BOARD OF REVIEW

REPORT ON CONSTRUCTION AND OPERATION IN GASEOUS AREAS

AGENDA

BOARD OF REVIEW

CONSTRUCTION IN GASEOUS AREAS

"SEPTEMBER 5, 1985"

		Time	
I.	INTRODUCTION	09:00AM	J.A. Dyer (15 min.)

A. Purpose

B. Goals and Objectives

C. Methodology

II.	DESCRIPTION OF THE PROJECT	09:15AM	J. Monsees (20 min.)

A. Alignment and Geology

1. Location
2. Geologic Deposits of Engineering Significance
3. Groundwater
4. Abandoned Oil Wells
5. Conditions on Alignment

B. Structures

1. Tunnels
2. Stations

C. Construction Approach

III.	GAS OCCURRENCES	09:35AM	D. Kasper (20 min.)

A. Field Investigation Activities

1. Geotechnical Exploration
2. Gas Probes
   a) 1983
   b) 1985

B. History of Gas Occurrences

C. Wilshire/Fairfax Building Construction

D. Ross Clothing Store Fire — 09:55AM — D. Bartlett (10 min.)

IV.	BASIS FOR DESIGN	10:05AM	J. Monsees (45 min.)

A. Gas Flow Conditions

1. Through Joints
2. By Diffusion
3. Through Cracks
4. Water Infiltration

B. Selection of Liners

1. Steel
2. Pre-Cast Concrete
3. Cast-in-Place Concrete

C. Membranes

1. Products Considered
2. Laboratory Tests
   a) Permeability
   b) Chemical Resistance
   c) Abrasion Resistance

D. Ventilation	10:50AM	A. Dale (15 min.)

E. Gas Monitoring

V.	SUMMARY OF DESIGN	01:30PM	J. Crawley (10 min.)

A. Gas Sensing and Monitoring

B. Ventilation System

C. Liners and Membranes

VI.	STATE REGULATORY REQUIREMENTS	01:40PM	B. Ishkanian (45 min.)

A. CAL-OSHA

1. Tunnel Safety Orders
2. Mine Safety Orders

VII.	CONSTRUCTION TECHNIQUES	02:25PM	H. Scott (15 min.)

A. Methods and Equipment

B. Gas Sensing and Monitoring

VIII.	<u>OPERATIONAL PROCEDURES</u>	02:40PM	A. Dale (15 min.)
IX.	<u>SUMMARY</u>	02:55PM	D. Hammond (15 min.)
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DRAFT REPORT

IN-HOUSE BOARD OF REVIEW

CONSTRUCTION AND OPERATION IN GASEOUS AREAS

EXECUTIVE SUMMARY AND RECOMMENDATIONS

The Los Angeles Metro Rail rapid transit project consists of an 18.6-mile subway, including 18 stations. It will run from Union Station through downtown, west along the Wilshire Corridor, and then north through the Fairfax and West Hollywood communities. The line will proceed eastward to serve Hollywood and will continue through Cahuenga Pass to the San Fernando Valley, ending at North Hollywood.

The subway line will be constructed by tunneling, and the underground stations will be constructed by cut-and-cover method. In several locations, the subway line will skirt or cross old oil fields. Of particular note are the La Brea Tar Pits, which overlie a part of the old Salt Lake oil field.

In view of the importance and magnitude of the Metro Rail Project, an extensive geotechnical and subsurface gas investigation program has been implemented throughout the design process. The "Report of Subsurface Gas Investigation," prepared by Engineering-Science, Inc., has documented the presence of methane gas along portions of the Project alignment. Sixty-five monitoring wells were installed along the route from Union Station to Universal City to measure subsurface gas pressures and concentrations.

Geotechnical reports prepared for the District indicate that gassy ground exists from the yard portal to Union Station, from the 7th/Flower Station to the Wilshire/Alvarado Station, and from the Wilshire/Crenshaw Station to the Fairfax/Santa Monica Station. Potentially gassy ground could exist from Union Station to the 7th/Flower Station. Based on this and other information supplied by the District, Cal-OSHA has assigned a "gassy" classification.

The explosion and fire that occurred at Third Street and Ogden Drive on March 24, 1985, increased the awareness of gas in the Fairfax District. The City Task Force formed to investigate the incident identified the general area at the Fairfax District as "high potential risk zone" and the area adjacent to the Fairfax/Beverly, Wilshire/Fairfax, and Wilshire/La Brea Stations as "potential risk zone."

Extensive research and investigation have been conducted throughout the design process in the selection of tunnel lining materials and gas-proofing membranes. Extensive coordination has occurred with Cal-OSHA and other concerned agencies to establish a safe procedure for tunneling through gassy ground. Specific plans have also been formulated for a safe operation during revenue service.

It is recommended that steel tunnel liners be installed to prevent gas infiltration in areas identified as "high potential risk zone" and "potential risk zone." In all MOS-1 tunnels and stations, HDPE gas barrier membranes will be applied in conjunction with CIP concrete, or gas barrier coatings will be applied to precast concrete liners.

During revenue operations, gas buildup to hazardous levels will be prevented by the following system features:

(1) Natural ventilation, ventilation created by train movements, station supply ventilation, and UPE systems.

(2) A ventilation system of fans and controls that can bring in fresh air and exhaust gases and smoke, when required.

(3) A gas sensor system that will detect changes in the presence of gas. If the gas readings increase over a period of time at a given sensor location, the source of the increase can be located and resealed.

When tunneling through gassy ground, all precautionary measures required by Cal-OSHA should be employed to ensure that construction is undertaken in a safe environment. The primary requirements are to ensure that adequate ventilation is provided and that prescribed work rules are rigidly enforced. Another measure that will be used to ensure safety during construction is to install a gas detection and monitoring system to determine any presence of gas in the ground during tunneling operation.

Based on the available information, gassy ground poses no unusual hazard in construction if appropriate precautionary measures are implemented. Previous experience in this area demonstrates that tunneling in gassy ground can be successfully accomplished.

It is concluded that the potential of having gas in the Metro Rail tunnels is recognized, and measures have been taken to mitigate the presence of gas by:

(1) Providing ventilation to dilute and exhaust residual gas.

(2) Providing sensors to monitor changes in gas concentration.

(3) Installing probes to measure the gas in the field.

(4) Providing concrete or steel lining for the tunnels.

(5) Providing barrier membrane or coating to back up the concrete lining.

These measures represent the state-of-the-art in prudent design for the conditions expected. Furthermore, rigid enforcement of Cal-OSHA Orders during construction will ensure a safe place of work and a safe means of transportation.

I. INTRODUCTION

On March 24, 1985, a methane gas explosion and fire occurred at the Ross Dress-For-Less Clothing Store at 6298 West Third Street in the Fairfax area of Los Angeles. The Ross site is located approximately 0.2 mile from the Metro Rail alignment.

The incident was apparently caused by methane gas rising from some depth below the ground surface. The gas penetrated the building through small openings between the floor slab and the foundation walls and was ignited by a source from within the building.

As a result of this incident, the SCRTD General Manager directed that a thorough in-house review be conducted of all plans for tunneling and operating in areas classified as gassy.

A. In-House Board of Review

The Assistant General Manager for Transit Systems Development, with the concurrence of the General Manager, invited a group of technical experts to assemble in order to review, discuss, and provide recommendations on the various elements of the Metro Rail Project that are impacted by a gassy environment.

Each individual participating in the proceedings of the Board is thoroughly familiar with the Metro Rail designs and is an expert in a specific engineering discipline. All the key technical areas are represented on the Board.

The In-House Board of Review comprises following individuals:

- SCRTD

  J. E. Crawley - Director of Engineering, Transit Facilities - Chairman
  S. K. Louis - Manager of Engineering Design
  R. W. Wood - Chairman, Fire/Life Safety Committee
  J. A. Strosnider - Director of Construction

- Fire/Life Safety Committee

  D. E. Bartlett - Battalion Chief, LAFD

- Metro Rail Transit Consultants

  J. Monsees - Chief Tunnel Engineer - Vice-Chairman

  T. Kuesel - Chairman of the Board, PBQD

  R. Peck - Special Tunneling Consultant

  T. Brekke - Special Tunneling Consultant

- PDCD

  H. C. Scott - Deputy Construction Manager

  F. W. Thompson - Zone Construction Manager

  J. R. York - Manager, Safety/Security

- Lindvall, Richter & Associates

  R. J. Proctor - Executive Secretary, Board of Geotechnical Consultants

B. Goals and Objectives

The goals and objectives of the In-House Board of Review were to:

(1) Reexamine the steps that have been taken to ensure the system's safe and efficient construction, activation, and revenue service.

(2) Reexamine the hardware and operating procedures that are planned for use during the operation phase of the Metro Rail Project to ensure that there is a permanent, safe working and operating environment.

(3) Review Metro Rail plans in light of the relevant recommendations of the City Task Force Report on the Ross Dress-For-Less Store incident and, also, the results of the latest gas probe readings along the Metro Rail alignment.

(4) Reexamine construction methods and procedures that are feasible and desirable, considering practices in the U.S. and elsewhere for tunneling construction in a gassy environment.

C. Methodology

The In-House Board of Review met at the District on August 21, 1985. The Board members participated in a review and discussion of the various aspects of the Project together with members of the Metro Rail design and construction team. Participants submitted technical papers covering the areas of their expertise. The various papers were compiled into this report, which represents the opinion of the members of the In-House Board of Review.

II. OVERVIEW/FIELD CONDITIONS

The locally preferred rail rapid transit project is an 18.6-mile subway including 18 stations (Figure II-1). Known locally as the Metro Rail Project, it runs from Union Station through the downtown central business district, west along the Wilshire Corridor, and then north through the Fairfax and West Hollywood communities. The line then proceeds eastward to serve Hollywood and continues beneath the Cahuenga Pass to the San Fernando Valley, where station locations are proposed at Universal City and North Hollywood. The project traverses the Los Angeles Regional Core, the densest area of the Southern California metropolitan region. The project would provide much needed transit capacity and substantially reduce travel times through and within the Regional Core.

At the request of the U.S. Department of Transportation, a smaller operating segment has also been defined. This smaller segment is known as MOS-1 and covers the initial downtown 4.4 miles of the Metro Rail Project, from the Yards and Shops through the central business district to the Wilshire/Alvarado Station (Figure II-2).

The line sections of the Metro Rail Project will be constructed principally by tunnel-boring methods. The

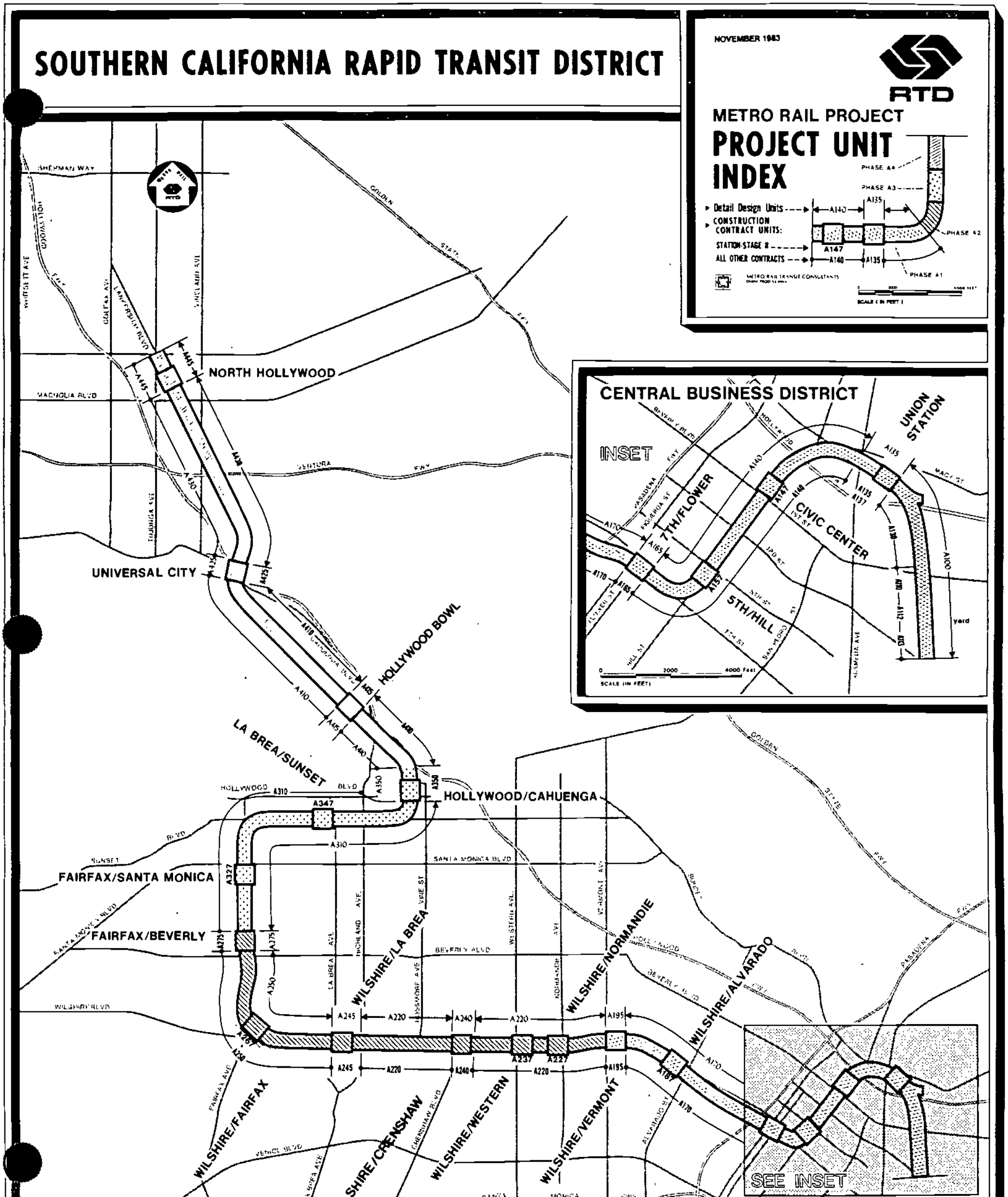
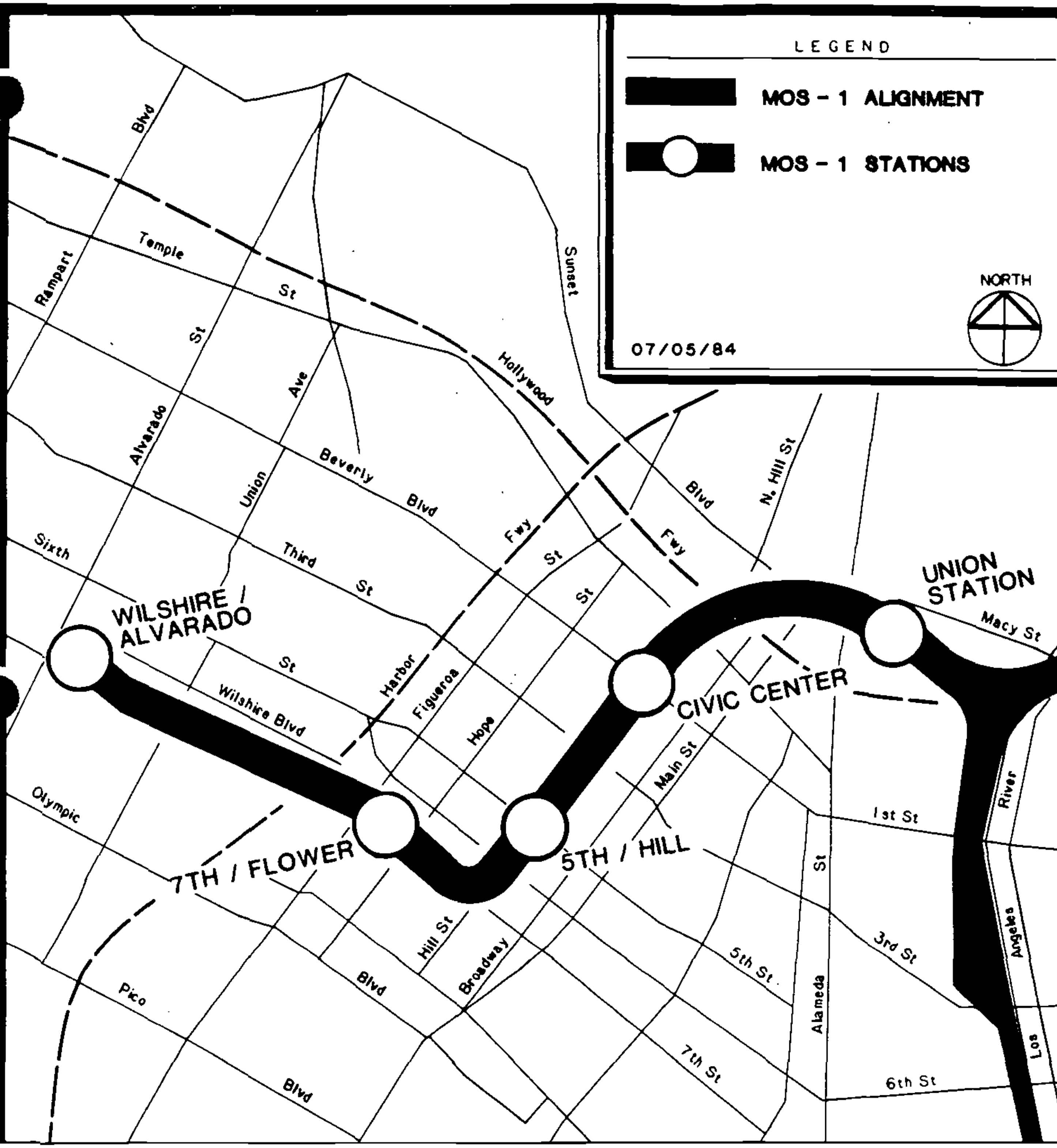


Figure II-1 18.6 Mile Locally Preferred Alternative



Southern California Rapid Transit District

Metro Rail Project

Figure II - 2

MOS - 1

twin tunnels (21-ft diameter) vary in depth from 25 ft to approximately 125 ft beneath city streets and up to 700 ft in depth beneath the Santa Monica Mountains. In general, the twin tunnels will be in the conventional side- by-side configuration. At frequent intervals along the line, cross-passages will be mined between the tunnels to provide passenger access to the adjacent tunnel in the event of a safety-related incident requiring passenger evacuation. A rendering of a typical RTD vehicle in tunnel is shown in Figure II-3.

The underground stations will be constructed by cut-and-cover methods. Depths of trench excavations will be as shallow as possible, consistent with: (1) minimum earth cover allowance for utilities, (2) structural thicknesses required for the several levels of slabs, and (3) interior vertical heights dictated by clearance requirements. The width of the trench excavations will depend on the platform and trackway widths as well as the calculated thickness of the structural walls. The widths of construction are further augmented by the thickness of the systems installed for support of the excavation sheeting. A typical center-type train loading platform and station interior are shown in Figure II-4.

Figure II - 3
RTD Vehicle in Tunnel

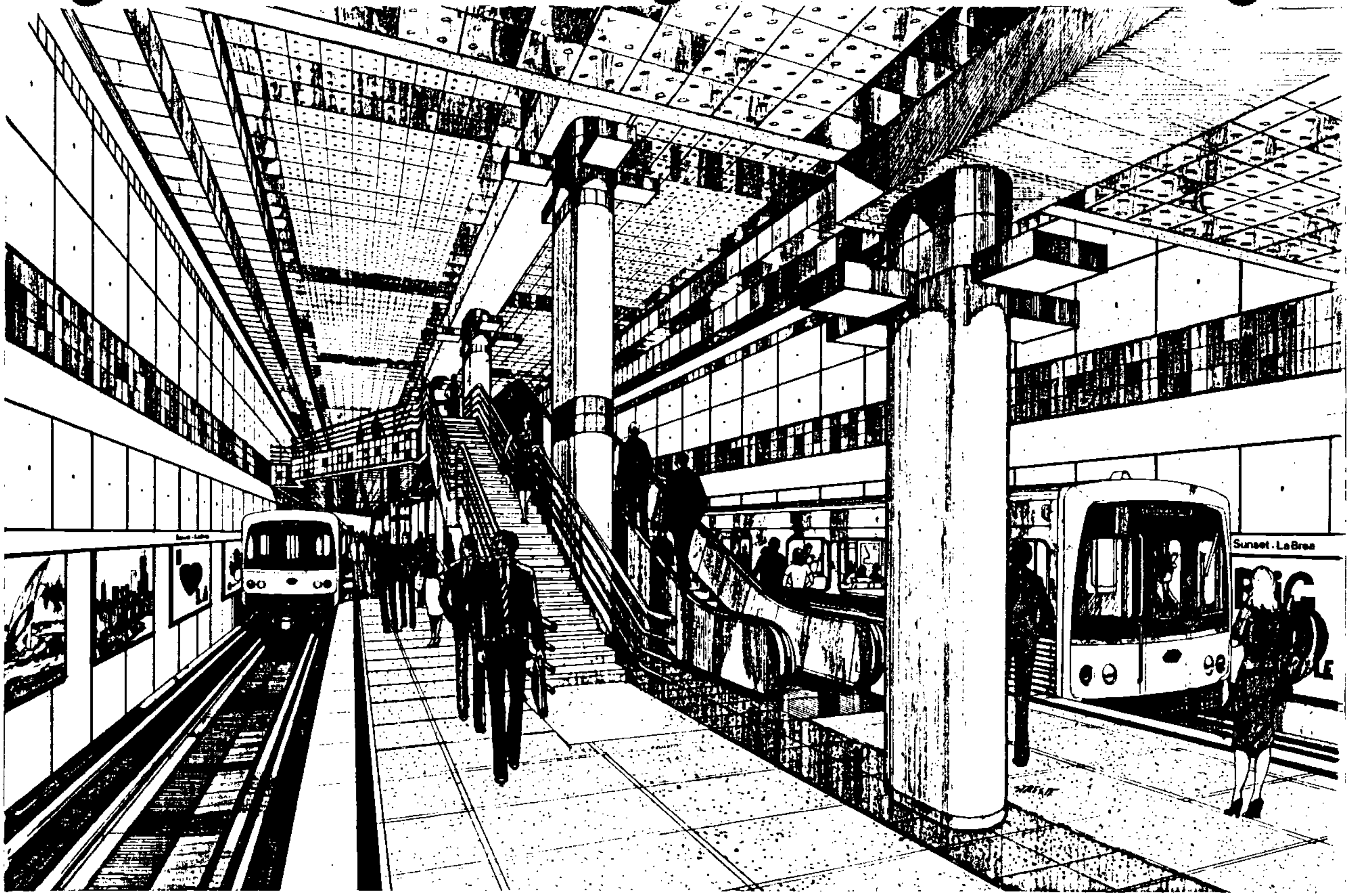


Figure II - 4
Center Type Platform

A. Alignment and Geology

1. Location

The proposed 18.6-mile Metro Rail Project is mainly in the City of Los Angeles, California. The route, as shown in Figure 1, extends from the downtown Los Angeles Union Station area to North Hollywood via:

- Yard north to Union Station, across the Los Angeles River, west on Macy Street to Hill Street.
- Southwest on Hill Street to 7th Street.
- Northwest on Hill Street to Alvarado Street.
- West on Wilshire Boulevard to Fairfax Avenue.
- North on Fairfax Avenue to Sunset Boulevard.
- East on Sunset Boulevard to Cahuenga Boulevard.
- North on Cahuenga Boulevard to the Hollywood Bowl.
- Northwest beneath the Santa Monica Mountains to Universal City.
- Northwest on Lankershim Boulevard, terminating at Lankershim across Chandler Boulevard and the Southern Pacific Railroad tracks.

