26] The use of a crude petroleum fraction resulted in the synthesis of a large number of isomers with a general (rather than a specific) dodecylbenzene sulfonate structure. The bacteria separated the biodegradable and the non-biodegradable fractions and allowed the non-biodegradable fractions to accumulate in the liquid phase. It took considerable research to demonstrate to the detergent industry that the bacteria followed specific patterns of metabolism, and that a change in raw materials could produce more agreeable biodegradable syndets. Once the public demanded that the detergent industry change its product, the industry changed in the United States and Europe and the problem disappeared in these areas.

Mixing

In the early 1960s the advent of complete mixing concepts provoked discussions on the value of complete mixing versus plug flow activated sludge systems. Mathematically, plug flow systems produce a better quality effluent than completely mixed systems.[27] The effluent quality for a plug flow activated sludge system was predicated with the following equation:

$$F = (Fi)(e^{-Kt})$$

Where:

F = unmetabolized organics remaining, mg/L BOD5

Fi = initial organics, mg/L BOD5

K = metabolism factor, 1/hr

t = aeration time, hrs

The effluent quality for a completely mixed activated sludge system was predicated with this equation:

$$F = Fi/(Kt + 1)$$

The unmetabolized BOD5 will be less in the plug flow system than in the completely mixed system for reasonable aeration times. Twenty years later, there is still considerable discussion on the comparative merits of the two processes.

The complete mixing system produces a better environment than the plug flow system for maintaining a balanced microbial population over varying organic loading conditions that occur in the real world. Laboratory and field data proved that complete mixing activated sludge systems were superior to many activated sludge plants that were similar to plug flow systems since they possessed long, narrow aeration tanks (see Figure 6). However, research showed that the conventional activated sludge systems were not entirely plug flow systems. A significant body of research demonstrated that longitudinal mixing was significant in long, narrow aeration tanks.[28,29,30,31] The longitudinal mixing in the aeration tanks was found sufficient to create complete mixing. In actuality, these systems are partially mixed systems.

Other researchers at Northwestern felt that three compartments would produce better results than a single tank since the three tanks would better approach the plug flow concept.[32,33] Mathematically, the effluent quality from the three-compartment system should be superior to the single tank system. Researchers at M.I.T. in the early 1950s had already examined a multi-compartment system. The results with a ten-compartment aeration tank showed that stabilization was essentially complete after the third compartment. A three-compartment aeration tank was tested next. Stabilization was essentially complete after the first compartment. These results and the simplicity of a single tank system demonstrated that a single tank system was preferred over the multi-compartment aeration tank system.

The one factor that was overlooked in the mathematical analyses was oxygen transfer. All mathematical analyses of activated sludge systems were based on the assumption that oxygen was not limiting in the aeration tank. This was not entirely correct. Most, if not all, plug flow activated sludge systems and conventional activated sludge systems are oxygen limiting at the head end of the aeration tank where the organic concentration is high. Only the completely mixed system is able to maintain excess dissolved oxygen (DO) at all times, giving it an advantage of eventually having better effluent quality.

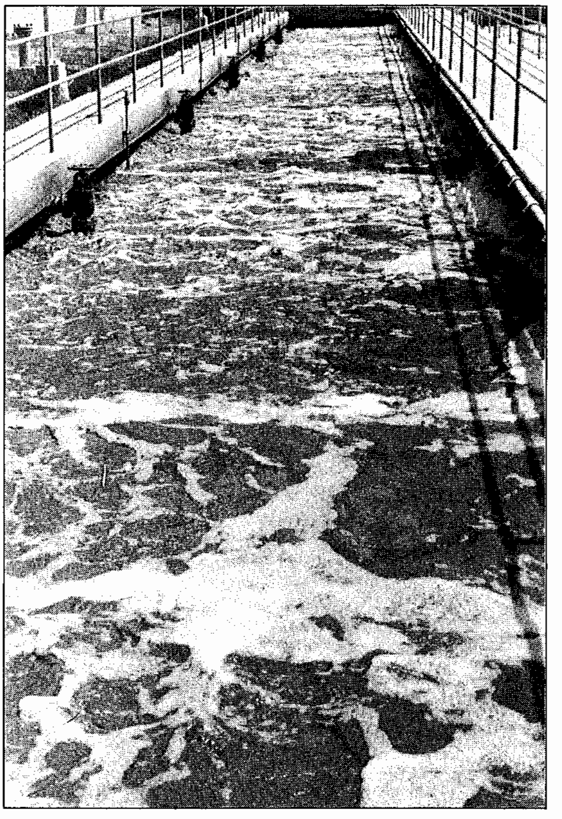

FIGURE 6. Typical diffused aeration-activated sludge aeration tank illustrating the long, narrow aeration tank. The Lake Tahoe wastewater treatment plant is shown.