2. Geologic Deposits of Engineering Significance

Based on the evaluation of the subsurface conditions and engineering properties along the proposed alignment, the tunnel route has been divided into the following "reaches" having geologic similarities:

- Reach 1 - Los Angeles River Area: East Portal to Hollywood Freeway

  Deep, loose to dense stream-deposited Young Alluvium (soil) of the modern Los Angeles River channel with soft-rock siltstone and sandstone near the surface at each end of this reach. The permanent groundwater level was found at a depth of about 25 ft. Oil and gas occur in the eastern portion.

- Reach 2 - Downtown Central Business District: Hollywood Freeway to Harbor Freeway

  Deep, loose to dense Young Alluvium of the ancestral Los Angeles River channel and soft-rock formations were encountered. A relatively deep (below 90 ft) permanent groundwater level was measured. Minor amounts of oil were detected.

- Reach 3 - Harbor Freeway to Wilshire Boulevard/Normandie Avenue

  Shallow, dense Old Alluvium was found over soft rock. There was an upper perched water table in the Old Alluvium and a deeper permanent groundwater level in the rock. Oil and gas were encountered at the intersection of Wilshire and Alvarado.

- Reach 4 - Wilshire Boulevard: Normandie Avenue To La Brea Avenue

  Shallow to deep, dense Old Alluvium overlies dense saturated sand of the San Pedro Formation, which is underlain by soft rock. A shallow perched water table was measured in the upper alluvium along with a deeper (below 130 ft) permanent groundwater level in the soft rock. Oil was not found.

- <u>Reach 5 - La Brea Avenue to Fairfax Avenue/ Melrose Avenue</u>

  Deep, dense Old Alluvium overlies dense, oil-saturated sand (La Brea Tar Pits area), which is underlain by soft rock of the Fernando Formation. Shallow perched water was found in the alluvium, with a deep permanent groundwater level in the soft rock. Oil and ground containing gas were found throughout the reach. Three inactive faults are located in the Salt Lake oil field, and the potentially active Santa Monica fault zone will be crossed near Melrose Avenue.

- <u>Reach 6 - Hollywood: Melrose Avenue to Yucca Street</u>

  Deep, dense Young and Old Alluvium overlies soft rock to depths greater than 200 ft. The permanent water table was not encountered in the test borings. Shallow water levels were contained in upper alluvium, and oil and gas were encountered. This reach is bounded by the Santa Monica fault zone on the south and the Hollywood fault on the north at the base of the Santa Monica Mountains.

- <u>Reach 7 - Santa Monica Mountains: Yucca Street to Universal City Station</u>

  This entire reach within the Santa Monica Mountains consists of a thin layer of weathered bedrock over hard rock (basalt and sandstone). The sedimentary rocks on both sides of the mountain are not as hard as those in the central portion. Minor gas readings occurred near the Hollywood Bowl. The tunnel alignment will pass through several faults that may contribute to groundwater inflow to the tunnel.

- <u>Reach 8 - San Fernando Valley: Universal City Station to North Hollywood</u>

  Deep, loose to dense Young and Old Alluvium of the modern Los Angeles River channel was underlain by soft rock at depths greater than the test borings (200 ft). A deep permanent groundwater level (below 110 ft) and nongassy ground conditions are indicated.

The tunnel alignment will pass near or penetrate numerous geologic faults, all but two of which are judged to be inactive. The Hollywood fault (vicinity of Yucca Street) is judged to be active, and the Santa Monica fault (vicinity of Melrose Avenue) is thought to be potentially active. The project is 30 miles from the nearest point of the active San Andreas fault. Figure II-5 shows the location of faults and oil fields in the Los Angeles area.

3. Groundwater

The proposed alignment will traverse four hydrologic units each having distinct characteristics with respect to storage and transmission of groundwater. Three of these units are considered groundwater basins. The fourth is the Santa Monica Mountain mass. These units, starting from downtown Los Angeles to North Hollywood, are:

- Los Angeles Forebay Area (Central Basin)
- Hollywood Basin
- Santa Monica Mountains
- San Fernando Valley Basin

Figure II - 5 Location of Faults

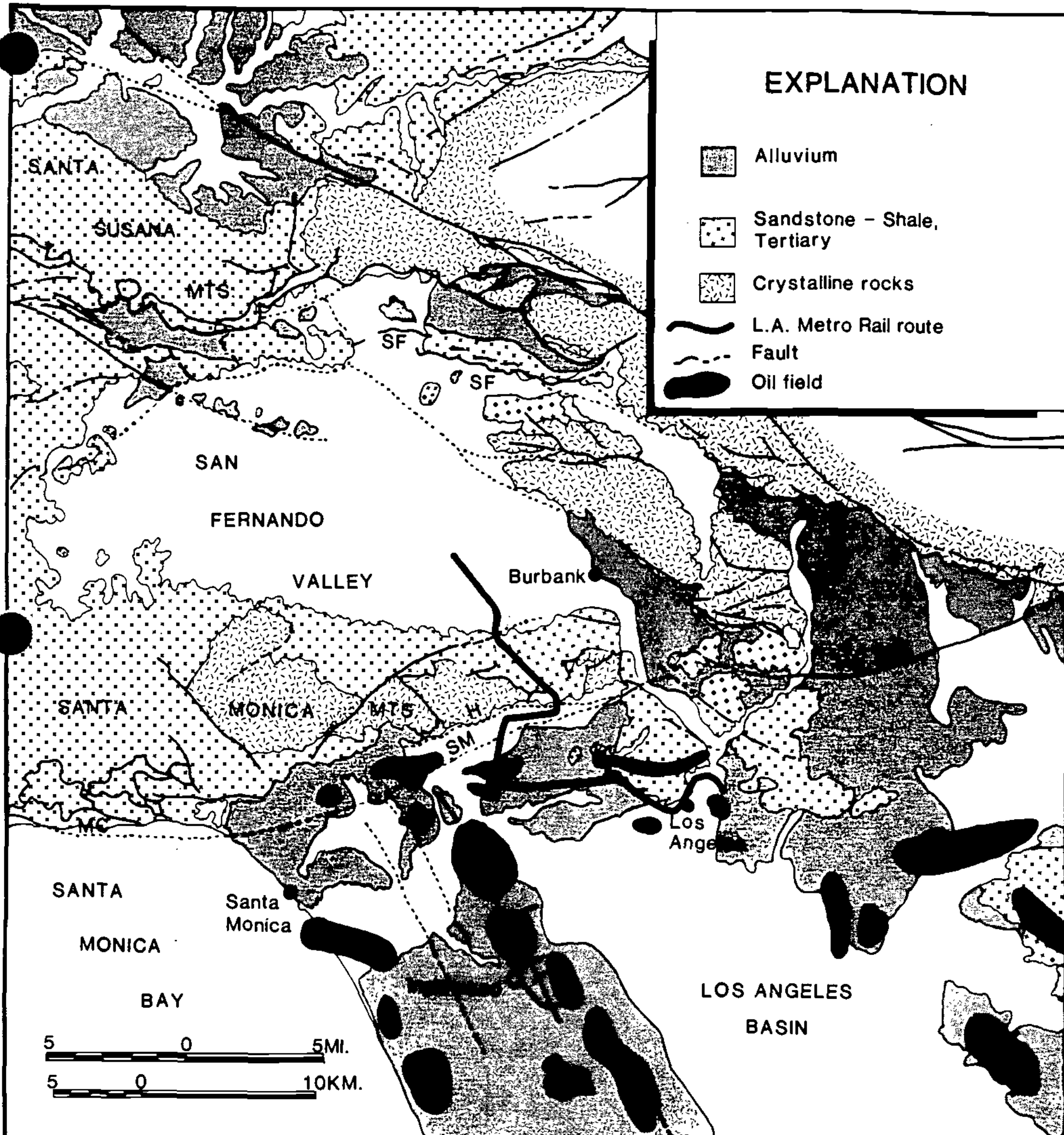


FIGURE 2. Geologic map of the Los Angeles, area showing Metro Rail route, major faults and oil fields. Identified faults are MC, Malibu Coast; RH, Raymond Hill; SF, San Fernando; SM, Santa Monica; H, Hollywood; route shown crossing Salt Lake oil field.

a) Los Angeles Forebay Area

The Los Angeles Forebay area is in the Central Groundwater Basin, extending southerly and westerly in an irregular semicircular fashion from the mouth of the Los Angeles Narrows near downtown Los Angeles. The forebay area includes the area traversed by the proposed alignment from downtown Los Angeles to the Hollywood Basin. The term "forebay" refers to an intake area where substantial infiltration of surface water into the basin can occur. This concept is a simplification. Several aquicludes of sufficiently low transmissivity occur locally, permitting perched groundwater conditions along the alignment. Where the aquiclude is missing, the aquifers are in direct hydraulic continuity with the surface. Groundwater occurs in Young Alluvium, Old Alluvium, and other underlying pervious Pleistocene sediments. The known water-bearing sediments extend to depths of 1,600 ft below the ground surface in the southern parts of the forebay. The Tertiary sedimentary rocks beneath the basin are essentially nonwater-bearing.

b) Hollywood Basin

This basin extends from the southern margin of the Santa Monica Mountains southerly to the Santa Monica fault. Many water wells were present in the Hollywood Basin around the turn of the century, but most of these have since been destroyed as land use has changed. Most of the water wells were located in the deeper portions of the basin corresponding to the Hollywood synclinal axis near the Santa Monica Mountains. Sediments containing known aquifers extend to a maximum depth of 650 ft and include alluvium and Pleistocene sediments. In general, aquifers in the Hollywood Basin possess relatively low transmissivity rates. A zone of differential subsidence, coincident with the Santa Monica fault on the south side of the basin, is attributed, in large part, to groundwater withdrawals. This subsidence is judged not to impact the Metro Rail Project, provided there is no more heavy pumping and attendant water level declines.

c) Santa Monica Mountains

This mountain range does not constitute a groundwater basin, but rather a mass of Tertiary sedimentary, volcanic, and other older crystalline rocks with a limited capacity for transmission of water. The term "nonwater-bearing" has been used by others but is meant to imply that these materials yield relatively limited quantities of water to wells, not that the materials contain no water. Wells that intersect extensive joint-and-fracture systems can produce groundwater in fairly sizable quantities for short periods of time. Such joint-and-fracture systems are significant in tunneling. A case in point occurred during construction of MWD's Hollywood Tunnel in 1941. At that time, flash flows of up to approximately 600 gallons per minute (gpm) were encountered, lasting for a few hours.

d) San Fernando Valley Basin

This basin lies on the north side of the Santa Monica Mountains. In this basin, groundwater occurs chiefly in the Young and Old Alluvium that, in places, reaches depths of 1,000 ft. In this area, the water-bearing sediments are about 600 ft thick. These sediments are permeable and freely yield water to wells. In general, water levels in the San Fernando Basin have declined markedly, in some cases 100 ft or more, since the mid-1940s in response to heavy pumping. Efforts by both the City of Los Angeles and the Los Angeles County Flood Control District to replenish the basin with imported water seem to have arrested this decline.

e) Groundwater Quality

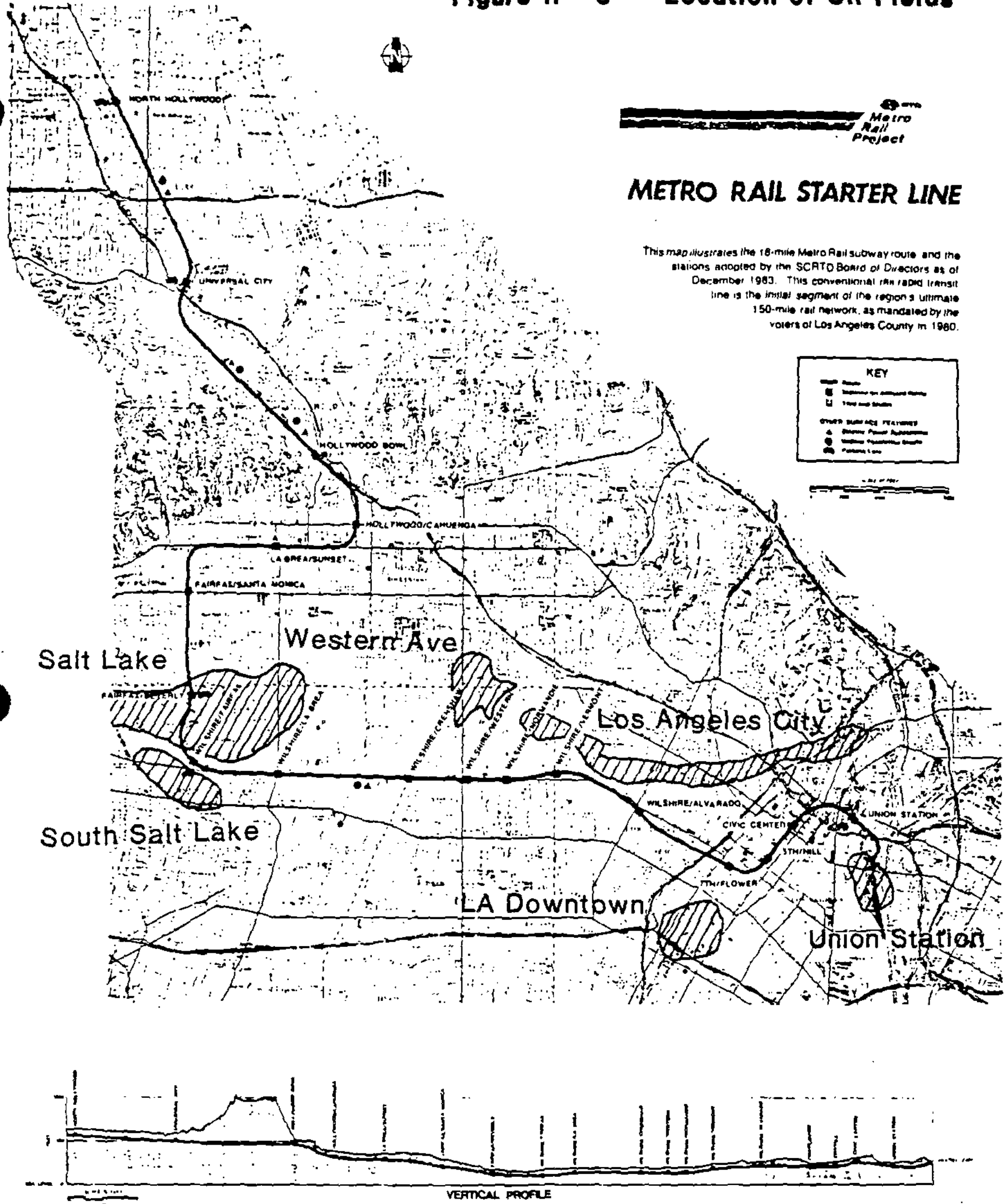
With very few exceptions, water quality along the alignment is poor, i.e., exceeds 500 parts per million (ppm) total dissolved solids (TDS), which is the U.S. Environmental Protection Agency (EPA) drinking water standard. Chloride, sulfate, and TDS contents are very high, as is conductivity. Mineral springs were common in the Hollywood area at the turn of the century, and above-normal concentrations of certain ions are to be expected where groundwater is associated with oil and gas.

4. Abandoned Oil Wells

Oil was first discovered in the Los Angeles Basin in 1880, and the Los Angeles City Oil Field was discovered in 1892, based on oil seeps at the surface. Oil is produced chiefly from thick deposits of lower Pliocene and upper Miocene strata. About 58% of recovered oil has come from the lower Pliocene rocks and about 42% from upper Miocene rocks. In relation to area, the Los Angeles Basin is the most prolific of California's oil-producing districts and is one of the most prolific in the world. Great thicknesses of intercalated source and reservoir rocks include numerous permeable conduits through which the fluid hydrocarbons were expelled by load compression toward preexisting and developing structural traps (faults).

The proposed Metro Rail alignment will pass over or near six oil fields (Figure II-6) which are described below:

Figure II - 6 Location of Oil Fields



a) Union Station Oil Field

Little is known of this oil field, but it does produce from the Puente Formation at very shallow depths. Oil was observed in borings less than 15 ft below the ground surface.

b) Los Angeles Downtown Oil Field

This oil field was discovered in 1964 by Standard Oil Company of California, and it produces from the Puente Formation. The field is located south of the proposed alignment. Oil was not encountered in Project borings nearest this field, although traces of gas were encountered.

c) Los Angeles City Oil Field

This field was discovered in 1892 and produced more than a million barrels of oil per year for a few years. The northern limit of production is probably controlled by the Los Angeles anticlinal structure. Shallow production from the Puente Formation is low-gravity oil (12-20 API), and production parallels the strike of bedding (east-west trending). The oil field contains shallow accumulations of petroleum, surface seeps, and more than 1,250 wells, only 54 of which were active in 1974. Most of the wells, drilled before 1900, were not surveyed or otherwise accurately located, and the ground surface has since been developed for cultural uses. Consequently, no accurate record exists on the location of many of these wells. The east-west trending structure dips southward about 30°, extending to depths of 500 to 1,000 ft below the surface. Gas and seeping oil were encounteed in 1976 during construction of the Los Angeles County Flood Control District's Sacatella Tunnel near Hoover Street. Gas was encountered in several borings.

d) Western Avenue Oil Field

This oil field is apparently a westward extension of the Los Angeles City Oil Field on the south flank of the Los Angeles anticline. Little is known of this oil field.

e) Salt Lake Oil Field

This field was first developed in 1903 but was long known by large seeps of heavy oil on the north side of Wilshire Boulevard. The tar around the seeps was mined in pits in the early days and yielded the famous Rancho La Brea fauna of Pleistocene vertebrates. This field was created by anticline and synclinal structures in concert with several minor faults - 6th Street, 3rd Street, and San Vicente. Tar, oil, and gas are present in the underlying Fernando Formation as well as the overlying San Pedro Formation and alluvial deposits. The possibility exists that the project excavations could encounter abandoned oil well casings.

f) South Salt Lake Oil Field

Little is known except that commercial oil production began in this field in 1903. Since 1908, the oil field has produced less than 10 barrels per day from about 100 wells. This decrease is attributed to the need for deeper drilling and the growth of the residential district. This field is considered part of the overall Salt Lake Oil Field.

5. Seismicity

California is known as earthquake country, and the Los Angeles area, which the Metro Rail alignment will traverse, is no exception. California is located within the Circum-Pacific Seismic Belt, along which 80% of the world's earthquakes take place. For at least the past 30 million years, the tectonics of Southern California have been dominated by relative motion between the Pacific and North American tectonic plates. The San Andreas fault zone is the boundary between these tectonic plates. The Pacific Plate continues to shift northwesterly with respect to the North American Plate at a rate of about 2.2 in. (5.5 cm) per year. South of the Transverse Ranges, this motion is manifested as right-lateral slip on several mapped, northwest-trending faults. However, the northwesterly plate motion is impeded within the Transverse Ranges and along their north and south flanks, resulting in north-south-oriented tectonic compression, which is manifested as mountain-building and reverse faulting. Nearly all tectonic movement in Southern California occurs as seismic fault slippage; i.e., permanent crustal deformation is accompanied by earthquakes that suddenly release gradually accumulated elastic strains. No permanent deformation is known to result from nonseismic (creep) displacements in the Metro Rail alignment area.

Some of these are historically active faults; i.e., displacing the ground surface as in the 1971 San Fernando earthquake (M 6.4), which occurred on the east-west trending Sierra Madre fault zone. Others are seismically active faults that have not displaced the ground surface in historic times; e.g., the 1933 Long Beach earthquake (M 6.3), which occurred on the Newport-Inglewood fault zone.

6. Gas

The proposed Metro Rail alignment will pass over or near six major oil fields and has been classified as gassy ground. Tunneling in gassy ground can hardly be avoided in the Los Angeles Basin. In addition to being a potential construction hazard, the presence of gas can reduce construction excavation rates substantially, require special lining provisions for certain portions of the alignment, and mandate adequate gas monitoring and ventilation systems for the finished project.