Oxygen transfer is essential for the proper operation of activated sludge systems. Yet, it was not until the 1960s that many field measurements were made on the oxygen transfer characteristics of aeration tanks. Equipment manufacturers made claims for the oxygen transfer rates of their equipment, but design engineers never verified that the equipment met those transfer rates in the field after the plant was put into operation. Part of the problem lay in the lack of an acceptable test to verify oxygen transfer. Because of the difficulties with an aerated lagoon system in Kansas City, it was recognized that the design engineer had to take responsibility for writing specifications for aeration equipment that required field testing

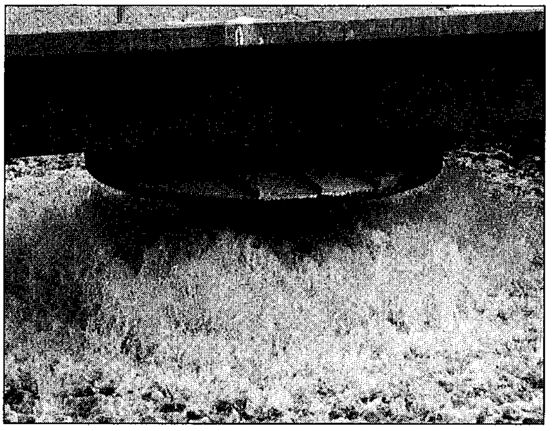

FIGURE 7. A surface mechanical aerator currently used for activated sludge at Lawrence, KS.

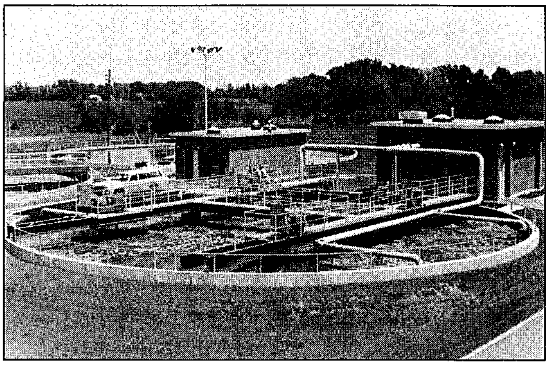

FIGURE 8. Typical aeration tanks with four turbine type aerators. The Grand Island, NE, plant is shown.

to demonstrate oxygen transfer characteristics. The Grand Island, NE, wastewater treatment plant was the first plant that had comprehensive testing specifications for aeration equipment.[19] Since 1964, consulting engineers have specified field testing of aeration equipment with the accumulation of considerable data on oxygen transfer for different aeration equipment.[34]

Recently, a new procedure was developed for evaluating diffused aeration equipment in conventional activated sludge systems having long, narrow aeration tanks.[35] This procedure consists of taking DO and oxygen uptake measurements at regular intervals down the aeration tank. By plotting these data, it is possible to determine the point when the system shifts from being oxygen limiting to having excess oxygen. The DO data remains low as long as DO is limiting and shows a sudden rise when the system has excess DO. The oxygen uptake rate at the point of change in DO is a measure of the oxygen transfer of the aeration equipment. It is possible to check that data from the remaining data with excess DO. Data from several different treatment plants have shown that most conventional activated sludge plants operate under partial oxygen deficient conditions. The net result of partial oxygen deficiencies is less endogenous respiration in the aeration tank and more excess sludge to remove from the system. The effluent quality is acceptable as long as excess oxygen occurs before the end of the aeration tank.

Based on general relationships, field data indicated the following oxygen transfer for different aeration equipment:

- 10-15 mg/L/hr for coarse bubble aeration in a conventional aeration tank
- 20-30 mg/L/hr for fine bubble aeration in a conventional aeration tank
- 40-60 mg/L/hr for fine bubble aeration over the entire bottom of an aeration tank
- 20-30 mg/L/hr for a high-speed surface aerator
- 40-60 mg/L/hr for a slow-speed surface aerator (see Figure 7)
- 60-70 mg/L/hr for both mechanical and diffused turbine aeration (see Figure 8)
- 100-130 mg/L/hr for pure oxygen

These values are for aeration equipment in normal tank volumes. Increasing the tank volume will decrease the rate of oxygen transfer; while decreasing the tank volume will increase the oxygen transfer rate. Aeration equipment must be tested in the actual aeration tank. The only valid testing technique for aeration equipment today is the clean water test. Dirty water, or mixed liquor, testing has too many variables to be used for aeration equipment certification. However, dirty water testing is useful for evaluating general oxygen transfer under operating conditions.

Since adequate oxygen is essential for the efficient operation of activated sludge plants, adequate oxygen must be present in the aeration tank. A simple test for adequate oxygen is nitrification. If there is adequate oxygen in activated sludge systems, there should be some nitrites or nitrates in the mixed liquor. Without adequate oxygen, many activated sludge systems produce filamentous bacteria with poor settling characteristics. Filamentous bacteria are as capable of metabolizing organics as dispersed bacteria, but they are normally not as efficient. Under oxygen limiting conditions, mixing is generally not very turbulent, allowing the floc particles to remain relatively large. The filamentous bacteria project from the floc and project a larger surface for metabolism than the bacteria in the large floc particle. The net result is that low turbulence favors filamentous bacteria, not because of oxygen limitations, but because of more favorable competition for the oxygen and the food. As mixed liquor suspended solids concentrations increase, the amount of turbulence for good oxygen transfer and proper growth of non-filamentous bacteria must also be increased. Too often this fact has not been recognized by design engineers or plant operators.