B. Field Investigation Activities

1. Geotechnical Exploration

Field exploration consisted of subsurface drilling, sampling, and testing, combined with geophysical testing along the proposed alignment. Simultaneously with and following the field investigation, an extensive laboratory program was conducted, consisting of over 1,100 individual tests. The purpose of the field and laboratory investigation was to develop a comprehensive understanding of the subsurface conditions at selected locations along the proposed route and to establish the physical properties of the various soil, rock, water, and gas samples obtained during this investigation.

The geotechnical drilling exploration program was begun for the SCRTD in 1980. Additional drilling was done in selected areas to supplement the earlier exploration. A detailed description of the Metro Rail Project drilling exploration program, boring logs, colored core photographs, water pressure tests, groundwater level monitoring, piezometer installation, and gas analyses is presented in the Geotechnical Investigation Report, Appendix A, Volume II, prepared by CWDD in November 1981. Using the initial and supplementary exploration results, detailed geotechnical reports were developed for each design section of the Metro Rail Project.

a) Soil Classification

All soil types were classified using the USBR Unified Soil Classification System. Based on the characteristics of the soil, this system indicates the behavior of the soil as an engineering construction material. Using the Unified Soil Classification System, which is based primarily on laboratory test results, the site geologists arrived at a classification in the field that would be the same as the one obtained in the laboratory. Although particle size distribution estimates were based on volume rather than weight, the field estimates were within an acceptable range of accuracy.

b) Groundwater Level Monitoring and Piezometer Installation

A total of 6,047 linear feet of 2-in. plastic ABS pipe was installed in 31 of the 41 geology borings. In addition, 906 linear feet of 1-in. PVC plastic pipe was installed in 11 of these borings, alongside the 2-in. pipe, to monitor perched water levels. When double piezometers were installed in a boring, the two piezometers were separated vertically by a bentonite seal placed below the upper piezometer and above the highest perforation of the lower piezometer. Several water-level readings were taken, the last in March 1981.

c) Water Pressure Testing

Water pressure and holding tests were performed in 16 of the 41 geology borings. Similar results were obtained using both pneumatic and push packers in the Puente and Fernando formations. Because of the more massive and clayey nature of the Fernando Formation, slightly better data was gathered. The fine sand interbeds of the Puente

Formation tended to wash out around the packers at pressures between 20 to 60 psi. However, enough reliable data was obtained to demonstrate that both the Puente and Fernando formations are very tight and, in almost all cases, would take less than 1 gpm over a 20-ft test interval.

d) Summary of Geotechnical Report

The results of the geotechnical investigation indicate that the proposed alignment for the Metro Rail Project is favorable for modern economical tunnel construction. Sixty percent of the planned route traverses competent soil materials (Old Alluvium) and soft-rock formations most suitable for excavation by soft ground shields and tunnel boring machines (TBMs). Approximately 15% to 20% of the route is expected to encounter hard-rock formations of the Santa Monica Mountains that may be excavated either by hard-rock TBMs, drilling/blasting methods, or excavation by cut-and-cover methods.

2. Gas Probes

a) Introduction

In 1982, the Metro Rail Transit Consultants (MRTC), at the direction of SCRTD, contracted with Engineering-Science, Inc. (ES), to conduct a monitoring program for subsurface combustible gases and hydrogen sulfide (H_2S) along the Metro Rail subway route. The program was to provide detailed information regarding gas content and pressures along the route and to verify the 1962 findings of Kaiser Engineers and the reported occurrences of gases, especially in the Wilshire/Fairfax area.

The program began in the winter of 1982 when 66 borings were made and two-level probes were installed (Figure II-7). The borings were located at intervals of approximately 1,000 ft, up to the south side of the Santa Monica Mountains and then at the Universal City station site. The two-level probes were to sample the gases at about 80 ft and 40 ft below surface. The probes were placed in the

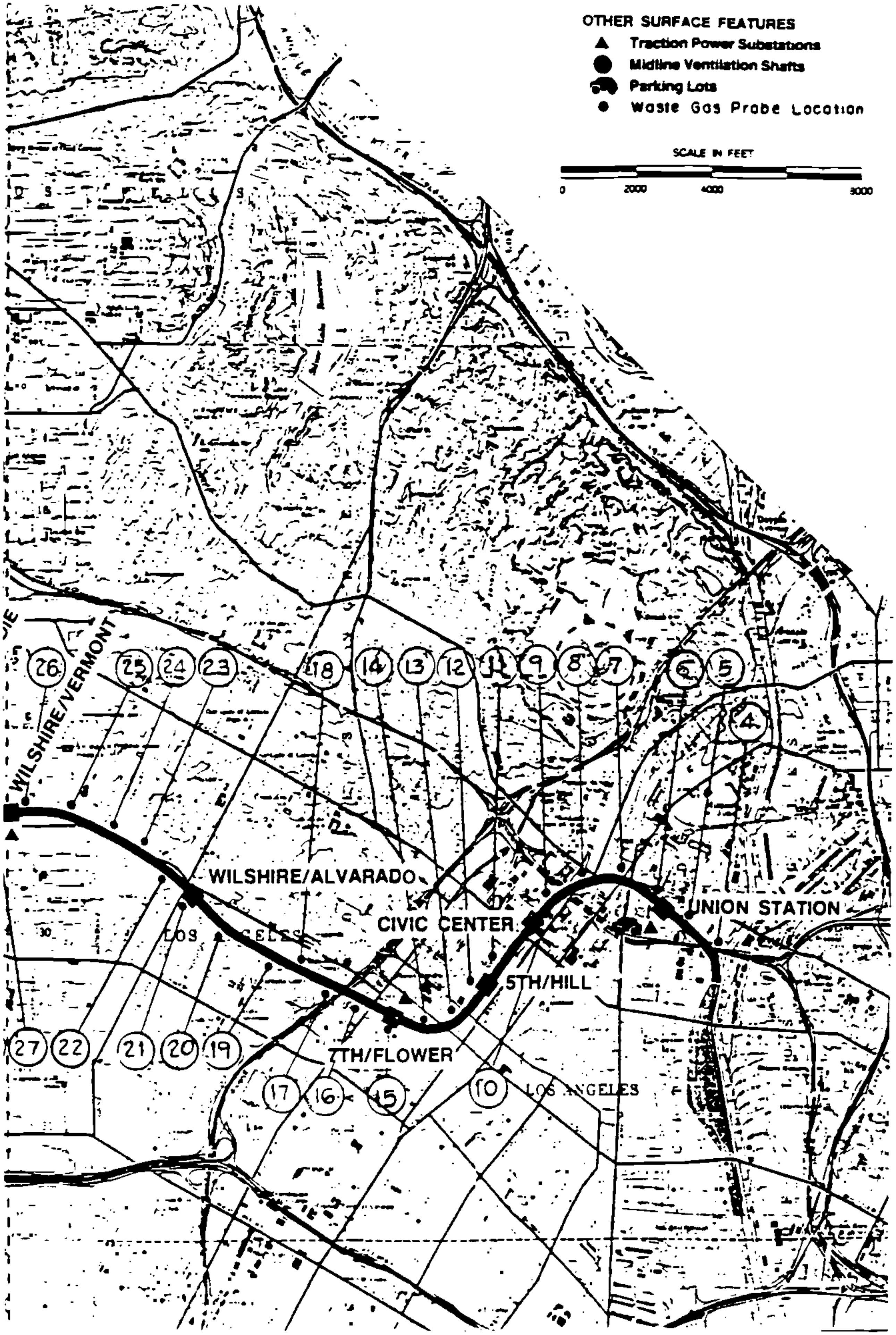


Figure II - 7 Location Of Gas Probes

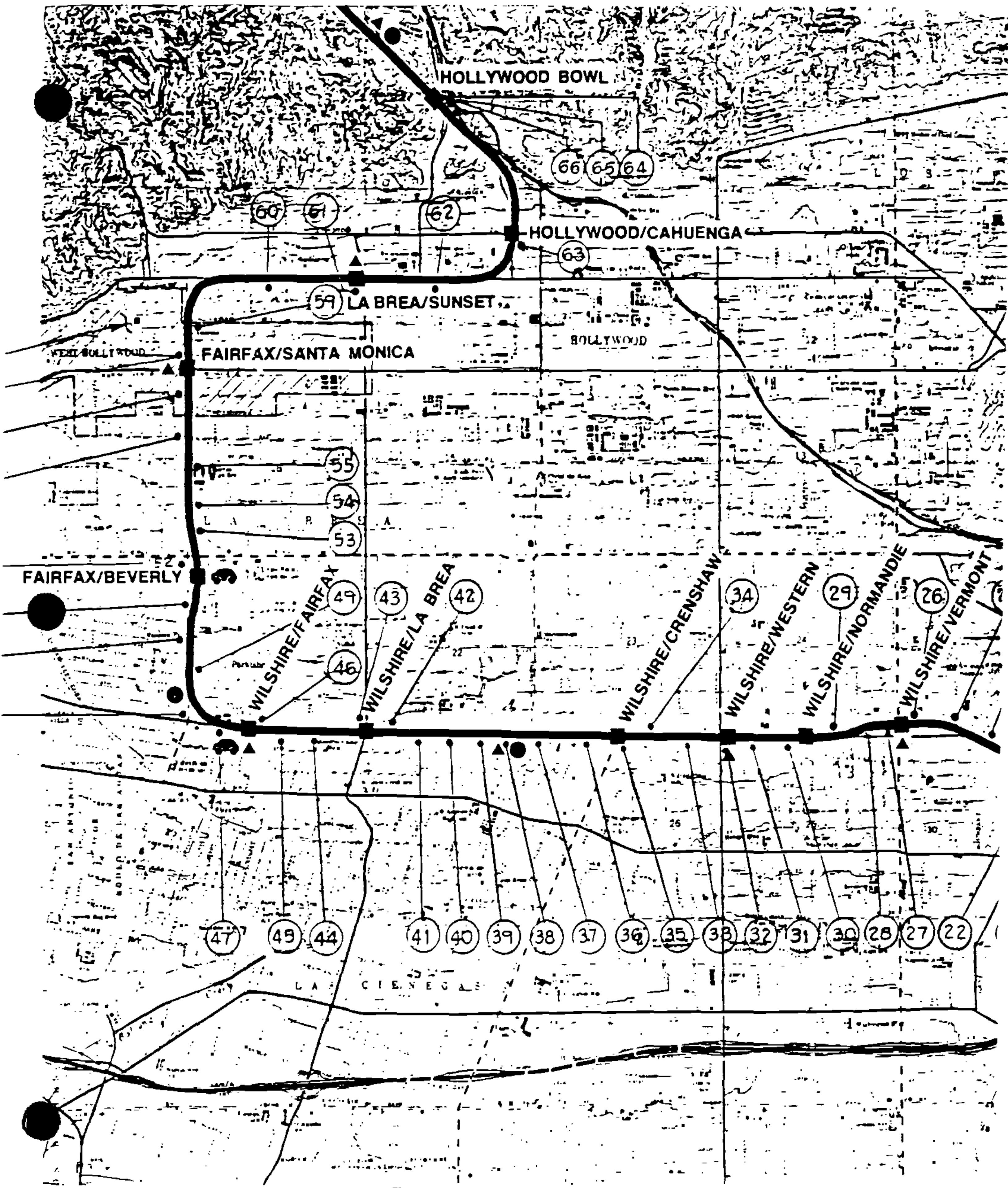


Figure II - 7 (cont'd)

bores, surrounded by coarse sand and gravel, and then separated within the bore by at least 30 ft of bentonite seal. Above the upper probe, the bore was sealed with bentonite and concrete.

After at least 6 months, 65 gas probes were surveyed in August and September 1983. The survey involved three measurements of gas concentration and pressures for methane and the concentration of Hydrogen Sulfide. The readings are summarized below and indicate that primary sections of concern were between the Wilshire/Western and Fairfax/Santa Monica station sites. The highest readings (1983) were found at the following sites:

Probe No.	Location	Highest Content (% volume)	Gas Pressure (psig)
11	4th/Hill	7-79	-
15	7th/Harbor Fwy	0.2-22	-
33	Wilshire/ Western	10-35	-
39	Wilshire/ Hudson	80-95	7
46	Wilshire/ Fairfax	24-78	-
47	"	30-80	2.5
48	"	20-65	-
52	Fairfax/ Beverly	5-45	-
55	Fairfax/First	5	-
57	Fairfax/ Santa Monica	5	-

58	"	5	-
59	"	5	-
60	Sunset/Orange	5-12	-

The remainder of the probes had readings of less than 5.0% by volume with 8 readings at less than 1.0% by volume (20% LEL) and with 44 measurements between 1% and 5% by volume.

In the spring of 1985, ES repeated the gas probe measurements to update the data on subsurface gas concentrations and pressures along the Metro Rail route from Union Station to the Hollywood Bowl Station and at the Universal City Station. These services supplement the January 1984 by ES, "Report of Subsurface Gas Investigation - Southern California Rapid Transit District Metro Rail Project Wilshire Corridor Alignment."

The services performed included a review of the 1983 monitoring data, inspection and repair of probes installed in 1983, monitoring combustible gas composition and pressure, laboratory analysis of gas samples, and an analysis of the data. The objectives of the 1985 program were to supplement the finding of the 1983 monitoring of subsurface gases and pressures along the Metro Rail route and to compare and evaluate this data in relation to the 1983 monitoring data and the criteria for gas monitoring control designs.

b) Conclusions and Recommendations

The results of the 1985 subsurface gas monitoring along the Metro Rail route basically confirm the findings of the 1983 investigation. However, some modifications to the hazardous classification and pressure criteria were made for gas monitoring control designs. A summary of monitoring data is shown in Table II-1.

The locations where higher gas concentrations were found are:

(1) Along Seventh Street between Flower Street (probe 15) and Valencia Street (probe 19)

(2) Near Wilshire and Crenshaw Boulevards (probes 34, 35 and 36)

Table II – 1
Summary of Monitoring Data

Probe No.	Route Station Number	Subway Station Name	Methane[a] Round 3 1983	Methane[a] 1983	Methane[a] 1985	Pressure[b] 1983	Pressure[b] 1985	Hydrogen Sulfide[c] 1983	Hydrogen Sulfide[c] 1985
5	100		0.2	1.2	0	0	0	–[4]	–
6	110	Union	0.5	1.8	T[5]	0	0.4	0	–
7	120		0.3	2.0	0.3	0	0.2	–	–
8	130		0.5	1.5	0	0.07	1.2	–	–
9	140		0.3	1.3	T	0.05	0.6	–	–
10	148	Civic Center	0.3	1.5	0	0	0	–	–
11	160		79.0	79.0	60.0	0.1	0.2	0	0
12	170	5th/Hill	0.2	1.2	0.7	0.06	0.2	–	–
14	190		0.5	3.0	0.5	0	0.2	–	–
15	200	7th/Flower	22.0	60.0	100.0	0.2	0.8	0	–
16	210		–	3.0	–	0	–	–	–
17	220		0.5	1.6	2.5	0.45	0.2	–	–
18	228		0	2.0	T	0.2	0	–	–
19	240		0.3	0	0.8	0.05	0	–	–
20	250		0.2	0.5	0	0.4	0	–	–

Table II - 1 (cont'd)

Probe No.	Route Station Number	Subway Station Name	Methane[a] Round 3 1983	Methane[a] 1983	Methane[a] 1985	Pressure[b] 1983	Pressure[b] 1985	Hydrogen Sulfide[c] 1983	Hydrogen Sulfide[c] 1985
21	265	Wilshire/Alvarado	0	3.0	0	0.04	0	-	-
22	270		0.3	1.0	0	0.1	0.1	-	-
23	280		0.3	3.0	0.5	0	0	-	-
24	290		0	0	T	0	0.5	-	-
25	299		0.3	0.3	0	0	0.6	-	-
26	312	Wilshire/Vermont	0.3	0.3	0	0	0.1	-	-
27	321		0.7	0.2	0	0	0.4	-	-
28	329		0	0	0	0.1	0.6	-	-
29	337	Wilshire/Normandie	0.6	0.6	0	0.05	0	-	-
30	350		1.1	1.1	0	0.12	0.1	-	-
31	360		0.7	1.0	0	0	0	-	-
32	370		0.3	0.2	-	0	-	-	-
33	380		35.0	35.0	16.0	0	2.4	0	-
34	390		0.2	0.7	4.5	0	0	-	-
35	399	Wilshire/Crenshaw	2.2	2.2	2.7	0	0.5	-	-
36	410		0	0.2	0.4	0	0	-	-

Table II - 1 (cont'd)

Probe No.	Route Station Number	Subway Station Name	Methane[a] Round 3 1983	Methane[a] 1983	Methane[a] 1985	Pressure[b] 1983	Pressure[b] 1985	Hydrogen Sulfide[c] 1983	Hydrogen Sulfide[c] 1985
37	420		0.4	0.8	0	0	0.7	-	-
38	430		0.4	1.0	0	0	1.0	-	-
39	440		94.0	95.0	65.0	194.0	24.0	160	0
40	451		1.5	2.0	15.0	0	0	-	-
41	459		0	0.4	0	0	0.7	-	-
42	470		0	0	0	0	0	-	-
43	479	Wilshire/La Brea	0	0.2	4.5	0	0.3	0	-
44	491		4.0	4.0	0	0	2.0	-	-
45	499		0.5	3.0	45.0	0	1.2	-	-
46	509	Wilshire/Fairfax	-	78.0	-	27.0	-	160	-
47	520		70.0	80.0	32.0	83.1	6.1	60	4
48	530		85.0	65.0	55.0	0.4	0.3	0	0
49	540		1.2	3.1	3.0	1.0	0.8	-	-
50	551		0	0.5	0	0.14	0.5	-	-
51	561		1.5	2.8	9.0	0.9	0	-	-

Table II - 1 (cont'd)

Probe No.	Route Station Number	Subway Station Name	Methane[a] Round 3 1983	Methane[a] 1983	Methane[a] 1985	Pressure[b] 1983	Pressure[b] 1985	Hydrogen Sulfide[c] 1983	Hydrogen Sulfide[c] 1985
52	568	Fairfax/Beverly	45.0	45.0	70.0	2.0	194.0	160	0
53	581		0.2	1.5	2.2	1.0	7.6	-	-
54	589		0	1.3	6.0	0	0.2	-	-
55	600		1.1	3.4	T	0.04	0.4	-	-
56	609		0.5	0.5	6.0	0	0.5	-	-
57	620		0	0	T	0	0	-	-
58	631		3.0	3.0	-	0	-	-	-
59	640		0.5	0.5	0	0	0	-	-
60	669		1.7	5.0	T	0.02	4.2	-	-
61	696	La Brea/Sunset	1.0	0.5	T	0	0	-	-
62	722		0.9	0.9	T	0	0	-	-
63	754	Hollywood/Cahuenga	1.2	2.5	0	0.7	0	-	-
64	791	Hollywood Bowl	0.9	1.9	0	0	0	-	-
65	794	Hollywood Bowl	1.4	1.5	T	0	0	-	-
66	796	Hollywood Bowl	1.2	1.2	-	0	-	-	-
67	932	Universal City	0.6	1.5	11.0	1.3	0.3	-	-

Table II - 1 (cont'd)

Probe No.	Route Station Number	Subway Station Name	Methane[a] Round 3 1983	Methane[a] 1983	Methane[a] 1985	Pressure[b] 1983	Pressure[b] 1985	Hydrogen Sulfide[c] 1983	Hydrogen Sulfide[c] 1985
68	938	Universal City	0.2	1.0	0.6	0.25	0	-	-
69	942	Universal City	0.3	0.3	T	0.6	0.4	-	-

Dash line (-) only indicates not measured or data not recorded.
T indicates a trace amount (a small single excursion of the meter and return to near 0).
Probes 16, 32, 58, and 66 were destroyed by new construction.
Probe 46 covered by asphalt.

a Highest measured combustible gas concentrations in percent by volume (from monitoring rounds in 1983 and 1985).
b Highest measured pressure (inches of water column).
c Highest measured concentration of hydrogen sulfide (in ppm).

(3) Along Wilshire Boulevard at probes 40, 43, and 45.

(4) Fairfax Avenue north and south of Beverly Boulevard (probes 51, 52, 53, 54 and 56)

(5) Universal City (probe 67)

The number of probe well locations where gas pressures greater than 1 in. of water column were measured increased from 7 in 1983 to 10 in 1985. Probes 39 and 47, with relatively high pressures sustained by gas flows into the probes, decreased to less than 1 in. of water column in 1985 after being vented to the atmosphere. Because of the experience of others with nearby producing gas wells, the continued presence of high pressures should be assumed in the area of these probes. The potential for high gas pressures was also indicated along Fairfax Avenue by the recent fire and explosion at Third Street and Ogden Drive. Although not indicated by any of the probe pressures measured, subsurface gas may exist with pressures equal to or greater than the hydrostatic head on the tunnel structure.

Based on the hydrostatic head from water levels measured in the probes, gas pressures higher than the 7 psig previously assumed may exist.

Hydrogen sulfide was found at only one of the four locations (probe 47) monitored in 1983 but should be considered to be present in all the locations found in 1983.

c) Summary of Monitoring Results

Monitoring data is contained in the "Report of Subsurface Gas Investigation" by ES, May 1985. Table II-1 contains a summary of the monitoring data and tabulates the highest combustible gas concentrations, pressures, and hydrogen sulfide readings from 1983 and 1985. Combustible gas measurements for the third monitoring round of 1983, which would be the least affected by volatiles from adhesives used in probe construction, are also tabulated in Table II-1 for comparison with the other measurements. Hourly readings of barometric pressure at the Los Angeles International Airport taken during the monitoring by the

U.S. Weather Service are in Table 8 of the ES Report. A Gas Sampling Log is in ES Table 9. A Summary of Laboratory Results Compared to Occupational Health Limits (TWA) is in ES Table 10. The laboratory analysis of samples taken at 10 locations along the route are in Appendix B to the ES Report.

(1) Combustible Gas

As shown in Table II-1, probes 5, 6, 8, 9, and 10 show a decrease in gas concentrations to zero or trace amounts from that found in 1983. High concentrations of gas continue to be found in probe 11 at Second and Hill Streets and in probe 15 at Seventh and Flower Streets. Relatively low concentrations were detected in probes 12, 14, 17, 18, and 19. Between probes 20 and 31, gas was detected in only two probes in 1985, compared to 10 in 1983. Between probe 33 (at Gramercy Place and Wilshire Boulevard) and probe 56 (at Waring and Fairfax Avenues), the number of probes in which gas was detected remained about the same as in 1983, except the number of probes with gas concentrations above 4% increased from 5 to

12. The remaining probes 57 to 67 were where the concentration increased from 1.5% to 11%.

(2) Gas Pressures

Table II-1 shows that in 1983 combustible gases at pressures of 1.0 in. of water column or more were measured in probes 39, 46, 47, 49, 52, 53, and 67. Of these probes, relatively high pressures of 194, 28, and 83 in. of water column were measured in probes 39, 46, and 47, respectively. In 1985, pressures of 1.0 in. of water column or more were measured in probes 8, 33, 38, 39, 44, 45, 47, 52, 53, and 60. Although probe 46 was abandoned to asphalt in 1983, the continued presence of combustible gas at the 1983 pressures should be assumed in the area of probe 46.

The high pressures measured in probes 39 and 47 in 1983 decreased to much lower values in 1985. A momentary pressure of 24 in. of water column was measured in probe 39 in 1985; it quickly went to zero when the probe was vented to air. In 1983, the pressure measured in probe 39 was 194 in. of water column with no decrease in pressure when gas was discharged from the probe. Probe 47 showed a decrease in pressure from 83 in. of water column in 1983 to 6.1 in. in 1985. Air injection to force water out of the probe did not restore the gas pressure. Measurements indicated the water level in the probe to be well above the perforations.

During monitoring on March 14, 1985, probe 52 indicated an unusual transient increase in pressure to 194 in. of water column. This was an increase in pressure from an earlier reading of only 2.6 in. of water column on March 3, 1985. On March 15, 1985, the probe was monitored again, repeating the procedure. At this time, an initial pressure of 8.7 in. of water column was reduced to -10 in. of water column when an attempt was made to evacuate two gas volumes in accordance with the monitoring procedure.

The pressures and behavior of shallow gas-producing wells near probe 39 indicate that a gas pressure of 5 psig or more is still present in the area. These wells reportedly show a decrease in pressure as a result of water and mud flowing into the wells, and they must be periodically pumped out to restore gas pressure and flow. The present maximum well pressure in a clean well is reported to be about 5 psig. The water level in probe 39 (deep probe) measured 41.5 ft during monitoring and was well above the perforations. Forcing water out of the probe by air injection, however, did not restore gas pressure as was expected from the experience reported with the gas wells in the area.

The negative pressure, P_2, measured during the monitoring activities was caused by the pump in the gas detection instrument used to withdraw gas from the probes; negative pressure, P_3, was caused by the pump used during monitoring to evacuate the probes. The pumping rate of the detection pump is about 1 cubic foot per hour (cfh) and for the pump used to evacuate the probes about 6 cfh. Pressures P_2 and P_3, after evacuating the probes, indicate which probes have gas in flow rates less than 1 cfh and 6 cfh, respectively. Probes that simultaneously indicated the presence of a combustible gas and some gas inflow are 11, 15, 18, 23, 33, 35, 36, 40, 51, 55, 56, 57, 62, and 67. Gas under pressure, which may be present at other locations, may not have been indicated because of water or mud blocking the flow into the probes.

Because of the method used to seal the end of the probes, some may not have been tightly sealed. Changes in pressure caused by variations in barometric pressure or seasonal changes of water level in the probe would not be observed in the monitoring time interval. However, because of the small probe volumes and sensitivity of the pressure measurements, relatively small flows (<.01 cfm) would be indicated by an increase in pressure.

No correlation between probe pressures and barometric pressures could be determined.

(3) Hydrogen Sulfide

Hydrogen sulfide was detected in probes 39, 46, and 52 in 1983 but only in probe 47 in 1985. It should be assumed this gas is still present in these locations and may be found at other locations along the route.

(4) Water Levels

Water levels in probes measured during monitoring show that of the deep probes only 15, 57, 59, 60, 61, 62, and 63 have perforations not covered by water. With the exception of probes 14, 42, and 69, these measurements correlate well with pressures measured when drawing gas from the wells. Perforations in 21 of the shallow probes were below water. These probes and four additional probes were evacuated to -10 in. of water column when attempting to evacuate two probe volumes in accordance with the monitoring procedures.

(5) Laboratory Analysis

Ten gas samples in 500-milliliter Tedlar bags, three Tenax tube samples, and three activated carbon absorption tube samples were taken for analysis by mass spectometry and gas chromatography. The bag samples were taken from the following probes: 11 shallow, 15 deep, 33 shallow, the 57-ft-deep gas well at 4680 Wilshire Boulevard near 39, 48 shallow, bar hole in the box at 52, 56 shallow, 60 deep, and 67 shallow. Absorption tube samples were taken at probes 15, 39, and 67 at the same depths as the bag samples.

The laboratory results for the permanent gases (atmospheric and carbon dioxide) and hydrocarbons verified that the concentration of methane and oxygen gases at the probes sampled was comparable to the field measurements, with the exception of the sample from the gas wells at 4680 Wilshire Boulevard. The laboratory analysis of this sample, which was expected to show a high (80% to 95%) concentration of methane gas, was essentially air. In a subsequent conversation, the building superintendent at 4680 Wilshire Boulevard reported that the system had been down for well cleaning and that the gas lines would contain air if not purged for sufficient length of time prior to sampling. The methane gas wells at 4680 Wilshire Boulevard provide fuel for heating and air conditioning an office building at that address.

The values found for permanent gases were in the range of those typically experienced for these types of sources. The values for C_2-C_7 hydrocarbon were in trace amounts. Close observation of these constituents will be made during construction.

3. Wilshire/Fairfax Building Construction

The new Wilshire Building under construction at the southwest corner of the intersection of Wilshire Boulevard and Fairfax Avenue by Dillingham Construction is an example of a current construction project requiring deep excavation in the tar sands of Rancho La Brea and in the area classified by the City as a "high potential gas risk zone."

a) Background

The $20,000,000 building is a 16-story structure featuring such embellishments as 210 operative balconies and 16 sliding glass doors per floor. The foundation is seated in sands of the San Pedro Formation to a depth of 60 ft below street level.

Based on soils reports used in the building design by the William L. Pereira and Associates of Los Angeles, only traces of gas were indicated and gassy conditions were not expected to present any problems. However, in the course of excavation, gas was observed bubbling at water puddles; therefore, ES was retained for a program of testing in May 1984. At this point, the excavated surface was at approximately elevation 20 ft.

ES measurements of gas concentrations were uniformly low (less than 100 ppm), except for a single occurrence with a reading of 1%. Safety measures were immediately placed in effect, including no smoking, limited welding operations, spark arrestors on equipment, and daily gas detector monitoring. Additional safety procedures were imposed, including: (1) tiebacks requiring lagging at the point of drill entry were to be wet down, and a hollow stem auger was to be used to allow pressure grouting to seal the bottom of the hole; (2) welding was permitted when the gas concentration was less than 1.2%; at 1.2%, a blower was to be added; and when more than 1.2% with a blower, shutdown was required; and (3) personnel were instructed to be aware of any developing cracks in the surfaces during grading operations.

For the permanent construction, ES recommended a shielded foundation slab using high density polyethylene (HDPE) over a mud slab and under the structural slab (Figure II-8). Also recommended was the use of a dumbbell-shaped PVC waterstop in all construction joints in conjuction with the use of a Xypex waterproofing agent on the interior walls. The waterproofing is expected to control gas penetration through the concrete walls because the moisture will build at the exterior face of the wall, which then acts as a gas barrier.

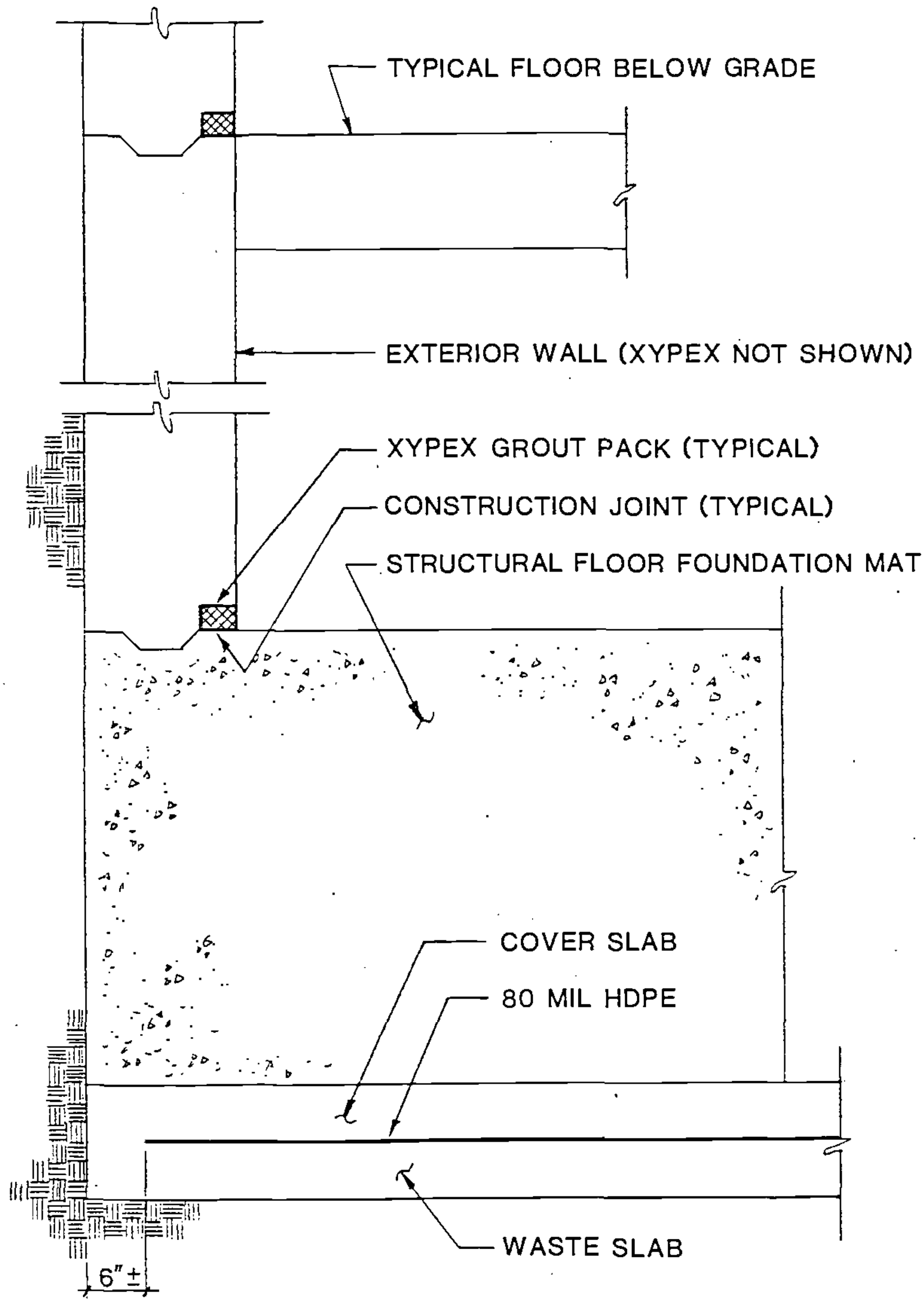


Figure II - 8 Typical Section Showing Membrane & Waterproofing

It should be noted that prior to the selection of HDPE as a gas membrane under the foundation slab, other materials such as PVC, Hypalon, LDPE (low density polyethylene), and neoprene were considered. Following testing, the leading candidates were HDPE and LDPE, resulting in the selection of HDPE at a 60-mil thickness to enhance its impermeability and resistance to punctures.

Quality control during field installation was considered critical; therefore, it was recommended that field testing be accomplished by a manufacturer's representative, as well as an owner's representative. Testing would be dielectrically performed in the shop after fabrication and in the field after placement. Collars of HDPE and caulking were recommended for all belowgrade wall penetrations.

b) Excavation

Construction permits did not require unusual submittals. In accordance with City requirements, a soils engineer was employed, disposal haul routes were submitted for approval, and a bond covering liability for system removal and detensioning of tiebacks was furnished.

The excavation support system used tiebacks and timber lagging. It was necessary to reinforce the system with localized struts at the surface when movement was detected near the top of the support system. It is to be noted that there was one occurrence of a minor explosion while drilling a tieback hole, resulting from a laborer lighting a cigarette contrary to standing safety orders.

Excavation was accomplished by direct loading into trucks until the ramp into the excavated area became too steep. The remainder of the material was loaded by clam into trucks at street level. The excavated surface down to elevation of 3 ft (approximately) was sufficiently stable to support construction equipment such as front-end loaders, small dozers, and drills. At the conclusion of excavation, however, it was necessary to dress the area and refrain from having equipment move over areas where the final lift had been removed until approximately 2 ft of gravel had been placed for stabilization.

Dewatering was performed using sumps as the excavation progressed; 2,000 gpd of water was pumped into two 4,000-gallon holding tanks from which it was removed with a vacuum tank truck.

c) Disposal of Excavated Material

The excavated material did not contain free-flowing oil/material; however, it was saturated with tar and as the excavation progressed, gas bubbles were observed at isolated puddle locations. The material was classified nontoxic by the State of California and was initially disposed of in landfills at Griffith Park, Culver City, and a freeway fill. Use of these disposal sites was discontinued either due to the oily odor or the intention to provide vegetation. The final portion of the excavation was placed in a commercial disposal site in Irwindale.

The principal gas control measure finally used in the building construction was to shield the foundation slab with 80-mil HDPE. The exterior walls were not treated on the basis that gas would rise vertically with minimum horizontal movement. The application of Xypex on the interior walls served to reduce moisture flow into the structure and, at the same time, allowed moisture buildup in the concrete as a gas barrier.

d) Conclusion

Through the use of capable engineering services and the application of good safety practices, construction techniques and management, building work at Wilshire and Fairfax demonstrated that construction in tar sands and gassy conditions of the La Brea area can be accomplished in an effective working situation and in a safe manner, both for construction and occupancy.

4. Ross Clothing Store Fire

The following material is extracted from the June 5, 1985, letter from the LAFD to the Honorable Henry A. Waxman.

On Sunday, March 24, 1985, at 1647 hours, the Los Angeles City Fire Department responded to a reported explosion and fire at the Ross Dress For Less store at 6298 West Third Street, West Hollywood.

Upon arrival, the Fire Department found a 155 x 135 ft one-story, brick masonry structure of which an area approximately 120 x 40 ft had been directly impacted by the explosive blast, causing the ceiling and a 70 x 40 ft roof section to collapse with associated buckling of one exterior wall. This 70 x 40 ft area was the only section of the building that was involved with fire.

The Fire Department commenced fire suppression and rescue and medical treatment operations. Upon suppression of the major portion of fire, it was found that gas was still seeping and sustaining fire between the floor slab and the walls of the

70 x 40 ft portion of this building. Fire was also sustained by gas seepage at the exterior of the building including areas around planters, cracks in pavement and between sidewalks and curbs.

The Fire Department, with the assistance of the Southern California Gas Company, began monitoring hazardous gas seepage at many locations within the area. Though, at the onset, the Fire Department suspected that methane gas had been the cause of the explosion, it could not be immediately confirmed. With this thought in mind, it was determined that Southern California Gas Company would shut down their natural gas mains in the vicinity to determine that it was not the source. Shut down of the natural gas did not cause diminishing or ceasing of any of the ground seepage fires.

Since the general area was in the location of an old oil field abandoned some 40 to 50 years ago, it was confirmed that the gas seepage was that of methane deposits from below ground pockets. At this time, the Fire Department caused the original evacuation area to be expanded to encompass a three square block area.

On Monday, March 25, 1985, the Fire Department chaired a meeting to discuss the method for alleviating the methane gas and associated hazard. Attendance at this meeting was provided by some 60 agencies, which included State Division of Gas, Getty Oil Company, McFarland Oil Company, County Department of Sanitation, Engineering Science Consulting Firm, Los Angeles City Attorney, Department of Building and Safety, to name but a few. The determination resulting from this meeting was that a well would be drilled in an attempt to relieve the gas pressure.

The well drilling site, located in the Ross Store parking lot, commenced at 2200 hours on Monday, March 25, 1985, and was completed to 80 ft depth by 0930 hours on Tuesday, March 26, 1985. The well was provided with a shut off and pressure gauge. Pressure remained constant between 7 and 8 psi through Tuesday night, being bled off every hour. On Wednesday, March 28, 1985, at 1500 hours, the well was opened and the well flare was ignited, reducing the pressure to approximately 3 psi. By Thursday, March 29, 1985, the ground fires had all extinguished due to reduction of gas pressure relieved by the well and the well itself had a reduction in pressure such that combustion of the flare could no longer be maintained.

On Thursday, March 29, 1985, at 0900 hours, the property owners were notified that they could open their establishments. Routine monitoring throughout the area was maintained.

On Monday, April 1, 1985, the Fire Prevention Bureau took over emergency command and control of the incident. From April 1, through April 9, 1985, the Fire Department, with assistance of other agencies, continued gas monitoring, including drilling of additional monitoring wells.

On April 9, 1985, a debriefing session was held with the property owners and letters were hand delivered to them regarding the incident and the Department's requirements for monitoring and protecting these properties from any future methane gas problems.

Currently, the property owners have contracted with private consulting firms to continously monitor the subject area and to recommend to the Fire Department their findings and recommendations to preclude a similar incident in the future.

5. History of Gas Occurrences

Oil and gas in the Metro Rail corridor have been known from prehistoric times, and human remains in the asphalt of Hancock Park dating back to 7000 B.C. are reported. The Los Angeles oil boom that began in the early 1900s eventually expanded from the early Los Angeles City Field westward to the Salt Lake Field at Third and Fairfax and then southward.

Gases have been known in the area, and construction for utilities, residences, and commercial and government buildings has taken precautions for oil seepage, odors, and combustible gas.

Various geotechnical investigations have reported the presence of oil, petroleum gases, and methane for 30 years. Based on the reports, the RTD conducted additional geotechnical studies and special gas monitoring studies to develop engineering measures to deal with gas problems in tunnels and stations. Figure II-9 shows the areas where boreholes indicated the presence of gas or oil. MRTC also reviewed the special problems of construction in oily and gassy ground.

Figure II - 9 Geotechnical Borings Containing Gas or Oil

a) Natural Seeps

The natural oil or asphalt seeps in Hancock Park were the basis for the naming of Rancho La Brea. Other seeps occurred north of Lafayette and MacArthur Parks. Seeps formed from vertical cracks extending down to the oil deposits, along the geological faults known to cross the Los Angeles Basin, or where oil-bearing formations are exposed at the surface. Pressures within the deeper geological formations have forced the oil, water, and gases upward along the most permeable pathways. In some areas, these pathways may be covered by soil and alluvium, and the oil and asphalt spread laterally through the porous alluvium without ever reaching the surface of the ground.

b) Oil/Gas Fields

Oil field development in the Los Angeles Basin began at the natural oil seeps near MacArthur Park, where asphalt was excavated for waterproofing and rendering for kerosene. With the increased demand for lubricating and fuel oils and, eventually, gasoline, oil exploration was accomplished first by hand-dug wells and then rapidly expanded with the introduction of drilling rigs. More than 1,000 wells were drilled north of the central city and Wilshire corridor segment of the Metro Rail route in three oil fields: Los Angeles City, Western Avenue, and Salt Lake. These wells have been largely abandoned, although additional oil-bearing horizons have been located by new drilling programs even in the 1960s and 1970s. Additional minor oil fields have been found south of the Metro Rail route; these include the Union Station, Los Angeles Downtown, and South Salt Lake oil fields. These minor fields have produced both oil and gas, but in much smaller quantities than that produced from the older, larger, more northern fields.

Maps and historical photographs clearly indicate that wells were drilled on the Metro Rail alignment on Wilshire and Fairfax. Several wells that may be encountered by Metro Rail tunnels are marked on a Division of Oil and Gas map (Figure II-10).