Solids Separation

An important part of the activated sludge process is the separation of mixed liquor suspended solids (MLSS) from the final effluent by gravity. A portion of the separated suspended solids are returned to the aeration tank to provide sufficient living microbes for rapid metabolism and to provide sufficient flocculent solids to ensure rapid flocculation and separation in the secondary sedimentation tank. The system requires daily wasting of suspended solids by direct wasting or loss in the effluent. Since loss of suspended solids in the effluent is not desirable, wasting of excess sludge must equal the amount of sludge produced each day.

In laboratory activated sludge systems fed a soluble organic substrate, the MLSS will be composed of active microbial mass, dead cell mass and inorganics. As indicated previously, the active microbial mass is a function of the metabolized organics and the number of times the microbes are recycled through the system. The dead cell mass is a function of the active mass in the MLSS and the length of time the microbes are retained under aeration since the dead cell mass is created by endogenous respiration of the living mass. The inorganics are incorporated in the microbes, both living and dead, to about ten percent of the microbial suspended solids and accumulate as the solids retention time (SRT) increases.

In field activated sludge systems, the wastewater contains suspended as well as soluble solids. Biodegradable suspended solids in the wastewater are metabolized in the same manner as the soluble organics, but the non-biodegradable suspended solids (both organic and inorganic) simply accumulate in the MLSS every time the MLSS is recycled through the system. Thus, these inert suspended solids become a major part of the MLSS and, eventually, control the operation of the activated sludge system.

Due to the effects of the active fraction of the MLSS, efforts are made to return the settled solids back to the aeration tank as quickly as possible. Hydraulic sludge collectors have been designed to collect settled sludge over the entire bottom of the secondary settling tank rather than using conventional sludge scraping equipment and center drawoff. Hydraulic sludge collection equipment has been viewed as removing settled solids faster than conventional sludge collection equipment. Hydraulic sludge collection equipment has become standard at the present time.

The surface overflow rate (SOR) controls the removal of particles by gravity sedimentation. T.R. Camp's concepts for activated sludge sedimentation tanks indicated that he favored rectangular tanks over circular tanks because of their hydraulic stability.[36] He pointed out that the design engineer should use density currents to advantage in solids separation and in designing secondary sedimentation tanks.

Norvell Anderson examined both rectangular and circular sedimentation tanks and felt that density currents were very important in both tanks.[37] The MLSS entered the secondary tank and dropped to the top of the sludge blanket and moved across the tank bottom to the outer wall and up to the effluent weir. As a result of his studies, Anderson recommended that the effluent weir be placed at 1/4 to 1/3 of the radius from the outer wall so that the rising suspended solids would have an opportunity to settle. Design engineers have found that specification requires too complex a structure for economical construction, but they have placed a double-sided weir box as far out as practical.

In 1963 K.L. Murphy made an excellent dye study of a model sedimentation tank and agreed with Anderson's ideas about weir location.[38] In spite of these innovations, secondary sedimentation tanks often failed to provide good solids separation and produced poor effluent quality. Effluent from a well-operating activated sludge system should have little soluble BOD5 (3-5 mg/L) with the suspended solids determining the effluent BOD5 quality.

Part of the problem with secondary sedimentation tanks resulted from the high MLSS recommended by some engineers. It was believed that the soluble effluent BOD5 was related to the MLSS concentration and the time of aeration. By increasing the MLSS it was thought that the soluble effluent BOD5 would be decreased. Examination of basic metabolism indicated that the soluble effluent BOD5 was a function of the BOD5 loading rate as long as an excess microbial mass existed in the aeration tank. It made no difference what the MLSS concentration was as long as it was above the minimum level for the specific system. Often, the ability to flocculate and settle was more the controlling factor than active microbial mass. Pflantz demonstrated that the effluent suspended solids depended upon the MLSS transported within the system.[39] Thus, the high MLSS concept tended to create more problems than solve them.

One problem with secondary sedimentation tanks in Minnesota led to a critical evaluation of the primary design criteria for secondary sedimentation tanks. It was found that SOR is not valid in activated sludge separation since secondary sedimentation tanks do not operate with uniform flow patterns to produce separation based on particle size. Incoming MLSS dropped to the bottom of the sedimentation tank and moved rapidly across to the outside wall and up to the effluent weir. The impact of the rising current at the wall was most evident in the afternoon when maximum flows arrived at the treatment plant. Increasing the rate of return sludge to move the settled solids out of the sedimentation tank and back to the aeration tank to handle the increased organic load simply increased the hydraulic problem and the loss of suspended solids in the effluent. Thus, basic design concepts and basic operating concepts combined to defeat treatment plant efficiency.