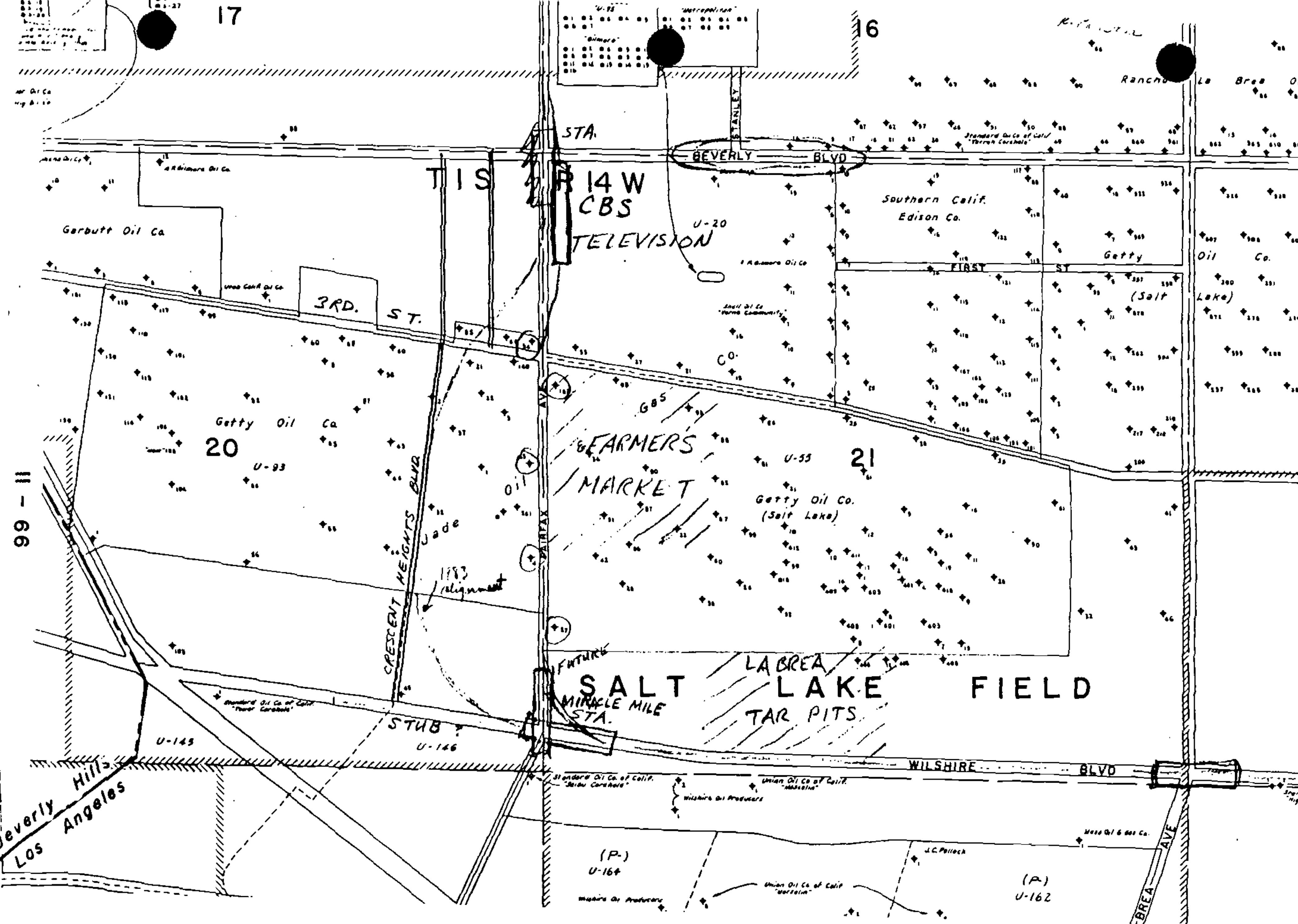


Figure II - 10 Existing Oil Wells Near Metro Rail Alignment Along Wilshire & Fairfax

The Union Station and Los Angeles Downtown oil fields contain oil-bearing horizons that may extend upward and northward beneath the Metro Rail alignment between 7th/Flower and Wilshire/Western.

c) Historical Fires and Gas Reports

The Los Angeles Fire Department and news agencies have reported burning gases from sidewalks and cracks in the ground. Underground utilities, especially storm drains, are entered only after proper ventilation because of expected problems and methane gas accumulation.

d) Geotechnical Investigations

The RTD has had several geotechnical investigation programs, and a gas monitoring program with more than 50 probe bores along the proposed routes and at alternative routes and station sites. Initial gas monitoring was conducted in most of the geotechnical bores, only where the odors of petroleum, "swamp gases," and sulfur were recorded. The presence of oil and gas odors was reported in the Wilshire/Fairfax corridor, at the Los Angeles River crossing for the East Portal, and at the East Junction under the Santa Ana Freeway.

A dewatering pumping test at Union Station had to be discontinued prematurely because of the interference of gas bubbles during a groundwater drawdown test. Sufficient gas was released to cause a minor explosion in the water well.

e) Geotechnical Investigations by Others

Many borings have been made along the Metro Rail route, but logs are often not available; some have been reviewed and indicated "natural gases" or the odor of the heavier petroleum gases. Generally, such observations occurred in those areas where later RTD borings indicated odors of petroleum gases or where gas probes indicated methane gases.

Geotechnical borings for CBS Television City may have encountered gases, but no information has been obtained. The main structure has a gas collection and venting system.

The basement of the Farmers Insurance building at Wilshire and Hudson was designed on the basis of four borings that penetrated to 60-80 ft below surface. Boring logs indicated petroleum gas odors, which were later confirmed by gas analyses and by gas production that attained commercial amounts of gas approximately 100% in volume and 3-8 psig pressure.

Geotechnical borings at the Wilshire Courtyard site (Wilshire/Curson) confirmed the anticipated presence of oil and gas in the alluvium. Excavation and designs for developments require gas monitoring and controls.

The Los Angeles County Flood Control District has constructed and will be constructing numerous large and deep storm drains and the Pan-Pacific Park and flood retention basin in the Fairfax and Wilshire areas. During the geotechnical boring programs to support design efforts for these facilities, down-hole measurements of combustible gases have been taken at several depths. In the area north of Santa Monica Boulevard, boring logs showed no detectable methane (probably levels of less than 2.0% LEL, 0.1% volume, and 1,000 ppm). Other records have not yet been reviewed.

f) Surface Gas Surveys

Immediately after the Ross Dress-For-Less explosion at Third/Ogden, emergency surface monitoring was initated. Detectable methane gas levels at the ground surface were found in protected localities more than 100 meters from the intersection. In nearby residential areas, levels of methane were undetectable at less than 10 ppm (0.001% volume), while at the school near Third/Ogden, planter boxes and storm drains contain levels of more than 100-1,000 ppm. A survey of protected areas in and around the tar pits of Hancock Park showed detectable levels, but below 1,000 ppm. The free air adjacent to the active tar pit pond had no detectable level because of the natural ventilation.

6. Other Developments

As indicated above, the presence of oily and gassy ground has been well documented in the Los Angeles downtown and Wilshire areas. Normal urban development has adapted various passive and active techniques regarding oil and gas handling. Utilities have built and operated underground facilities throughout the area without serious mishap. The March 1985 explosion has focused and intensified public concerns for the safety of facilities and activities in areas with high potential for gas and oil.

Complex interrelationships exist between the subsurface migration of gases and groundwater, the shallow geology, and the larger and deep buildings. The existing developments within the Wilshire/Fairfax area may have influenced the movement of gases in the area. Other buildings have not experienced problems of the magnitude of the Ross store at Third/Ogden. However, it should be remembered that they are also located in the high or potential risk zone for gas hazard. The following is a representative selection of the larger buildings in the area:

- Mutual Benefit Building (Wilshire/Stanley)
- LA County Art Museum (Wilshire/Ogden)
- LA County Page Museum (Wilshire/Stanley)
- May Company (Wilshire/Fairfax)
- Park La Brea (Residential Towers)
- CBS Television City (Fairfax/Beverly)
- Museum Square (North Wilshire/Curson)
- Farmers Insurance (Wilshire/La Brea)
- Prudential Building (Wilshire/Curson)

Many new buildings with deep foundation systems are anticipated along the Wilshire Corridor, and it is anticipated that they will be specially designed to control gas. The following three facilities are examples of future development in the Wilshire/Fairfax corridor:

- Wilshire Courtyard (South Wilshire/Curson)
- CBS Complex (Fairfax/Beverly)
- Gilmore Complex (North Third/Ogden)

a) Excavation

Excavation of Pan-Pacific Park will occur in the upper 30 ft of the alluvium east of the Third/Ogden explosion site and the Metro Rail route. High gas levels in the upper 30 ft at the Third/Ogden site indicate that displacement of the upper 30 ft of alluvium could influence the movement of gases around the structure.

b) Surface Treatments

The Wilshire/Fairfax corridor contains a large portion of asphalt cover for streets, parking lots, and playgrounds. These impervious areas reduce the natural venting of gases from the soil/alluvium. Similar coverings have been used in landfills to control the venting of gas and to improve concentrations for collection systems.

c) Subsurface Environment

Subsurface environments along the Metro Rail area have been strongly affected by natural and artificial underground developments. These influences include:

- o Groundwater infiltration and movement.
- o Deep reservoir oil/gas extraction.
- o Past earthquake shaking.

Groundwater levels in the Wilshire/Fairfax corridor and in the Union Station area lie within 20-30 ft of the surface. Gas released from the underlying geological formations locally may be under more than 20 psi pressure. During well drawdown tests at Union Station, the water column and confining pressures were reduced, which caused an immediate gas release into the water and well casings and thus to the atmosphere.

To reach the ground surface or alluvium, the migration of oil and gases respond to two conditions: sufficient pressure differentials between the reservoir formations and the surface, which supplies motive force, and suitable conduits of permeable formations (sands) or of fractured rock. The extraction of large volumes of gas and oil from the oil fields in the Los Angeles area should have greatly reduced the pressures in the deep geological formations and should reduce the differentials between the fields and the surface, as well as the resulting upward motive forces.

Seismic activity was not directly related to the Third/Ogden gas release, but the San Fernando earthquake and aftershocks are thought to have increased oil seepage in the Wilshire/Fairfax area. This increased seepage required construction of new oil sumps for storm drains and more frequent collection of oil from existing oil sumps.

III. CONSTRUCTION TECHNIQUES AND REQUIREMENTS

A. Previous Gassy Tunneling Experience in Los Angeles

The following section, with only minor changes, is taken from Section 6.0 of the "Metro Rail Project Geotechnical Investigation Report" prepared by Converse Ward Davis Dixon, November 1981.

Los Angeles is one of the world's largest cities in area, with a metropolitan population of over 7 million people. More than 60 tunnels, with total length greater than 50 miles, have been bored within the city limits. This history of local tunneling experience has been reviewed, with particular attention to case histories that involved geologic formations or settings similar to those anticipated along the Metro Rail alignment. Four gassy tunnels were selected for detailed study:

- Metropolitan Water District of Southern California (MWD) San Fernando Tunnel
- MWD Newhall Tunnel
- Los Angeles County Flood Control District (LACFCD) Sacatella Tunnel
- MWD Tonner Tunnel

The use of case histories can provide general information on the response of the materials to excavation, methods of excavation and support, construction problems, rates of advance, and costs. However, the overall success or failure of each tunnel project was dependent on the site-specific geology, methods of excavation and support, and organization of the contractor.

Geologic conditions, overall excavation progress, and construction methods have been summarized below for each case history. Similar geologic and excavation conditions have been noted and then compared to conditions expected to be encountered along the proposed Metro Rail alignment. These case histories indicate that rapid and economical progress can be made by soft ground shields or tunnel boring machines (TBM's) on the Metro Rail alignment. For example, excavation experience in Old Alluvium at the San Fernando Tunnel resulted in record advances using a shield with a digging spade. A total of 3,500 ft of tunnel was excavated in 1 month, and 277 ft during 1 three-shift day. When groundwater was encountered, advance rates were reduced to about 60 ft/three-shift day.

Specific tunnel excavation problems experienced on these previous projects are discussed in detail. In most instances, a majority of these problems (gas/oil, groundwater, caving, slow progress) were anticipated or could have been anticipated by the tunneling contractor prior to construction.

1. MWD San Fernando Tunnel

a) Facts and Figures

Item	Description
Tunnel length	29,100 ft (5.5 miles)
Tunnel diameter	22 ft OD excavated; 18 ft ID concrete lined
Initial support	Precast concrete segmented ring,4 segments/ring; segments 8 in. thick and 4 ft wide
Excavation method	Digger-type Robbins excavator mounted in a shield (the last 1,000 ft were conventional drill and blast)
Geology	Soft sandstone and silt-stone (Pico Formation) & Old Alluvium
Eventual use	MWD water supply tunnel
Contractor	Lockheed Shipbuilding & Construction Company

Bid price	$19,346,800 on February 20, 1969
Estimated bid completion time	1,360 working days
Tunneling period	January 1970 to November 1975; gas explosion stopped work for 27 months

b) Major Progress Prior to Groundwater Problem

During the latter period of the first 17,000 ft of tunneling, record advances were made using a Robbins-built shield, swinging and sliding boom with a rotatable digging head:

Advance (ft)	Time
104 ft	one 8-hour shift
277 ft	one 3-shift day
1,077 ft	one 5-day week
3,500 ft	one month

A special tunnel-liner erector installed 4-ft-long concrete segments at a rate of 12/hour over an 80-hour week to support the shield's 144-hour weekly operation.

Excavated material consisted of dry and water-bearing Old Alluvium sand, with minor gravel and cobbles, lightly cemented to the extent that slight ripping was required.

c) Groundwater in Old Alluvium

Just west of the North Olive View fault, substantial amounts of water (1,400 gpm peak inflow) were forecast and encountered in the Old Alluvium. In this area, tunnel cover was about 140 ft. Prior to encountering this water, rate of advance was 150-200 ft/3-shift day; in the water zone, the advance rate was still a respectable 60 ft/8-hour shift; the other two shifts drilled horizontal dewatering holes ahead of the shield.

- o In late 1970, the excavation encountered perched ground water that sprayed the miners with water under slight pressure.
- o Water pressure was relieved by 3-in. borings drilled horzontally ahead of the excavator 150 to 250 ft.
- o A 2-in. perforated plastic pipe was inserted to drain ahead of the heading. This reduced the digging to a single shift per day and slowed progress considerably.

d) Solution to Groundwater Problem

There are several perched water tables in the tunnel area, and test holes by the owner had pinpointed them before Lockheed Shipbuilding & Construction Co. started work. The solution was horizontal dewatering, because an impervious stratum just beneath the tunnel grade would have made dewatering by wells ineffective. Drilling ahead of the shield brought the water around it and into the tunnel where it could be pumped out.

- Horizontal holes were drilled from 150 to 250 ft ahead of the shield, i.e., starting about 30 ft back of the face, running as close to the tunnel edge as possible. The drill stem cut a 4-in.-diameter hole, and 10-ft-long, 1.5-in.-diameter hollow slotted plastic pipe sections were driven inside the drill stem.
- Water drained into the pipe slots and into the tunnel. There, a pair of pumps discharged the water into a surface flood control channel and through holes drilled down from a street above.

e) Effects of San Fernando Earthquake

On February 9, 1971, an M 6.4 earthquake occurred, with an epicenter only a few miles from the San Fernando Tunnel.

- The tunnel did not suffer any major damage; however, the shield was squeezed laterally and tightly bound in place. It took 2 weeks to free the shield by jetting along the skin at 3 o'clock and 9 o'clock.
- Tunnel work continued, with all workmen on hand, after a 3-day shutdown to assess damage.
- When level coordinates were shot from undisturbed benchmarks, it showed that the east portal elevation was 7.2 ft higher than its original position. The gate structure shaft, about midway through the tunnel, was 2.5 ft higher. The west portal, where the bore ties into Magazine Canyon shaft and Newhall Tunnel, was up 1.25 ft.
- There were no visible changes in the tunnel, largely due to the articulated precast tunnel supports. The segments are independent of each other, and there was opportunity for movement.

- Nearly 3.5 miles of tunnel were finished when the quake struck and the 7-ft uplift can be absorbed in moving individual segments such a slight amount that it would not be detected by the naked eye.

f) Caving Problems

In the Old Alluvium west of the North Olive View fault, where the groundwater was encountered, the contractor was plagued with problems. Approximately nine times there were runs at the face of several thousand gallons of water, sand, and gravel. A number of times a cave would develop up to 40 ft above the shield. When the shield had advanced beyond these runs, the contractor would drill a hole from the surface and drop sand into the void. Grout was then pumped into the sand. On one occasion, a 10-ft-diameter cave worked its way to the surface of Foothill Boulevard. The contractor poured sand into the void and added a surcharge of sand about 8 ft above the street. The next day, the sand had settled to around 12 ft below the street.

The shield was equipped with six breast doors that were used to support the upper half of the face. Generally, the contractor advanced the shield through these troublesome zones with the breast doors closed and the apron full of muck. This then imposed a greater thrust on the precast segments during shoves. This was when the contractor started using 10-in.-thick segments (instead of original 8-in.-thick segments) to develop the thrust necessary to shove the shield.

g) Fatal Gas Explosion

At 12:30 a.m. on the morning of June 24, 1971, a fatal gas explosion occurred in the tunnel. Of the heading crew, 17 workers died and one survived. The explosion halted work for 2-1/2 years due to settlement discussions and new contractual agreements. Only 2,500 ft remained to "hole-through" the 5.5-mile tunnel. The explosion occurred near the Santa Susana fault. Several events occurred that provided evidence of a possible gas hazard. The MWD geologic report, given with the specifications to all bidders, warned of the possibility of encountering oil and/or gas in the western part of the tunnel route. This warning was based on:

- Producing oil fields in the region, one within 1.7 miles
- Oil and tar seeps in the area
- The presence of Pico Formation sandstone, a known producer of oil in the western part of the tunnel route
- The presence of oil and gas in two nearby tunnels - DWP's Newhall Tunnel in 1912 and the MWD's Balboa Tunnel in 1967
- The location of the Santa Susana fault, which acts as an oil trap for the nearby Cascade oil field
- Several months prior to the explosion, the contractor posted a notice that stated "expect explosive gas ahead"
- One day before the explosion, a core with "kerosene or diesel smell" was extracted from the face
- One day before the incident, a minor gas explosion occurred that sent four miners to the hospital

Work resumed 27 months after the disaster, and was completed in November 1975. Most of the interval was spent working out an agreement between the owner and the contractor on procedures and costs, but without the admission of liability by either side.

To complete the tunnel, a board of tunnel consultants (J. Barry Cooke, Lyman D. Wilbur, and J. Donavan Jacobs) was convened. Their recommendations, all of which were complied with, included:

- o Increasing the ventilation system from the rated 35,000 cfm to 70,000 cfm (this can move air down the tunnel at the rate of 200 fpm.)
- o Building a remote hydraulic system to power the repaired boring machine
- o Installing a multiple-head constant monitoring system for gas, plus two full-time sniffer men
- o At all times during tunnel excavation drilling at a minumum of 20 ft into the face. (Contractor elected to drill 80-ft holes and use up 60 ft before redrilling.) Four holes were drilled into the face while in the Santa Susana fault zone.

- Limiting daily advances to 20 ft. (After this restriction and the TBM were removed, maximum progress was no more than 25 ft daily.)
- Drilling a ventilation shaft 150 ft deep, and incorporating a rescue chamber and emergency ladder 600 ft back of the heading.

After the explosion, and upon resumption of tunneling, with increased ventilation gas monitors did not detect concentrations greater that 7% LEL, and gas was not encountered when the heading was beyond the Santa Susana fault zone and into the siltstones, sandstones, and conglomerates of the Pico Formation.

In the opinion of B. P. Boisen, of A. A. Mathews, Inc., successful tunneling in gassy conditions is possible and can be attributed to:

Adequate ventilation	90%
Constant testing and monitoring	9%
Use of permissible equipment	1%

The 1% of success due to using permissible equipment is the major cost factor.

2. MWD Newhall Tunnel

a) Facts and Figures

Item	Description
Tunnel length	3.5 miles (Magazine Canyon to City of Newhall
Tunnel diameter	26 ft OD excavated; 20.5 ft ID
Initial support	Steel ring beams and wood lagging; also precast concrete lining 3 segments/ring, 12 in. thick and 4 ft wide
Excavation method	By Kiewit: a Calweld oscillating cutter head TBM (8,000 ft). By Dixon: a Calweld rotary cutter head TBM (10,000 ft)
Geology	Hard to soft sandstone (Pico Formation) & gravelly, cobbly sandstone (Saugus Formation) with oil seeps
Eventual use	MWD water supply tunnel
Contractor	L.E. Dixon Co., Arundel Corp., MacDonald & Kruse, Inc. & Peter Kiewit Sons' Co. (joint venture)

Bid price	$35,000,000 awarded June 1966
Tunneling period	1966-1970

b) Excavation Progress

After rotary boring 10,000 ft, the contractor chose to abandon the "mole," since the weakly consolidated sedimentary rock would frequently slough ahead and above the cutting wheel, stalling the machine and necessitating extensive hand-cribbing of the overbreak. Despite this setback, the average driving rate was probably better than what it would have been with conventional tunneling. Through ideal ground for the "mole" (in dry, moderately consolidated siltstone and sandstone), it bored over 100 ft in a single 3-shift day.

Later (September 1969), the contractor started a second heading using a Calweld oscillating mining machine. This machine is mounted in a 26-ft OD full-circle shield that thrusts against a tunnel support system almost identical to the Tabor (MEMCO) tunnel lining. Excellent progress was made (about 100 ft per working day) through soft but well-standing sedimentary rock.

Some sandstone at the face was so hard that it was broken down only by the shearing action of the drag cutters on the (oscillating) cutter head. Lenses of cobbles were noted in the face and these were sheared off or dislodged with some difficulty. The contractor did not experience any severe groundwater conditions; the ground generally was a fine-grained dense sandstone with a very low percolation rate.

Pushing the Calweld rotary shield through the earth required a very heavy thrust (nearly 4,000 tons) against a firm base. The contractor felt that the walls of the bore were too soft to serve as such a base; therefore, it was decided to axially thrust against the tunnel support system. This necessitated moving the wooden lagging from outside to between the circular steel ribs, where the "tight" lagging would provide support for the forward thrust of the shield.

3. LACFCD Sacatella Tunnel

a) Facts and Figures

Item	Description
Tunnel length	0.6 miles
Tunnel diameter	18 ft OD excavated; 14.5 ft ID
Initial support	Precast concrete liner (3 segments/ring)
Excavation method	Digger Gradall and shield
Advance rate	Maximum 32 ft/8-hr shift; average 15 ft
Geology	Claystone, siltstone and occasional interbeds of very hard calcareous cemented sandstone
Eventual use	Storm drain, LACFCD
Contractor	Glanville Construction Co.
Bid price	±$4,000,000
Extras awarded	±$500,000
Tunneling period	1975-77

b) Relationship to Metro Rail Alignment

Geologic conditions and tunneling methods in this tunnel are very important to the Metro Rail alignment because:

- Tunnel was excavated in a gassy reach under Hoover Street, north of Wilshire Boulevard, in claystone, siltstone, and sandstone of the Puente Formation.
- Total cover above tunnel crown ranges from 22 to 25 ft.
- Total bedrock cover above tunnel crown ranges from 2 to 25 ft.
- Old Alluvium (Qalo) cover above the tunnel crown ranges from 5 to 32 ft.

c) Peak Unconfined Compressive Strength

LACFCD test results of peak unconfined compressive strength, from six core samples obtained in the Puente Formation, are tabulated as follows:

LACFCD Boring	Unconfined Compressive Strength, Qu (psi)
1	401
1	603
2	441
2	384
2	377
7	172
Average	396

Core samples from Borings 1 and 2 were taken essentially normal to the bedding, while the bedding at Boring 7 was inclined at about 45° from the long axis of the core. This probably accounts for the considerably lower compressive strength test value for the sample from Boring 7. All core segments tested were selected for cross-sectional uniformity and freedom from cracking or damage and, as such, are considerably more competent than the average grade of rock encountered during drilling. Therefore, the values obtained for the compressive strength are probably greater than the average values that would be found during tunnel excavation (LACFCD, 1973).

d) Digger Excavator and Shield

The tunnel excavation was performed with a small (Model No. 2403) Gradall excavator. The rotating, telescoping boom was connected to a flat plate that had a single ripper tooth on one edge and several digger teeth on the other edge.

e) Geology

The Puente Formation is thin bedded, soft claystone and siltstone. The formation contained occasional interbeds of very hard calcareous cemented sandstone from 2 to 12 in. in thickness with unconfined compressive strength of 5,000 to 15,000 psi. These interbeds caused the "changed conditions," according to Donald Glanville, because they were not mentioned in the preconstruction reports. Some very hard interbeds were nearly horizontal and followed the face for several hundred feet; some were at a 45° angle to the tunnel alignment and followed the face for several tens of feet. This resulted in the following actions:

- Replaced single-tooth ripper with hydraulic jackhammer to break up hard layer (removed jackhammer in weak ground)
- Bent leading edge of shield, forcing contractor to stop and repair often; i.e., spent 8-hour shift digging, and the balance of the day repairing shield

- o Difficult to maintain line and grade in hard rock layers (These hard layers, although 12 in. or less in thickness, made drilling of 5-ft-diameter man-way shafts very difficult also.)
- o Advance rate cut drastically; i.e., often reduced advance rate to 1 to 5 ft daily.

f) Tunnel Gas Classification

The tunnel was classified as gassy because it traversed the Los Angeles City Oil Field. No fire or explosion occurred during the project.

- o The greatest apparent risk is where folding and a suspected fault may form significant traps (Wright, 1975, p. 8). Explosive-proof equipment was installed (although arc welding was permitted in the tunnel).
- o Face was continously monitored by a gas "sniffer" that automatically set off an alarm if high LEL readings were recorded. (Note: Alarm was never activated because ventilation was so effective.)

- Installed 4-ft-diameter ventilation duct and pumped air at 400 fpm through the vent pipe.
- Oil, seeping down the sides of the supports, was skimmed off the discharge water at the portal and hauled away by tank truck.

g) Abandoned Oil Wells

The tunnel encountered several uncharted, uncased, abandoned oil wells. Although oil was not encountered in these holes, several hundred gallons of water gushed into the tunnel for a few seconds, alarming the miners each time.

h) Groundwater

The tunnel was below a "permanent" water table. The water table was in the Puente Formation and the overlying Old Alluvium. The contractor drilled 12 dewatering wells at selected locations along the alignment prior to excavating the tunnel. This dewatering of twelve 24-in.-diameter wells, recommended by

Vic Wright, Tunnel Consultant, appears to have successfully kept tunneling conditions in the "dry." According to Wright, 1975, "... ground water problems in the (Puente) formations are expected to be related more to softening and weakening, especially in the sticky shale zones, rather than to water volume."

The wells pumped about 20 gpm each from about 25 ft of overlying Old Alluvium and 20 ft of Puente Formation. The water was pumped to the surface, and the contractor believes this kept tunnel inflow to a minimum, i.e., "dripping" condition rather than 10 to 100 gpm local inflows.

i) Stand-up Time, Slabbing, and Overbreak

Stand-up time was more than 2 to 3 hours prior to placing liner. Slabbing of flat-lying or steeply dipping beds did not occur. No overbreak was recorded, but minor air slaking developed due to the high air ventilation. Mr. Glanville called this "ideal" tunneling formation, except for the hard cemented layers.

j) Ground Settlement Above Tunnel

The tunnel was excavated about 40 ft below the street surface in a residential area with one hotel. No settlement was noted, or reported, by the residents. No known complaints of noise, except at portals, were registered by the residents living above the tunnel during construction.

k) Local Caving Problem

An abandoned 2-ft-diameter auger hole was penetrated. The hole caved upward to within 6 ft of the ground surface. The contractor drilled a hole from the surface into the cavern and filled the cavern with pea gravel prior to advancing the tunnel. The cave did not "daylight" to the surface.

l) Portal Excavation Problems

Both portal excavations encountered local, very hard sandstone interbeds that could not be excavated by small equipment. Therefore, heavy equipment (D-9 Caterpillar) was required.

m) Ground Loading and Support Requirements

The following data was reported by Mr. Wright.

Continuous light tunnel support will be necessary whether the tunnels are driven by boring machine or by drilling and blasting. The need for immediate support may often be marginal if the tunnel is machine-bored. However, the shales will need support eventually because of stress relief fracturing and slaking. Slaking was evident in a small percentage of the cores. The generally short core lengths are probably due to the stress relief. Ground loading assumptions in the specifications seem unreasonably high at 3370 psf. Maximum estimated loads for this study are 2400 psf, where the ground is wet and highly unstable. Lateral loading up to possibly 800 psf may buildup in the wet unstable reaches.

Six-inch, 15.5-lb steel horseshoe sets spaced 3 to 5 ft apart will hold the estimated loads. A few invert struts may be necessary where the formation is extensively softened by ground water, especially through low bedrock cover reaches.

4. MWD Tonner Tunnel

a) Facts and Figures

Item	Description
Tunnel length	3.4 miles (Tonner No. 1 - 4,600 ft, Tonner No. 2 - 18,400 ft, separated by several miles of pipeline).
Tunnel diameter	11 ft OD; 8 ft ID steel pipe
Initial support	Steel ribs & wood lagging
Excavation method	Calweld rotary head TBM
Geology	Sandstone & shale (Puente Formation)
Eventual use	MWD water supply tunnel
Contractor	J.F. Shea Co., Inc.
Bid price	$15,034,331; extra work, $314,000
Estimated completion bid time	830 working days; actual - 1,522

b) Application to Metro Rail Alignment

Geologic conditions and tunneling methods in Tonner Tunnel are very important to the Metro Rail alignment for the following reasons:

- o Both tunnels, within 300 ft of the working face, were classified as "gassy" within the meaning of Appendix B of U.S. Bureau of Mines Bulletin 644, and were the first tunnels driven under California's strict new safety regulations since the fatal gas explosion in the San Fernando Tunnel, June 1971.
- o Both tunnels penetrated the Puente Formation, a soft-ground geologic tunneling condition that may be similar to that anticipated in several areas of the Metro Rail alignment.
- o Maximum cover on Tonner Tunnel No. 1 was 400 ft.
- o Maximum cover on Tonner Tunnel No. 2 was 600 ft.

c) Unconfined Compressive Strength

Unconfined compressive strength of the bulk of the Puente Formation was 100 to 200 psi. However, one reach, about 1,500 ft long in Tonner Tunnel No. 1, encountered mixed face conditions (hard and weak zones) with the hard calcite cemented sandstone and conglomerate exhibiting unconfined compressive strengths of 12,000 to 15,000 psi. This hardness resulted in redesigning and rebuilding the Calweld TBM, as well as using conventional drill and blast for the last 1,500 ft of tunnel. To permit conventional tunnel driving, the tunnel had to be reclassified as "potentially gassy" by the California Division of Industrial Safety (DIS). The DIS approved reclassification, with stringent conditions.

In the high, unconfined compressive strength reach of the tunnel, the contractor drilled horizontal exploratory diamond bit core holes 70 to 75 ft in advance of the tunnel face, anticipating soft ground to accomodate the Calweld TBM.

d) Oil and Gas

Neither oil nor gas was a problem in either of the tunnels. Petroliferous sands were a common occurrence in the first 1,300 ft excavated in Tunnel No. 1, but significant accumulations of gas were not encountered. In Tunnel No. 2, the contractor encountered slightly petroliferous rocks on a regular basis, along with numerous minor tar seeps. Only one area of tar seep was large enough to cause concern. This was a 105-ft stretch near Station 824+00. A high concentration of gas that was encountered at Station 858+28 caused the sensors to automatically shut down the tunneling machine. This was the only significant gas accumulation encountered.

In some areas of Tunnel No. 2, particularly in the section where oil seepage had occurred during excavation operations, high gas concentrations were detected in the stagnant air space behind the steel pipe and the excavated tunnel wall (during pipe installation).

e) Disposal of Water and Oil

The CRWQCB required less than 2,000 microhms electrical resistivity in all discharge water and a maximum of 20 ppm content of grease and oil in the discharge water. Daily sampling was performed by the contractor to ensure that this requirement was being met. Water pumped from Tunnel No. 1 was discharged into a natural water course located at the southerly end of the work area and flowed into Arnold Reservoir approximately 0.5 mile away. The contractor had provisions for construction of oil-separating basins; however, removal of oil was originally successfully handled by holding the discharge water in a 12,000-gallon tank and then discharging water from the bottom of the tank. Oil was then removed from the top of the water as required and disposed of in accordance with specification requirements.

Essentially, the same setup was utilized at the south portal of Tunnel No. 2, where a series of two tanks was installed for removing suspended solids, oil, and grease. Provisions had to be made to discharge water into the Yorba Linda sewer system. The District installed a 16-in.-diameter pipeline to a retention basin, located immediately below MWD's Robert B. Diemer Filtration Plant, which the contractor was allowed to use for temporary storage of discharge water. The retention basin had been lined previously with an impervious membrane to prevent seepage. A conductive recorder, with sensors that automatically operated valves, was installed in the 16-inch-diameter pipeline. When conductivity was less than 2,000 microhms, water was automatically discharged into Telegraph Canyon. Water directed into the retention basin was then pumped, through a pipeline, into the Yorba Linda sewer system.

5. Summary Information On Selected Tunnels

Table III-1 presents information pertaining to local tunnels where excavation was performed by TBMs or where gas and oil were encountered.

Table III-1 Los Angeles Area Tunnels Excavated by TBM or Where Gas or Oil Was Encountered

Owner Tunnel Name	Location Length (mi)	Bore Diameter (ft)	Material Geologic Unit	Year Begun	Method Used & Comments
L.A. Co. Flood Control Dist. Storm Drain #1102 Hoover Street Sacatelle Tunnel	Downtown Los Angeles 0.6	17	Sandstone, Shale Puente Formation	1975	Gradall excavator in a shield. Prior dewatering required by specs. GAS & SEEPING OIL encountered in L.A. City oil field but controlled by strong ventilation.
Metropolitan Water Dist. Tonner 1 & 2	Near Yorba Linda Orange County 3.4	11	Sandstone, Shale Puente Formation	1972	Mainly rotary-head Calweld mole. Delay in Tonner 1 due to hard sandstone but rate in longer Tonner 2 averaged 60 ft/day; several days of over 100 ft/day. METHANE monitored.
Metropolitan Water Dist. San Fernando	Sylmar area 5.5	22	Sandstone, Siltstone, Boulders Saugus Formation Alluvium	1969	Digger-type Robbins mole. Dry old alluvium stood well; wet old alluvium caved, requiring dewatering from within tunnel. Progress up to 277 ft/day (world record), including precast segment supports. Mole handled boulders in old alluvium & Saugus. METHANE & HEPTANE encountered.
Pacific Telephone Co. Olive Street	Downtown Los Angeles 0.1	7	Siltstone Puente Formation	1969	Rotary-head Calweld mole. Siltstone damp; no problems encountered.
Metropolitan Water Dist. Balboa Outlet	Sylmar 0.7	16	Sandstone, Siltstone Saugus & Sunshine Ranch Formation	1968	Rotary-head Scott mole. Conditions mostly dry to dripping; rates up to 111 ft/day, but averaged 30 ft/day due in part to short tunnel length & adjustments to new mole.
Metropolitan Water Dist. Castaic 1 & 2	Castaic-Saugus, 3.5	26	Siltstone, Sandstone, Boulders Castaic & Saugus Formation	1967	Digger-type MEMCO mole handled large boulders in Saugus Formation with no significant problems. Average rate in Castaic 2 was 112 ft/day; best rate 202 ft/day (4100 cy excavated muck in 24 hrs). Precast concrete segment supports used.
Metropolitan Water Dist. Newhall	Newhall-Sylmar 3.3	26	Sandstone, Siltstone, Mudstone Saugus, Pico & Towsley Formation	1966	Rotary-head Calweld mole from south portal, oscillating "windshield-wiper" mole from north portal. Long segment in wet sandstone with boulders of Saugus was dewatered with surface wells; GAS & SEEPING OIL handled with strong ventilation.
Los Angeles City Aqueduct	Newhall-Sylmar 2.0	12	Sandstone, Siltstone, Mudstone Puente, Pico & Towsley Formation	1910	Spade, drill & blast. OIL encountered.
Southern Pacific Railroad No. 25	Newhall-Sylmar 1.3	22	Sandstone, Silstone, Mudstone Saugus, Pico & Towsley Formation	1875	Spade. OIL encountered.

*Chase, A.P., and others, 1978, p. IV-5 and IV-6.

B. Cal-OSHA Tunnel Safety Orders

1. Tunnel Classification

Whenever tunnel construction of any type is proposed within the State of California, the Tom Carrell Memorial Tunnel and Mine Safety Act of 1972 requires the Mine and Tunnel Unit of the California Division of Occupational Safety and Health (DOSH) to classify these tunnels as to their potential of encountering explosive or flammable gases (Policy and Procedure No. C-29 of DOSH). This classification assignment is made prior to contracts being awarded so that all bidding parties are aware of this classification. The following classification can be assigned to tunnels:

- Non Gassy
- Potentially Gassy
- Gassy
- Extra Hazardous

The Metro Rail tunnel from the East Portal near Union Station to the Wilshire/Alvardo station has been classified as gassy. This was based on the geotechnical conditions in the Project area, as determined by Cal-OSHA.

2. Contractor/Construction Manager Responsibilities

A Pre-Job Safety Conference is required with an authorized representative of the Cal-OSHA relative to all underground operations. Representatives of the owner (SCRTD), the contractor, the construction manager, and all appropriate personnel would be included in the pre-job safety conference. Safety and security procedures to be complied with are reviewed in detail. These include the RTD Construction Safety and Security Manual; the State, County, and City safety requirements; and the Cal-OSHA Tunnel Safety Orders relating to gassy tunnels. Specific measures consist of the following:

a) The contractor shall have a safety representative qualified to recognize and monitor hazardous conditions and certified by Cal-OSHA. He shall have the authority to correct unsafe conditions and unsafe practices and shall be responsible for directing the required safety programs.

b) Supervisory personnel shall conduct "tool box" or "tailgate" safety meetings with their crews at least weekly and the Contractor supervisor meeting at least monthly. A record of the meetings shall be logged and maintained for examination by concerned organizations.

c) When an employee is first engaged, the person in charge shall determine the employee's experience at the work for which he has been hired. He shall instruct the employee in the hazards of the job, the safe performance of his duties, and what is expected of him on this project for safe operations.

d) Each employee, when first engaged, shall have his attention directed to the provision of the "Safe Practices and Operations Code" for the projects and shall be given a copy of it.

e) Each employee shall be issued a copy of the Contractor's Safety Procedures Manual that the Contractor has developed and has had approved by CM's Safety/Security Manager. The employee shall be informed that there will be no deviation from the basic rules and regulations stated therein.

f) Every precaution shall be taken to ensure the safety of the workmen in all cases, whether or not provided in any of the safety procedure manuals.

3. Emergency Procedures and Equipment Requirements

At all times in gassy tunnels, the Contractor is required to provide and maintain permissible self-contained oxygen breathing apparatus in numbers and types as Cal-OSHA specifies. Each person underground is required to have a portable permissible hand light or permissible cap lamp available for emergency use unless natural light or emergency lighting systems are adequate for escape. Specific equipment requirements and testing procedures are as follows:

a) Automatic and manual gas monitoring equipment is provided for the heading and return air of tunnels using mechanical excavators. Tests for flammable gas are conducted in the return air and not less than 12 in. from the roof, face, floor and walls in any open workings. Tests for flammable petroleum vapors are conducted in the return air and not less than 3 in. from the roof, face, floor and walls in any open workings. Tests for gas are made by persons certified by the Division of Industrial Safety prior to the start of each work shift and at least hourly during working hours. When 20% or more of LEL is encountered, the tester or monitor shall signal the heading and shut down electrical power in the tunnel, except for ventilation equipment.

b) Ventilation systems that exhaust flammable gas or vapors from the tunnel are provided with explosion-relief mechanisms and are constructed of fireproof materials. The main ventilation system is so arranged that the air flow can be reversed from the surface. Ventilation includes continuous exhausting of fumes and air. Fans for this purpose are located at the surface and can be reversible from a single switch at the portal or shaft.

Ventilation systems are arranged to exhaust smoke and fumes to the atmosphere. Minimum ventilation required is 200 cfm per man underground. For diesel equipment, it is 100 cfm per brake horsepower and 60 fpm velocity is required in tunnels that are less than 30 ft in diameter.

c) Sufficient air is supplied to maintain an atmosphere of (1) not less thant 19% oxygen, (2) not more than 0.5% carbon dioxide, (3) not more than 5 ppm nitrogen dioxide, and (4) no petroleum vapors or other toxic gases in concentration exceeding the threshold limit values established by American Conference of Government Industrial Hygienist.

d) Whenever any working place in a tunnel is being advanced within 200 ft of areas that may contain dangerous accumulations of gas, petroleum products, water, or mud, the test holes of sufficient depth have to be drilled in advance of such workings to ensure that at least 20 ft of tested ground remains beyond the face. Test holes that are 20 ft deep also have to be drilled at angles of 45° into the walls, roof and floors when necessary.

e) A refuge chamber or alternative escape route is to be maintained within 5,000 ft of the face of the tunnel. Refuge chambers are to be equipped with a compressed air supply, telephone, and means of isolating the chamber from the tunnel atmosphere. This chamber and equipment must be acceptable to the Division of Industrial Safety.

f) There must be enough physically fit and trained men outside the tunnel to provide one or more crews of five men within reach by telephone or other means and available for service at the tunnel within 30 minutes.

g) Training is to be given annually with practice at least 30 minutes per month in the use of the rescue equipment for rescue crews.

h) A qualified first aid attendant is to be available and responsible for first aid care at all times when work is in progress. He is to be under the direction of a responsible licensed physician. All supervisors and at least one man on each tunnel crew are required to have had first aid training within the last 2 years and to be competent to give proper emergency treatment.

i) Only permissible locomotives and other equipment are used in any tunnel classified as gassy or extra hazardous. "Permissible equipment" means equipment tested and approved by the U.S. Bureau of Mines or other authorities acceptable by Cal-OSHA, which is safe for use in gassy or extra hazardous tunnels.

4. Cal-OSHA Safety Inspections

Cal-OSHA may conduct inspections at any time, indicating hazardous conditions and acts with their recommendations for correcting or removing. Repeated infractions of unsafe acts or conditions or failure to correct could result in a citation from Cal-OSHA and, in some cases, could consist of severe penalties, both financial and physical. The Construction Managers's Safety/Security personnel are responsible for making constant and continuous inspections of the work area and working personnel, with reports of their findings submitted to the Construction Manager.

These safety inspections do not alleviate the Contractor of the responsibility for the safety of his personnel and the personnel of his subcontractors regardless of tier.

The Construction Manager's safety personnel act as an extended arm of Cal-OSHA to maintain a safe place to work and promote safe working habits among the workers. The rules and regulations as established by Cal-OSHA and other agencies are enforced by the Construction Manager's safety personnel at all times.

C. Methods

When Cal-OSHA classified the Metro Rail tunnels as "gassy," it automatically imposed various requirements for ventilation and equipment design. This section will discuss the Cal-OSHA regulations on ventilation and the philosophy behind the Cal-OSHA rules. It will also discuss the effect of Cal-OSHA rules on equipment design and compare some of the MSHA regulations to the Cal-OSHA rules. Some of these issues will be illustrated with a description of a Robbins tunnel boring machine delivered to the British National Coal Board in 1981.

1. Ventilation

The Cal-OSHA Tunnel Safety Orders for ventilation requirements in a gassy tunnel are similar to the requirements of the standard ventilation section. The regulations require 200 cfm of air for each man underground; if there were 15 people underground, that would mean 3,000 cfm. The lineal velocity of the air flow in the tunnel shall not be less than 60 fpm. In the Metro Rail 18-ft tunnel that means about 15,000 cfm. The third requirement governs the amount of diesel brake horsepower that will be in the tunnel at any one time. The requirement is 100 cfm per brake horsepower; for example, if there were two 100-hp diesel locomotives underground, the requirement would be 20,000 cfm. Certain other provisions of the Cal-OSHA Ventilation Section should be noted; mainly, men should not be permitted, except in extreme emergencies, to work in a place where the oxygen content of the air is less than 20% by volume. Note that the concentration of oxygen in uncontaminated air at sea level is 20.95%. The main ventilation system shall be arranged so that the air flow in the fan line or ventilation duct can be reversed in case of an emergency, such as a fire.

To put some of these numbers into perspective, a 48-in. fan line with fans capable of producing 7 in. water column pressure is capable of producing 70,000 cfm of ventilation air. By the same criterion, a 30-in. fan line should produce about 27,000 cfm.