Examination of the hydraulic sludge collection system indicated that uniform solids collection could be obtained only when a high rate of return sludge flow was maintained to keep the return sludge concentration low enough for uniform flow. Most plants operated with 6000-8000 mg/L return activated sludge (RAS) concentrations. The high RAS flow rates combined with the normal maximum flow rates to blow suspended solids out in the effluent. The collection of solids at the outer wall created a strong fluid flow outward that produced a rising momentum force which helped carry solids out of the tank. Instead of improving solids removal, the hydraulic sludge collection system was part of the problem. Reexamination of Anderson's data indicated that the MLSS were removed as the solids entered the sedimentation tank under the centerwell. Data gathered by Katz and Geinopolos on hydraulic sludge collectors showed that the sludge was removed on entering the sedimentation tank.[40] Comparison of operating data with conventional sludge collection equipment showed that conventional sludge collectors produced thicker RAS concentrations, necessitating lower sludge return rates and lower density currents. For activated sludge systems maintaining the same MLSS concentrations, conventional sludge collection systems demonstrated better results than hydraulic sludge collection systems. Although hydraulic sludge collectors sounded like such a good idea, design engineers never made the necessary evaluation to show their value or lack thereof.

This lack of sound design criteria for secondary sedimentation tanks still leaves the problem up in the air. Few engineers even recognize that a problem exists. It most certainly does exist and it must be solved in order to obtain the maximum from activated sludge systems. Efforts have been made to modify the inlets to improve the hydraulic characteristics of secondary sedimentation tanks, but the results have been negative. The simplest solution to date has been to reduce MLSS to a relatively low level (1000-2000 mg/L), and to construct a baffle around the periphery of the tank under a single edge effluent weir to deflect the rising flow back to the center of the tank. As reported by Stukenberg, this design has produced positive results (see Figure 9).[41]

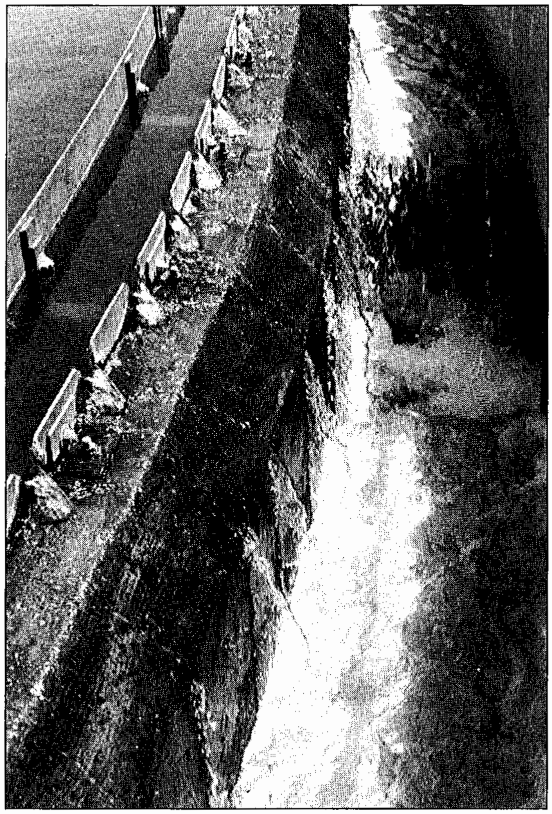

FIGURE 9. Final effluent from the activated sludge plant in Grand Island, NE, showing the clarity of effluent exhibited by the visibility of the submerged brackets for the scum baffle.

Design Criteria

Sound basic concepts translate into sound basic design criteria. For activated sludge systems, the fact that the oxygen transfer characteristics in the aeration tank control the entire process has been considered a secondary factor. Without adequate oxygen, microbes simply cannot metabolize organic matter completely. With an excess of oxygen, carbon can be metabolized to better than 99% and nitrogen can be metabolized to any desired extent beyond that required for carbon metabolism. Aeration equipment is required to keep MLSS in suspension and to mix organics with the microbes and oxygen. Tank configuration and aerator spacing affect the mixing patterns within the aeration tank and affect the oxygen transfer rates.

Oxygen is transferred to the water at a specific point at a specified rate and is mixed with unoxygenated water as the liquid moves around the tank. The DO in the liquid is reduced by dilution with unoxygenated water and by microbial metabolism. A DO profile around the aeration tank can be very helpful in evaluating hydraulic flow patterns.

The organic loading rate determines the effluent quality as long as adequate oxygen is available for metabolism. Normally, the rate of oxygen transfer limits the organic load on the aeration tank. The organic loading rate is related to the total organic load in the wastewater applied to the aeration tank and the time for aeration. It is possible to take wastewater having any organic concentration and produce a satisfactory effluent by keeping the organic loading rate relatively low. A low soluble effluent BOD5 cannot be produced at a high organic loading rate. The soluble effluent BOD5 will generally be slightly less than one-tenth the BOD5 loading rate under aerobic conditions. If activated sludge has a one to one ratio of BOD5 loading rate to oxygen demand rate, the maximum loading rate for aerobic conditions should be less than 60 mg/L BOD5/hr. With an average loading rate of half the maximum rate, the design rate would only be 30 mg/L BOD5/hr. Few activated sludge plants have been designed at such a low loading rate in recent years. This simply means that most activated sludge plants are operating under partial oxygen deficiencies for part of the day. A 24-hour composite sample permits the plant to meet Environmental Protection Agency (EPA) effluent citeria of 30 mg/L BOD5 and 30 mg/L suspended solids. The BOD5 leakage during partial oxygen deficiency is small and is diluted by the normal effluent quality produced with adequate oxygen.