In this Standard Ventilation Section, only one mention is made of gassy operations which is: "where flammable gas or air contaminants have been encountered, adequate ventilation shall be maintained to keep the gas or vapor concentrations within the safe limits as provided by Safety Order 8424 and the threshold limit values." Section 8424 of the Safety Orders deals specifically with dangerous or poisonous gases and is primarily slanted toward controlling the concentration of the gases in the atmosphere, which is a function of the volume or rate of inflow of incoming gases and of the volume of ventilation air being provided. With respect to methane or other flammable gas, if more than 10% of the LEL of the flammable gas or petroleum vapor is found in the tunnel, "any work therein shall be conducted with extreme care and steps shall be taken to improve the ventilation." In other words, the thrust of this section is to keep the concentration of explosive gas at less than 10% of the LEL. The LEL for methane is 5% by volume, so 10% of LEL is 0.5% of the total volume. For example, if the ventilation system were providing 20,000 cfm of ventilation air, the tolerable inflow of gas could be 100 cfm. If, however, the concentration of gas in the tunnel does exceed 10% of the LEL, and goes up to 20% of LEL or above, or if underground ignition of the gas occurs, then the underground work shall cease; all of the people underground shall be removed and reentry, except for rescue purposes, shall be prohibited until the Division has been notified and has authorized reentry. Section 8424 also stipulates the time table of testing for gas and states that "tests for gas shall be made by certified persons prior to the start of each workshift and at least every 4 hours in tunnels classified as potentially gassy; records shall be kept of such tests."

Section 8425 of the Tunnel Safety Orders regulates operations within gassy and extra-hazardous tunnels. Primarily, the section discusses the use of explosion-proof electrical equipment, prohibiting smoking, and controlling the environment for welding and cutting. It also specifies the use of automatic gas monitoring equipment, which will continously monitor the atmosphere and shut down the electrical power (except for ventilation) in the tunnel when 20% of LEL is achieved. In addition, a manual shutdown control shall be provided near the heading. The only reference to ventilation systems in Section 8425 stipulates that the ventilation system shall exhaust flammable gas or vapors from the tunnel, that it shall be provided with explosion-relief mechanisms, and that it shall be constructed of fireproof material.

Section 8427 of the Tunnel Safety Orders is a section that protects against unanticipated water or gas. Part b of this section states "whenever any working place in a tunnel is being advanced within 200 ft of areas that contain or may contain dangerous accumulations of water, gas, petroleum products or mud, test holes of sufficient depth shall be drilled in advance of such workings to ensure that at least 20 ft of tested ground remains beyond the face." In conversation with Cal-OSHA representatives, this has been interpreted as not being required because the operation is already classified as gassy, and that gas testing is going to be continously performed.

However, should a contractor become lax in following the spirit of the gassy operations sections of the Safety Orders, then Cal-OSHA may require the drilling of probe holes.

According to the philosophy of the Cal-OSHA rules, there are two distinct methods of preventing detonation of an explosive atmosphere:

- o The elimination of the explosive atmosphere, or the prevention of it from occuring, or the prevention of work if it should exist.
- o The elimination of sources of ignition in an explosive atmosphere while continuing to work in it.

The first approach is the most certain approach and it is strongly emphasized in the Cal-OSHA regulations. This first mode is generally favored in the MSHA operating rules, but not to the extent emphasized by Cal-OSHA. While the main thrust of the Cal-OSHA regulations is to eliminate the explosive atmosphere, the second mode (elimination of sources of ignition) is also enforced as a backup in the event of random failures of the first approach. Adherence to these Cal-OSHA rules should eliminate the possiblility of a disastrous explosion during the construction of the Metro Rail system.

2. Equipment

The Cal-OSHA rules have had effects on equipment design. First of all, with the exception of a blast-relief system in the ventilation system, no changes are required for ventilation. However, Cal-OSHA will almost certainly not approve of ventilation unless the designed system will provide 20,000 cfm or more. The major design impact will lie in the use of explosion-proof electrical and internal combustion equipment. Also for diesel engine or internal combustion eqiupment, compressed air starters will be required. Aside from that, all of the high-voltage transformers, low-voltage transformers, starters, motors, lights, etc., that are brought into the tunnel will all have to be explosion-proof in accordance with Title 24, Part III, Electrical Regulations of the California Administrative Code. Of less cost impact to equipment design, but potentially larger costs for delayed operations, is a requirement for continuous gas monitoring and automatic equipment shutdown in the event that the 20% LEL is achieved. Another consideration (not a requirement in the Cal-OSHA regulations) is that the equipment use as many bolted connections as is practical to minimize the use of cutting and welding equipment underground.

3. MSHA Regulations

All coal mines are classified as gassy by MSHA. However, as knowledge and experience gained from working in these mines increase, concerns about gas-related problems decrease.

a) Qualification/Approval by MSHA

(1) Mine supervisors from mine superintendent to section superintendent, i.e., Walker

(2) Gas tester

(3) Electrician

(4) Hoistman

- Steam driven
- Electrically driven

b) Regulations: MSHA regulates, with some common-sense rules, the following:

(1) Installation of main fans:

(a) Install 15 ft away from collar of shaft or tunnel that is main air supply/exhaust opening, to prevent damage in an explosion.

(b) Fans to be inspected daily. Continous recording pressure gauges are required.

(c) Minimum air velocity is 60 fpm.

(2) Methane examinations

Tests made at start of each shift, and every 20 minutes during mining operations. In addition, each coal excavator shall be equipped with continuous methane test equipment with automatic shutdown capability.

- Any time 20% LEL (1% vol) is detected, adjustment shall be made to bring more air to the work place. Electrical equipment shall be shut down until tests show that the methane concentration is <20% LEL.

- Any time 30% of LEL is detected, all equipment is shut down, and all persons shall be withdrawn from the endangered area of the mine until the methane concentration returns to <20% LEL.

- If a tunnel is being advanced into "virgin territory," if the return air is being continously monitored by a qualified person, and if the return air does not pass over trolley wires or trolley feeder wires, then the operations may continue until the methane concentration reaches 40% LEL.

(3) Electrical Equipment, Supplies, and Operation

MSHA regulations have very thorough regulations governing electrical equipment and the duties of all concerned with electrical hazard.

(4) Fire Safety

The MSHA regulations are much more comprehensive than anything to be found in the Cal-OSHA regulations.

4. The Robbins Tunnel Boring Machine

The Robbins TBM was manufactured in the Robbins (Seattle, Washington) plant and delivered to the British National Coal Board in 1981.

In connection with this study, the Robbins Company provided details on the machine that was sent to Britain in 1981. Part of the material furnished by Robbins is a copy of a paper presented by J.F. Tunnicliffe, who at the time was the Colliery General Manager of the mine operated by the National Coal Board, in which the Robbins machine was to drive an access tunnel. Of particular interest in this paper is a section on the mining requirements of the machine, quoted directly:

* MINING REQUIREMENTS OF THE MACHINE

The machine should be:

(a) Capable of driving a tunnel on a dipping gradient of up to 1 in 10 - the maximum gradient in the South Tunnel currently proposed is 1 in 12.9.

(b) Guaranteed to achieve a penetration rate when cutting of equivalent to 3 metres/hour in rock of strength 100 MN/m^2 (14, 500lb/in.^{2}) and 1.5 m/hr in rock of 140 MN/m^2 (20, 300lb/in.^{2}).

(c) Capable of dealing with soft conditions.

(d) Guaranteed to achieve in rock of 100 MN/m^2 (14, 500lb/in.^{2}) a regular advance rate of 120 metres/week in a drivage time of 90 hours.

(e) Built of components small enough to be transported through the mine with dimensions not exceeding a cross-section of 1.5 m x 1.5 m and a weight of 18 tons.

(f) Capable of cutting, loading, and supporting as a continous operation.

(g) Equipped with single-mounted cutter discs with provision for varying spacing.

(h) Provide as much support as possible to the tunnel wall from the face to the position where the permanent support is normally set.

(i) Able to have permanent tunnel support erected as close to the face as possible.

(j) Equipped with mechanical support handling and setting facilities.

(k) Provided with good access through the machine to allow the tunnel to be worked ahead of the machine if it should prove necessary.

(l) Provided with a means to contain dust produced by the cutting head and provided with dust suppression equipment to ensure compliance with the regulations.

(m) Provided with a means for monitoring ventilation and methane.

(n) Provided with anchorage from within the permanently supported tunnel either from the cut tunnel wall or from within the diameter of the permanent tunnel supports. These will be set at half-metre to one-metre spaces and will vary in section from 4 in. x 4 in. to 6 in. x 5 in.

(o) So equipped to give a peripheral speed of the cutting head not exceeding 92 metres/minute.

(p) Provided with facilities for drilling:

(i) in advance of the cutting head for forward probing and ground injection.

(ii) in the roof, floor and sides for rock bolts and ground injection.

(q) Provided with means of coping with water in the face of the heading.

(r) The machine shall be capable of being steered to within a tolerance of ±1 in. for grade and direction."

The most notable feature of these requirements is the almost unaddressed question of dealing with gas. The three aspects that are most notable in dealing with the gas are:

- Limitation of the peripheral speed of the wheel to 92 meters a minute. The technology in 1981 for the peripheral wheel speed provided in the vicinity of 450 fpm.
- Although not mentioned here, required to be fitted with explosion-proof equipment.

- o The Mining Act in Great Britain apparently does not allow the presence of men in between a piece of equipment and the places being excavated. Therefore, the wheel was fitted with provision for rear-mounting the disk cutters, which is very much different than the Robbins customary procedure.

In summary a number of concerns being expressed in Los Angeles stem from lack of experience in dealing with the gas problem. However, experience in coal mines shows that knowledge of the problem and adherence to the ventilation rules will permit safe construction of the Metro Rail Project.

D. Gas Sensing and Monitoring During Construction

General experience and practices of gas sensing and monitoring were presented in the discussion for 1983-1985 SCRTD gas monitoring program. Previous discussion of construction techniques reviewed the experience, requirements, and general character of equipment used in gassy conditions. The following discussion reviews the various types of gases required to be monitored during construction, monitoring equipment, monitoring procedures, elements of further monitoring for Metro Rail, and some of the controls (dynamic monitoring) that could be implemented in the event that large volumes of gases are encountered.

1. Gas Sensing

Gas sensing involves probes that provide access to underground gases, the meters capable of measuring the concentration of gases, and the gauges or manometers needed to measure the pressure on the gases beneath the surface. The meters are used to measure general combustible gases and suffocating gases; many other specialty meters measure specific combustible gases and toxic/hazardous gases. In general, the Cal-OSHA requirements will focus on the following gases:

- o Combustibles (including methane and other hydrocarbons)
- o Oxygen, carbon monoxide, and carbon dioxide
- o Hydrogen sulfide

For the purposes of this review, only the first is of major concern for the combustible character. The gas concentrations vary with the net flow into the site, and the flow depends on the pressures acting on the gases, soil-alluvium gas pressure, and site ventilation. Monitoring for the SCRTD, for the Ross explosion site, and for various energy production/landfill systems, generally focused on both the gas content and the pressure in monitoring probes. High pressures experienced at the explosion site further emphasized the importance of pressure to any gas problems.

2. Equipment

a) Probes

Probes for underground gases were discussed in the presentation for the SCRTD monitoring program. Generally, probes are tubes that directly transmit gases from various levels in the ground (e.g., -80 ft, -40 ft, and -10 ft) to the surface where the gas concentrations and pressures can be measured. More than 60 probes exist in the SCRTD monitoring system.

b) Gas Sensors

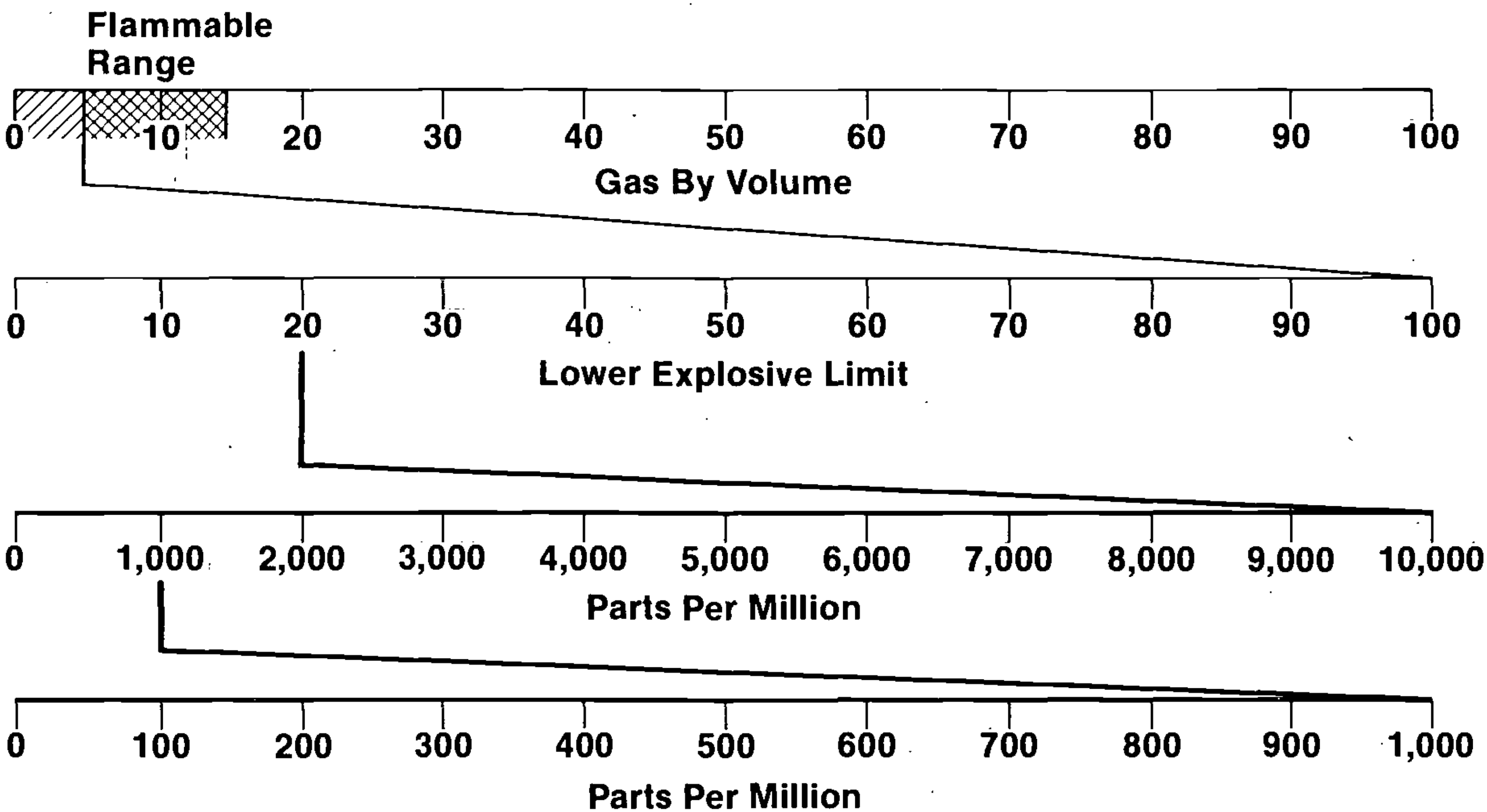
Several types of gas monitoring equipment are used throughout the United States for mine and tunnel safety, petroleum production and transportation, and general gas monitoring. The equipment can be divided into three general categories based on the ranges to be monitored:

PPM meters	(1-10,000 ppm of total air volume; use noncombustion, electronic sensor)
LEL meters	(1-20% of LEL; use catalytic combustion of gases to measure temperature)
Volume meters	(1-5% of total air volume; same as LEL meters)

These values are equivalents for Metro Rail construction requirements.

Figure III-1 shows general ranges for gas sensing studies.

Figure III-1 Gas Metering Ranges



Increasing demands for environmental/safety controls relative to natural/petroleum gases and oil and to processed petrochemical materials are bringing about many improvements in technology at the present time. New types of sensors are under development and will become operational during Metro Rail construction.

The presently available equipment provides both fixed and mobile (hand-held) sensors that measure at multiple or single points. Some new oil transportation systems include lineal sensors for pipelines that may be adaptable to tunnels and to large area monitoring.

c) Pressure Sensors

Many types of pressure gauges and manometers are available and can measure in the anticipated ranges with accuracies in ± 0.1 psig or in inches of water head (120 in. of water equals about 4.3 psi).

d) Equipment Accuracy and Reliability

With improvements in electronic technology and more strict governmental requirements for environmental monitoring and for hazardous materials controls, overall accuracies of the equipment are very high in their optimal ranges (±1% of reading). Accuracies in the middle range are far better than at the extreme low and high ends of the ranges. Many volume meters contain a dual system for LEL and volume gas meseaurements of combustible gases to maintain accuracies in the more important lower ranges.

For combustible gases, some instruments using catalytic processes require a minimum oxygen level to make accurate readings. When gases are high as in the probe monitoring, the available oxygen may be insufficient for accurate readings. Other instruments do not depend on oxygen and, therefore, tend to be more accurate and reliable in the high ranges of 40-100% combustible gases by volume.

Operational reliability of gas measurements does not depend on the accuracy of metering. Often, concerns are more directed toward the presence or absence of combustible gases and if the LEL is approached. Whether the value is 9% or 10% of LEL is not as important as knowing that the first-stage conditions have been or may be reached at any time and that responses will be required. In scientific or detailed production and use applications, more concern is directed toward accuracy because the commercial value of the gases and combustion energy are the primary concern, and a deviation of 1-5% may represent commercial losses of energy.

3. Procedures

As indicated above, the meters for gas concentrations and pressures can read very accurately in laboratory and point situations. However, ventilation, general environmental conditions, geological sources, and migration pathways can rapidly alter concentrations and increase temporal and locational variability in measurements. Problems in reliability of accurate measurements largely relate to the variable behavior of the gases and to the consistency of monitoring personnel in the field environment. Also, gas levels may vary more with the location of the sensors relative to the gas inflow than from the measuring inaccuracies of sensors. Therefore, sampling procedures are far more important than the equipment used.

A typical example may involve the hand-held combustible meter carried at hip height in a tunnel of 20 ft diameter. Because methane is lighter than air, the gas will rise immediately to the ceiling of the tunnel. If ventilation in the tunnel is strong, the side-wall boundary layer of turbulence may hold the gases close to the side-wall until a deflection occurs and the gas will again rise toward the ceiling. In any case, a meter at hip height may not get a true measure of gas in the tunnel.

Cal-OSHA requires measurements to be taken at exactly the same point on the side-walls and ceiling (12 in. from sides, floor, and ceiling at the face and in return air ducts). Requirements also require measurements to be taken by a certified gas monitor with appropriate training in gas behavior, sensors, and monitoring procedures.

4. Monitoring Programs

The SCRTD gas probe monitoring system still exists and can be expanded both before and during construction to improve identification of gas concentrations, pressures, and the influences of dewatering. Existing deep and middle probes can be augmented with shallow probes (10-15 ft depth), existing geotechnical piezometers may be modified to establish new deep and middle level gas probes, and new probes could be established for deep, middle, and shallow levels. Based on modifications of existing borings and the availability of future project-related geotechnical borings, about 25 to 30 probes per mile could be monitored on an average separation of 200 ft. Work at the Ross store indicated that gas did not extend more than 400 ft from the vent well, and the condition would have been detected with probes at such spacing. The Farmers Insurance gas occurrence appears to extend well over 200 ft and was, in fact, detected by two SCRTD probes in 1983 and 1985.

Monitoring of surface gas levels could locate the existing "hot spots" of gases under preconstruction conditions and may be used to locate the most effective sites for new gas probes. Continuation of the monitoring during the construction phase would permit the documentation of effects upon gas release and venting due to construction and suspension of dewatering. Surface results would also provide the final point in monitoring the release of gas from the bedrock, its subsequent movement through the deep, middle, and shallow levels of the alluvium, and finally its venting to the atmosphere.

More monitoring of the general environment will be undertaken to relate changes of gas levels with:

- o Rainfall (saturation of soil reduces gas venting and increases gas levels)
- o Temperature, winds, and barometric pressures (increased winds and temperatures increase venting of gas; increased pressure reduces venting)
- o Groundwater levels, temperatures, and quality (changes may increase pressure or total volume of gas alluvium)

- Seismicity (changes gas permeability and porosity of bedrock and alluvium)

During construction, many tasks will require deep borings into the alluvium and shallow geological formations. These borings would allow access to a greatly expanded number of monitoring points without significant additional capital costs, although they may be available for only short intervals during construction. These access points would include:

- soldier pile holes
- dewatering wells
- new geotechnical instrumentation holes

Any boring can be monitored with a typical hand-held meter during drilling; with a long extension cable, a sensor can be lowered into the bore and levels measured throughout its depth. Identification of gas-permeable layers would be very important to tunneling ventilation requirements.

5. Gas Controls

If large quantities of gas are encountered, artificial venting through bores may be undertaken as a means of monitoring the dynamic character of the gas and to reduce gas levels for the benefit of SCRTD construction. Often, monitoring probes may be adapted for venting puproses.

The Los Angeles City Task Force for the Methane Gas Explosion developed other controls for structures within the designated high potential area; potential risk zones include the Wilshire/Fairfax corridor. Recommendations of the Task Force Report for commercial facilities would require the installation of a permeable exterior layer that would allow gas to easily enter and migrate upward to the ground surface and vent to the atmosphere. In general, the Metro Rail design for gas control has included passive barrier systems on the exterior of stations, as well as tunnels and active ventilation systems within the facilities. The ventilation systems also include but do not depend on the influences of moving trains during operations of the system. Because of the presence of hydrocarbon-resistant membranes and large capacity ventilation, the passive venting of gases along the exterior of the walls has not been included in the design of the facilities. Furthermore, in areas with high water tables and moving tar/oil, venting systems may become clogged and, used alone, they may not be adequate measures.

In those areas where groundwater, tar, and oil would not interfere, gas probes used during construction for monitoring may be adapted for future venting along the tunnel alignment and around stations.

IV. DESIGN CONSIDERATIONS/DECISIONS

A. Basis for Design

This section provides the rationale for the tunnel linings recommended for the SCRTD subway project by evaluating the effectiveness of segmented precast concrete, cast-in-place (CIP) concrete, and segmented steel linings to restrict the flow of gas into the tunnels. This section also considers the further mitigation of gas during subway operation by means of ventilation already provided in the subway for fresh air intake and for heat dissipation.