It is possible to achieve a reasonable effluent BOD5 under overloaded conditions, but more excess activated sludge will be produced than under completely aerobic conditions. The effluent from activated sludge systems is made up of soluble, unmetabolized organics and excess suspended solids not removed from the final clarifier. In the aeration tank the oxygen demand is generated by the synthesis reaction and the endogenous respiration reaction. The synthesis reaction rate is normally about five to ten times the endogenous respiration rate. Under oxygen deficient conditions the major portion of the oxygen is used for synthesis with less oxygen being used for endogenous respiration. With a limited overload, organic matter is removed in almost the same manner as excess DO. Normally, activated sludge systems produce soluble effluent BOD5 values of 1 to 2 mg/L. With limited oxygen the soluble BOD5 can rise to 10 to 15 mg/L, still a reasonable value. If the final clarifier removes the activated sludge to around 10 to 20 mg/L under both cases, the total effluent BOD5 will rise from the 7 to 10 mg/L range to the 20 to 30 mg/L range, still meeting EPA effluent criteria. Since there is less endogenous respiration under the oxygen limiting conditions than under excess oxygen conditions, there will be less oxidation of microbial solids produced. The net effect will be more suspended solids to be wasted from the system.

Another key component in activated sludge design is the microbial mass in the aeration tank. The microbes must be greater than required for the organic load. Since microbes are maintained at high concentrations through recirculation, most activated sludge systems have many times more microbes than needed. To handle 60 mg/L BOD5/hr, only 120 mg/L active microbial mass would be needed. The synthesis reaction would produce 49 mg/L volatile suspended solids (VSS)/hr while endogenous respiration would use only 3 mg/L O_2/hr for this microbial mass. Needless to say, 120 mg/L microbial mass would not produce a good settling sludge with a highly clarified effluent. The MLSS must be increased by recycling settled sludge. The return activated sludge will bring back inert suspended solids, dead cell mass and active microbial mass. Each recirculation increases all fractions. Normal activated sludge systems require 800-1000 mg/L MLSS for good flocculation and solids separation. The return of active microbial mass increases the potential for endogenous respiration without any increase in the active mass produced by metabolism. At a 60 mg/L BOD5 loading rate, the oxygen demand rate for synthesis should be approximately 34 mg/L/hr, with 26 mg/L/hr for endogenous respiration. At 20°C with a 0.02 endogenous respiration rate, 0.022 mg/L/hr O_2/mg/L active microbial mass, the active mass should be about 1180 mg/L, 10 times that required to metabolize the BOD5 in wastewater. If the wastewater had a significant amount of inert suspended solids, the MLSS would be much greater than the 1180 mg/L. The inert suspended solids in the wastewater normally determine the active microbial mass fraction in the MLSS. Some inert inorganic suspended solids should be in the wastewater to provide some mass to help the rate of sedimentation of the floc. However, too great an amount of inert solids can result in filling the tank with MLSS and have the net effect of little benefit for the treatment process.

The RAS is critical for maintaining the desired MLSS under aeration. Good activated sludge will settle and thicken to 10,000 mg/L. The RAS flow should not be any greater than needed to maintain the desired MLSS concentrations in the aeration tank. If the MLSS is around 2000 mg/L, the RAS flow will be about 25% of the wastewater flow with a sufficient settling sludge. Sound design criteria should provide flexibility between 10 and 50% wastewater flow rates for the RAS flow rates. In recent years the RAS flow rates have been closer to 100% or more of the wastewater flow rate, too high for beneficial control.

Wasting excess activated sludge is essential. The daily increase in suspended solids must be removed from the system each day, if the system is to continue to function properly. The excess suspended solids must either be wasted or discharged in the effluent. If the goal is a high quality effluent, then the majority of the excess activated sludge must be removed by wasting. Waste activated sludge (WAS) is removed from the RAS to minimize the quantities of solids removed. Normally, the WAS flow rate will be less than five percent of the wastewater flow. Removing more WAS will lower the MLSS; removing less WAS will permit the MLSS level to rise. Accurate and timely WAS measurements are important in monitoring this process.

Operational Evaluation

Design engineers must not only understand the basis of design, but should also understand how to evaluate treatment plant operations. Operational data are predominantly collected on a grab sample or composite sample basis. Some of the data will have only historical value, such as BOD5 data. Flow and suspended solids measurements are of paramount importance since the treatment process is essentially a solids handling process. DO data and oxygen uptake data can aid in evaluating activated sludge, but these data must be properly collected to be of real value. Alkalinity and nitrogen data can also be useful.

Failure to recognize the basic concepts of the activated sludge process has resulted in improper operation of most plants. There has been a tendency to overanalyze and overcontrol the activated sludge process, resulting in poor effluent quality. The problem lies in the fact that aeration and sedimentation tanks are coupled systems that permit temporary imbalances, resulting in improper data collection and evaluation. The net result is a cyclical, and unsuccessful, attempt to adjust the system for uniform operation. This is especially true when the rates of return sludge are adjusted several times a day in the attempt to meet the variations in incoming loads. Wasting sludge without regard to organic loading rates and synthesis reactions will produce widely fluctuating results.

A recommended operational technique is to set the return sludge rates at the average desired rates and not vary the return sludge rates with the load. There are more than enough microbes in the system to stabilize the organics. At low flow conditions excess sludge will be removed from the secondary sedimentation tanks and transported to the aeration tanks. The aeration tanks will then show an increase in MLSS. As the excess load comes into the aeration tank, the extra MLSS will handle it easily. The sedimentation tank will then have the capacity to absorb the increase in MLSS displaced from the aeration tank without blowing solids out into the effluent. By wasting a constant flow fraction from the RAS, the system will automatically rise and fall as the load changes. Slight adjustments in WAS can be made every few days or weekly to keep the MLSS within the desired concentrations. Microcomputer analyses for daily mass balances of suspended solids throughout the system can help the operator maintain tight control of the system with a minimum of effort and variation.

Anaerobic Treatment

Anaerobic treatment of organic wastes has been recognized as a means of waste treatment for a longer period of time than aerobic treatment. However, anaerobic treatment had developed an initial negative reputation. Anaerobic metabolism results in the production of obnoxious compounds that can be considered undesirable. Yet, septic tanks can provide excellent stabilization of settled solids. Imhoff in Germany developed a two-story

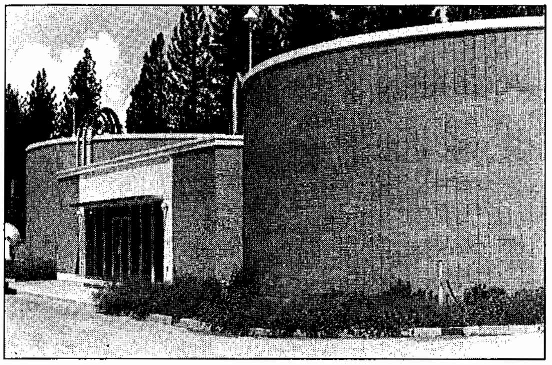

FIGURE 10. Typical anaerobic digestion tanks for domestic sewage sludges. The Lake Tahoe wastewater treatment plant is shown.

tank that allowed the sewage solids to separate and undergo separate digestion. Gas produced by digestion was initially allowed to escape through scum vents to the atmosphere. When it was recognized that the gas produced by anaerobic digestion could be burned, efforts were made to collect it.

Anaerobic Digestion

The technology for separate anaerobic digestion of sewage sludge was slow to develop. The first tanks were open tanks that were not mixed or heated. Scum formed on the liquid surface and acted as the top of the tank. The settled solids digested slowly and were relatively stable when removed from the digestion tank. The solids dewatered easily on the soil and did not produce obnoxious odors or attract flies. In addition, the stability of the sludge after digestion made it very attractive for subsequent use.

Research on anaerobic digestion began during the 1920s with studies on changes in the chemical characteristics of sewage sludge over time. Acid production occurs first, followed by the metabolization of the acids with the accompanied production of methane and carbon dioxide. After the methane production slows, the sludge is considered stable. Acid fermentation had been studied before, but the acid metabolism intrigued Buswell. Together with S.L. Neave, Buswell examined how the bacteria in sewage sludge metabolized acetic acid and propionic acid to methane and carbon dioxide.[42] Later, Buswell and Boruff studied the metabolism of more complex organic compounds such as cellulose, casein, peptone and stearic acid.[43] Research on anaerobic digestion moved ahead slowly until the 1950s when Stadtman and Barker used radiotracers to show the metabolism of some fatty acids and alcohols.[44,45]

In the 1950s anaerobic digesters were heated with hot water to about 85°F to increase the rate of metabolism. It was believed that the normal gasification process was adequate to achieve the mixing necessary for digestion. The digester had three major layers: a grease layer at the top, an actively digesting layer in the middle, and a well-digested layer at the bottom. Digesters required a long retention time (20-30 days) for stabilization. It had been noted that acid production was the most critical operating parameter. Excessive organic loading rates could result in rapid acid production and a drop in pH with the accompanied cessation of methane production. Alkalinity had to be added and a fresh microbial seed was necessary to get the system back into good operation. Buswell indicated that volatile acids were toxic if their concentrations exceeded 2000 mg/L. This was the most critical operating parameter that needed to be controlled.

The major step forward in anaerobic digestion came with P.F. Morgan's research on catalytic reduction (see Figure 10).[46] Morgan found that continuous gas recirculation increased organic loading by a factor of 10, and reduced the retention time to only 7-8 days. He indicated that the recirculation of gas created an increased rate of reaction. W.N. Torpey also experimented with increased rate of digestion.[47]

Biochemical Studies

Morgan and Torpey's work helped stimulate interest in anaerobic digestion as research was progressing on activated sludge. At M.I.T., C.N. Sawyer examined the problems associated with high-rate anaerobic digestion in the laboratory. One concern was volatile acid toxicity. An early study had indicated that volatile acids above 2000 mg/L were not toxic, but the cations associated with the volatile acids could be toxic at high concentrations.[48] Additional research eventually showed that volatile acids *per se* were not toxic.[49] When volatile acids reached 2000 mg/L, the pH suddenly dropped as the buffer was all used up. The toxicity was the result of low pH and not the volatile acids. It was possible to have metabolism at 20,000 mg/L volatile acids as long as the volatile acids were neutralized and the pH was above 6.5. At high volatile acids, the toxicity was caused by high concentrations of soluble cations. Monovalent cations were more soluble and toxic than divalent cations.

These early studies at M.I.T initiated further research that took over 25 years to complete. The studies on volatile acids showed that adequate digestion proceeded for several weeks and then began to slow as the original seed sludge was displaced from the digester. Sufficient microbial digestion could be regained only by adding an amount of sewage sludge. Sewage sludge contained something the microbes required. Dried sewage sludge yielded the same results as liquid sludge. Efforts to locate the critical material were not successful. Iron and cobalt were two important materials required for adequate digestion, but something else was missing. In the later 1970s, mass spectroscopy studies of methane enzymes indicated the presence of nickel in one of the enzymes. This appeared to be the missing key that was needed to make anaerobic metabolism of pure organics a stable process. Schonheit, Moll and Thauer found that a methane bacteria that metabolized hydrogen and carbon dioxide to methane needed minute amounts of nickel, cobalt and molybdenum.[50] Just 0.009 mg of Ni was needed per g of cell mass produced; 0.0012 mg of Co per g of cell mass; and 0.0018 mg of Mo per g of cell mass. This study stimulated interest in determining the role these trace metals played in anaerobic digestion. Murray and van den Berg, and Speece *et al.* have shown that nickel is essential for maximum rates of anaerobic metabolism.[51,52]

The value of nickel in anaerobic digestion was accidentally observed and ignored as early as 1941. In addition, a published study in 1947 by Wischmeyer and Chapman confirmed the 1941 results.[53] Laboratory research on the anaerobic digestion of sewage sludge with varying amounts of nickel ammonium sulfate and nickel sulfate added to domestic wastewater to simulate plating wastes indicated that, at low concentrations of nickel, the rate of gas production was greater than the rate of gas production in the control digester. As the concentration of nickel increased, the nickel became toxic, and both the rate and the total gas production dropped below that of the control digester. Since nickel was not considered to be an essential trace element, but rather a toxic metal, the results of this research study passed without notice.

Current research at the University of Kansas is examining the role of several different trace metals in the metabolism of butyric acid. Not only are iron, nickel, cobalt and molybdenum being examined, but also zinc, copper and manganese. Butyric acid was chosen as the substrate since it is soluble and requires beta oxidation to be broken down to acetic acid before the acetic acid can be split to methane and carbon dioxide. The hydrogen atoms removed during beta oxidation were used to reduce carbon dioxide to methane and water. The net result is a mixed microbial population with different energy levels of metabolism. It will be interesting to see how the rate of metabolism is affected by the different trace metals.

Soluble Organics

P.L. McCarty and J.C. Young developed the anaerobic rock filter to treat strong, soluble organic wastes. The anaerobic filter appeared to be a effective system for treating certain types of industrial wastes. Over the next decade a large number of laboratory studies were made to demonstrate the ability of the rock filter to treat specific industrial wastes.

It was not until the energy shortage in the early 1970s that interest in anaerobic treatment shifted to the treatment of organic solubles. A few treatment plants appeared in Europe for treating sugar processing wastewater. In 1980 the Bacardi Corporation of Puerto Rico constructed the largest anaerobic filter for treating industrial wastes. This plant had a 125 ft diameter plastic media, downflow type anaerobic filter with 30 ft diameter depth in a 42 ft deep tank. Since the Bacardi plant went into operation in 1982, it has operated without major problems and has successfully survived annual shutdowns for plant maintenance. Over half of the energy needs of the manufacturing plant are met by recycling the gas produced by the anaerobic metabolism of the rum distillery wastewater. The success of this large scale treatment system and others in recent years has clearly demonstrated the potential for anaerobic filters with energy recovery for plant operations.

Basic Concepts

Basic concepts of anaerobic digestion have developed slower than the basic concepts for aerobic systems. This is not surprising since the anaerobic systems have been more difficult to operate and require longer operating periods to obtain basic data. It is possible to use the basic concepts from early studies on aerobic reactions to provide similar relationships for anaerobic reactions. The basic metabolic reaction is the synthesis reaction. Organic metabolism is directed towards the production of microbial cell mass. The early studies at M.I.T. had indicated that 1/3 of the organics metabolized were oxidized to convert the remaining 2/3 of the organics to cell mass. The microbial protoplasm is a complex mass of hundreds of different organic compounds that have a relatively fixed chemical composition when introduced to an excess of nutrients. It has been found that 0.48 g of VSS are produced from each g of COD metabolized. Each g of cell mass produced requires 4.7 Kcal of energy in the protoplasm, with 2.3 Kcal of energy required to manufacture the protoplasm. These relationships hold for anaerobic microbes as well as for aerobic microbes. The amount of organic matter converted to cell mass will be exactly the same for anaerobic microbes as for aerobic microbes. The difference lies in the energy yields from the energy metabolism reactions. The aerobic reactions yield more energy than the anaerobic reactions. The net result is that less organics are oxidized aerobically and more organics are converted to cell mass than in anaerobic reactions.

Of the many different anaerobic reactions, there are two fundamental reactions that supply energy for the microbes. The first major reaction is the splitting of glucose to acetic acid. This reaction produces 71 Kcal for each molecule of glucose converted to acetic acid (0.37 Kcal/g COD). Approximately 6.2 g COD as glucose would have to be metabolized for energy for each g of cell mass. That one g of cell mass contains 1.4 g COD, requiring a total of 7.6 g COD from the glucose. Restated, the cell mass yield for one g COD metabolized as glucose should be 0.13 g. The second reaction results in the splitting of acetic acid to form methane and carbon dioxide. This reaction only yields 0.16 Kcal/g COD. The energy reaction for the acetic acid split requires 14.4 g COD/g of cell mass. The 1.4 g COD/g of cell mass for protoplasm and the 14.4 g COD/g of cell mass for energy gives a total COD requirement/g of cell mass of 15.8 g. For each gram of acetic acid metabolized, the cell mass yield is 0.063 g VSS. By combining the two reactions to give an overall synthesis for the metabolism of glucose to methane and carbon dioxide, approximately 0.18 g VSS is produced per one g COD glucose metabolized. Approximately 260 ml methane is also produced. The COD in the metabolized organics are simply transformed into the COD of the cell mass and the COD of the methane gas. If other end products are produced by anaerobic reactions, a portion of the COD may be tied up in those end products. The methane reaction is the most important anaerobic reaction since the low solubility of methane in water permits methane to be captured as a gas and used as an energy source. It is important to recognize that the energy in the original organic waste materials will be converted to microbial cell mass and methane. The methane is easily trapped as a gas, but the cell mass suspended solids pose the ultimate separation problem.

The early studies on bacterial flocculation at M.I.T. demonstrated that, under aerobic conditions, flocculation occurred when all of the organic matter was metabolized. If these concepts hold true, it should be possible to obtain flocculation under anaerobic conditions when all the organic matter has been metabolized. Recent studies at the University of Kansas have demonstrated that anaerobic flocculation occurs under the same environmental conditions as aerobic flocculation. The addition of excess iron salts also can assist natural flocculation by artificially concentrating the dispersed bacteria, thus permitting complete metabolism rather than the loss of active, dispersed bacteria.

Complete metabolism under anaerobic conditions approaches the same degree of metabolism as under aerobic conditions, reaching 98 to 99%. The important parameter is microbial retention and rate of metabolism. Since the ability of the microbes to obtain sufficient energy for synthesis is the controlling factor, the rate of organic processing will ultimately limit the organic load and the extent of metabolism.

Future Studies

Anaerobic treatment offers the advantages of less excess microbial solids for ultimate disposal, and energy for easy reuse in the form of methane. It also offers the potential for high treatment efficiencies. However, few systems have demonstrated the full potential of anaerobic systems. There is still much research needed to define the critical factors affecting both the design and operation of anaerobic treatment plants. Anaerobic systems are harder to start than aerobic systems and require more skill in maintaining efficient operation. Yet, the fundamental concepts of anaerobic systems are the same as aerobic systems. The understanding that has been generated by studying aerobic treatment systems over the years can be utilized to shorten the time and effort required to develop sound anaerobic systems. The chemical characteristics of microbes in anaerobic systems are the same as in aerobic systems. The mechanisms for processing the organics for energy and synthesis are also the same. Only the electron transfer process and the ultimate electron acceptor are different. While anaerobic treatment can provide a high degree of treatment, aerobic treatment after anaerobic treatment can be used for a high quality effluent.

The future of biological treatment looks very bright. The design and operation of wastewater treatment systems are firmly established on sound basic concepts of microbiology and biochemistry, coupled with good engineering. There is no reason to doubt that efficient and economical plants will be provided as needed to meet the challenges of the future. Reusing and recycling water, nutrients and microbial solids will ensure the sufficiency of these valuable resources for the benefit of everyone whatever the demands of the future might be.

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