1. Gas Flow Conditions

Gas may enter the tunnel in three ways.

a) Through Joints

The first way that gas may enter a tunnel is by the gas flow through the joints, which occurs when either precast concrete or prefabricated steel segments are used. The flow rate of gas, Q, through the joints is estimated by the equation:

$$Q = AV$$

where V is the velocity of the medium (the gas) through the joints (determined by using the D'Arcy equation for incompressible flow) and A is the area of the opening of the joints where gas will infiltrate. The term A is indeterminate but is very sensitive to details of fabrication and construction, such as proper gasket installation and caulking in the segment joints.

b) By Diffusion

The second way for gas to enter a concrete-lined tunnel is by diffusion. Studies of this phenomenon have been made (Donaldson; Katz and Chen), although it is not suggested that it is, at present, an exact science to predict the amount of this flow.

MRTC and ES have estimated the amount of flow by diffusion into the concrete tunnels and have found that the flow by diffusion through concrete is approximately 15% of the total flow. For this reason, it has been decided to delete the separate estimation of flow by diffusion into the tunnel by this method.

c) Through Cracks

The third way for gas to get into the tunnel is through cracks in the concrete. Cracks occur in concrete as the result of stresses, temperature effects, and shrinkage. Initially, ES suggested that flow by this mechanism be estimated by assuming one crack (1/32 in. wide and 10 ft long) per each 1,000 ft of tunnel. No laboratory or field data have been found to support this assumption, however, and it has been decided to estimate the flow into the tunnels based on field measurements of water flow as outlined in the following paragraphs.

d) Water Infiltration

A review of available data on flow of water into tunnels was conducted, and the most complete set of information was found in "Guidelines for Tunnel Lining Design" (O'Rourke, 1984). The "Guidelines" report inflow in two forms:

(1) Maximum infiltration rates specified for several U.S. rapid transit systems are shown in Table IV-I:

Table IV-I

Infiltration Rates in Various U.S. Rapid Transit Systems

System	Inflow Rate (gal/ft^2/day)
Bay Area Rapid Transit, San Francisco	0.02
Washington Metropolitan Area Rapid Transit Authority, Washington, D.C.	0.02
Metropolitan Atlanta Regional Transit Authority, Atlanta, Ga.	0.02
Baltimore Regional Rapid Transit, Baltimore, Md.	0.02
Massachusetts Bay Transit Authority, Boston, Ma.	0.042
Niagra Frontier Transit Authority, Buffalo, N.Y.	0.005

(2) Measured infiltration rates at several tunnels: a total of 16 highway, railroad, and rapid transit tunnels reported that the average inflow (with cast iron

linings) is approximately 0.015 gal/ft^2/day. All of these 16 tunnels have surrounding water pressures of 20 psi or greater. Adjusting all data to 14 psi yields a flow of approximately 0.011 gal/ft^2/day.

Additional data was found in the report "Special Study of Precast Concrete Tunnel Liner Demonstration" (Wightman et al., 1980), wherein it is reported that the actual measured flow into Baltimore subway tunnels, lined with precast concrete segments, is approximately 0.16 gal/ft^2/day under an average water pressure of 14 psi. However, with tightening of joints, recaulking, and patching, the flow was "essentially reduced to zero." The report points out that this is total flow and cannot be allocated to the three individual sources (diffusion, joints, and cracks).

To estimate the flow into the tunnel, the Darcy-Wiesbach equation is used, as follows. This equation was used to estimate the gas flow into the tunnels as explained further in Section V, Final Design.

$$V = \sqrt{\frac{\Delta p \; D \; 2g}{f \rho L}}$$

Δp = pressure differential
D = hydraulic diameter
g = acceleration due to gravity
f = friction factor
ρ = density of fluid
L = flow path length
V = velocity

or

$$Q = AV = A \sqrt{\frac{\Delta p \; D \; 2g}{f \rho L}}$$

A = area of opening

Writing the equation for water and for gas and combining:

$$Q_g = Q_w \sqrt{\frac{\Delta g_m \; D \; 2g \; f_w \; \rho_w L}{\Delta p_w \; D \; 2g \; f_g \rho_g \; L}} \times \frac{A}{A}$$

This flow is turbulent when the Reynolds number is greater than 4000 and the friction factor (f) is independent of fluid properties (Hydraulics Handbook by H. W. King). Approximate calculations of the Reynolds number indicate it to be above 4000, so that $f_g = f_w$. Making this substitution and factoring all common terms:

$$Q_g = Q_w \sqrt{\frac{\Delta p_g \; \rho_w}{\Delta p_w \; \rho_g}}$$

Taking Δpw = 14 psi as the most conservative case consistent with the above-reported data and substituting the densities:

$$Q_g = Q_w \sqrt{\frac{\Delta p_g \times 62.4}{14 \times 0.0424}}$$

$$= 10.253 \; Q_w \quad \Delta p_g$$

Δp_g in psi

2. Membranes

To eliminate the majority of the gas flow through cracks and through diffusion, it has been decided to include a gas-resistant membrane in tunnels with CIP concrete linings and a gas-resistant coating in tunnels with a lining of precast concrete segments. Laboratory tests of hydrocarbon permeability, chemical resistance to hydrocarbons, and abrasion resistance were performed by Matrecon, Inc., of Oakland, California, a laboratory that has done many such tests for EPA and other agencies seeking to control hazardous wastes. Matrecon's reports on these tests are included in the Appendices.

From an initial screening of literature, existing practice, and manufacturers, 14 barrier material candidates were submitted for testing. Of these, six were prefabricated membranes supplied in roll or sheet form; the remainder were liquid coating materials intended to be applied in the field by spray or brush. Two manufacturers of sheet material (for use with CIP concrete) and two for coating materials (for use with precast concrete segments) have been selected and specified for the project. Laboratory tests showed the selected materials to be approximately 99% effective in stopping the gas; for design, an efficiency of 90% has been assumed.

3. Ventilation Subsystem

a) Methane Purge by Ventilation

Results of exploratory drillings have substantiated the existence of gas-bearing formations along certain sections of the Metro Rail alignment. ES has undertaken a field testing program and measured the gas field concentrations and pressures at several locations along the subway alignment. Between Crenshaw and La Brea stations, methane concentrations as high as 95% by volume at a pressure of 7 psig were detected by one of the probes.

During revenue service, it is anticipated that the air flows generated by the piston action of the trains will adequately disperse and dilute any methane present in the tunnels. However, during periods of system shutdown, when train operations cease, ventilation is being used to mitigate gas accumulation. Pending results of actual field measurements, it is expected that air velocities of at least 100 fpm may have to be maintained to prevent the formation of gas layers withing the tunnels. This is approximately equivalent to flows of 20,000 cfm in the selected tunnel cross section.

b) MOS-1 Analyses

As indicated before, the minimum operable segment (MOS-1) is the initial 4.4-mile segment of the 18.6-mile Metro Rail Project. None of the tunnels in the MOS-1 section require a mid-tunnel ventilation shaft. Tunnel purging during periods of system shutdown, except in a fire emergency, is accomplished by operating the ventilation systems at adjacent stations. A computer program has been used to predict the air flow rates that can be achieved in each MOS-1 tunnel segment by operating station ventilation systems based on various concepts as described below.

c) Concepts

(1) Supply and Exhaust: This concept consists of ventilating a pair of tunnels between adjacent stations by operating the under platform exhaust (UPE) system (128,000 cfm) at one station and the supply air system (150,000 cfm) at the adjacent station in a "push-pull" mode.

(2) Augmented Exhaust Capacity: This is similar to the basic concept, except that the station smoke exhaust system is also operated to supplement the UPE system. The total exhaust capacity available at each station is shown on Table IV-2.

TABLE IV-2

Station Exhaust System Capacities

	Flow Rate (cfm)		
	UPE	Smoke Exhaust	Total
Union Station	128,000	168,000	296,000
Civic Center	128,000	133,200	261,000
Fifth/Hill	128,000	186,000	314,000
7th/Flower	128,000	129,000	257,000
Wilshire/Alvarado	128,000	77,000	205,000

(3) Exhaust Only: Tunnel purging is accomplished by operating both the UPE and the smoke exhaust systems at a given station. The supply air system at the adjacent station is not operated. This condition was examined to provide a contingency mode of operation in case the current supply air duct configuration proves to be an ineffective means for delivering fresh air to the tunnels.

d) Assumptions

In all cases analyzed, the following assumptions apply:

(1) At the ventilation shafts adjacent to the stations at which the ventilation systems are operating, fans and bypass dampers are in the closed position.

(2) Train operations have ceased and no trains are present in the tunnel sections examined.

(3) In the simulations using the station supply air system, the effect of discharging the air at a high velocity toward the center of the station and away from the tunnels was ignored.

e) Results of MOS-1 Tunnel Purging Simulations

The results of the computer simulations for revenue tunnels are summarized on Table IV-3 and are also shown schematically on Figures IV-I through IV-4. The results for the nonrevenue tunnels east of Union Station are shown on Figures IV-5 and IV-6. The results indicate the following:

Tunnel air flows ranging between 18,700 and 24,900 cfm can be generated in the tunnels between Civic Center and Wilshire/Alvarado and about 10,200 cfm (corresponding to about 50 fpm velocity) between Union Station and Civic Center by operating the UPE systems (128,000 cfm) at one station and supply air systems (150,000 cfm) at the adjacent station.

Table IV- 3 Summary of Revenue Tunnel Purging

Simulations for MOS-1

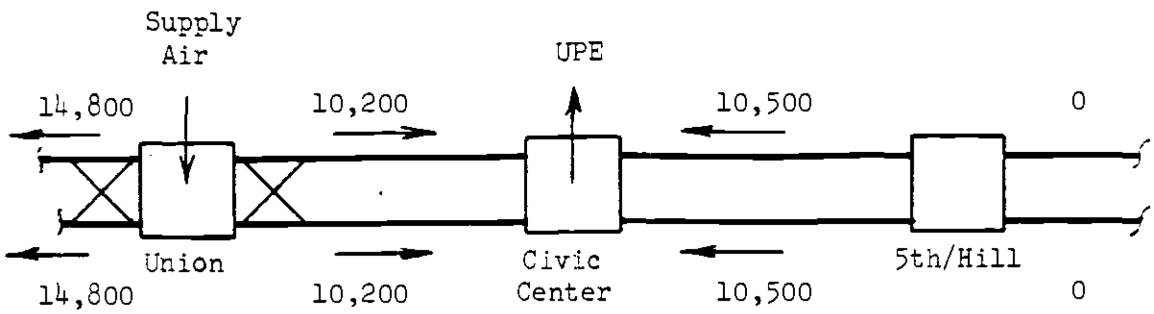
Case No.	Location (Between)	Air Flow Rates (cfm)	Air Velocity (fpm)	Location of Station Systems Activated S/A	UPE	S/E
A-1	Union	10,200	50	Union	Civic	-
A-2	and	22,500	105	Union	Civic	Civic
A-3	Civic Center	19,700	95	-	Civic	Civic
B-1	Civic Center	18,700	90	Civic	5th/Hill	-
B-2	and	30,700	145	Civic	5th/Hill	5th/Hill
B-3	5th/Hill	23,500	110	-	5th/Hill	5th/Hill
C-1	5th/Hill	24,900	120	7th/Flower	5th/Hill	-
C-2	and	32,900	155	7th/Flower	5th/Hill	5th/Hill
C-3	7th/Flower	21,700	105	-	5th/Hill	5th/Hill
D-1	7th/Flower	21,200	100	Wil./Alv'do	7th/Flower	-
D-2	and	32,500	155	Wil./Alv.do	7th/Flower	7th/Flower
D-3	Wil./Alvarado	25,400	120	-	7th/Flower	7th/Flower

Legend:

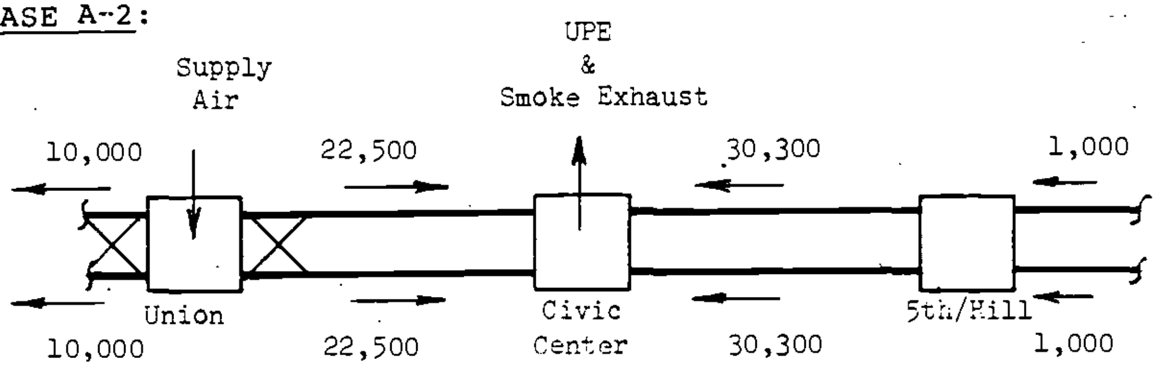
S/A - Supply Air System
UPE - Underplatform Exhaust System
S/E - Smoke Exhaust System

Figure IV-1 Results of Revenue Tunnel Purging Simulations for Cases A-1 through A-3

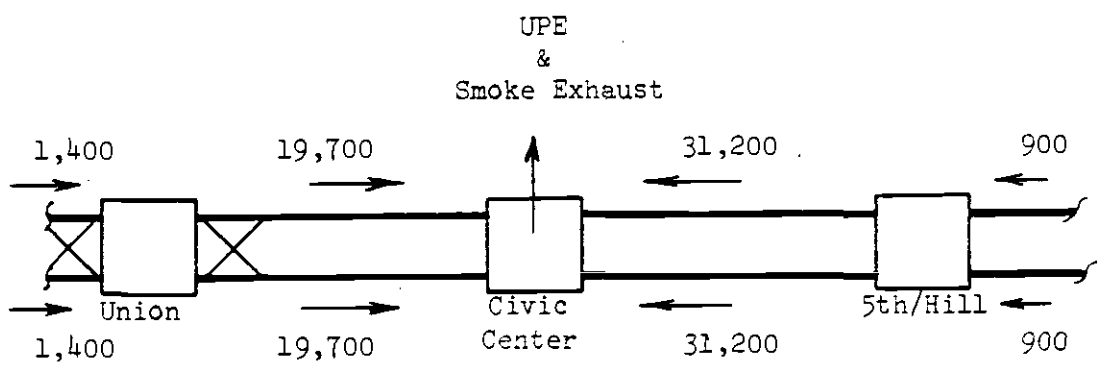
CASE A-1:



CASE A-2:



CASE A-3:

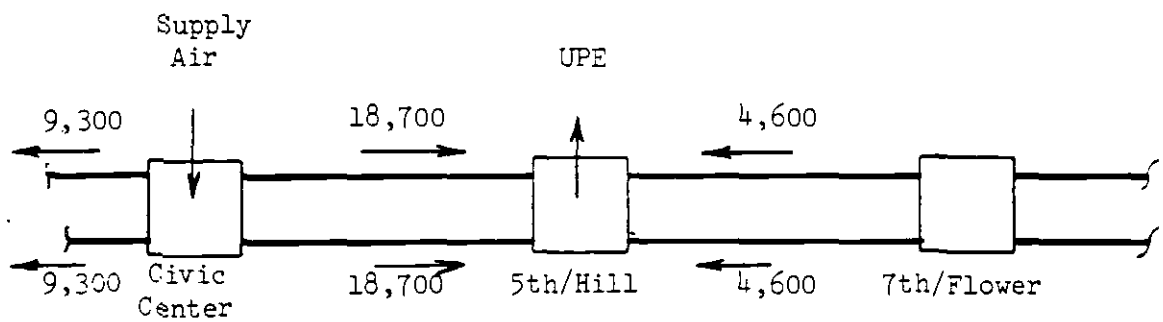


Notes

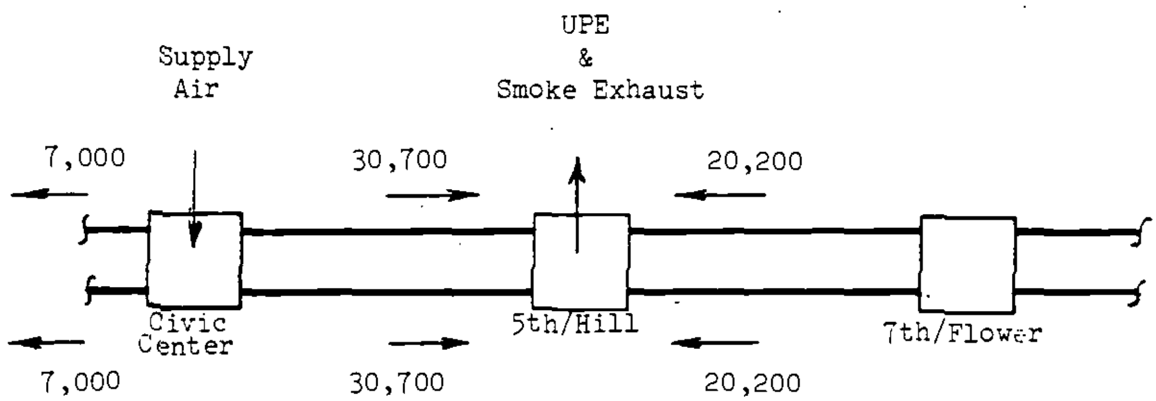
1. Above numbers represent air flow rates in cfm.
2. For station exhaust system capacities, refer to Table IV-3

Figure IV-2 Results of Revenue Tunnel Purging Simulations for Cases B-1 through B-3

CASE B-1:



CASE B-2:



CASE B-3:

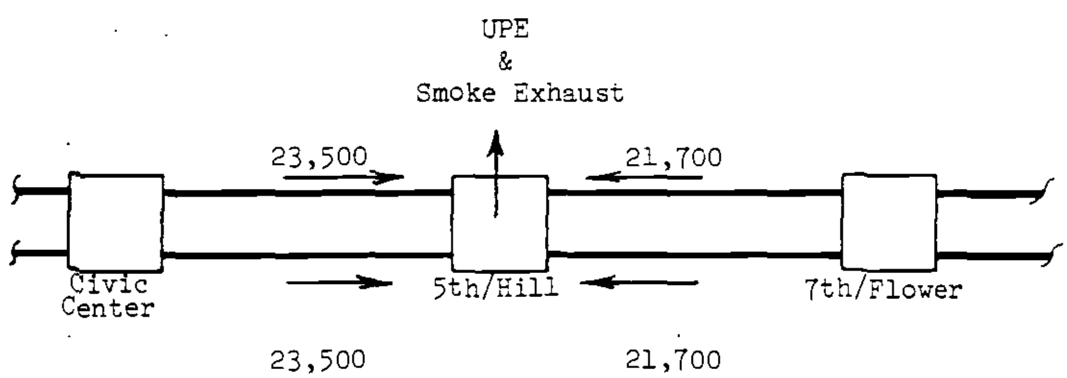
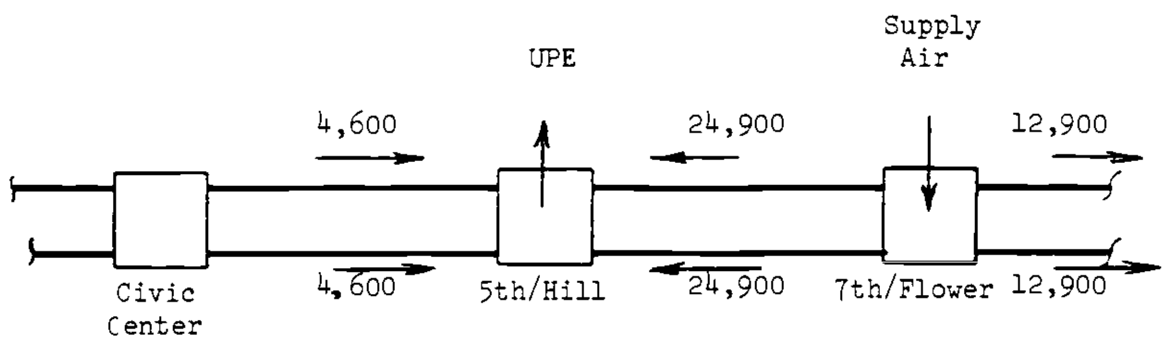
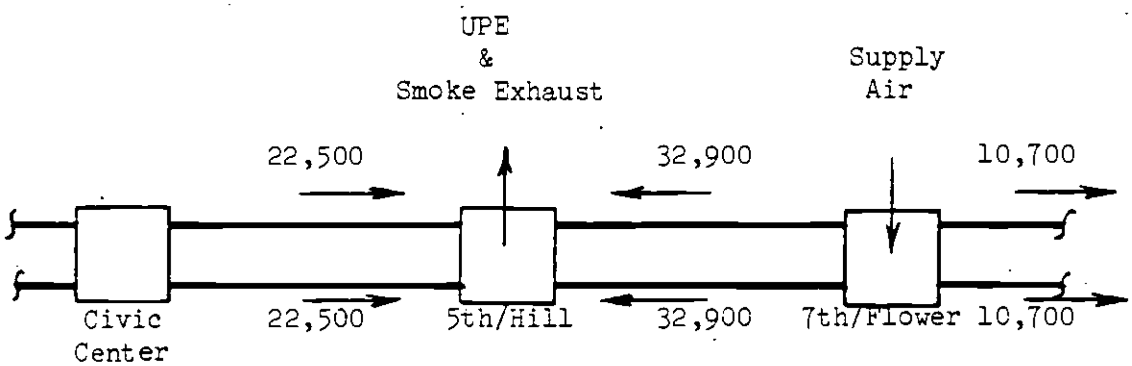


Figure IV-3 Results of Revenue Tunnel Purging Simulations for Cases C-1 through C-3

CASE C-1:



CASE C-2:



CASE C-3:

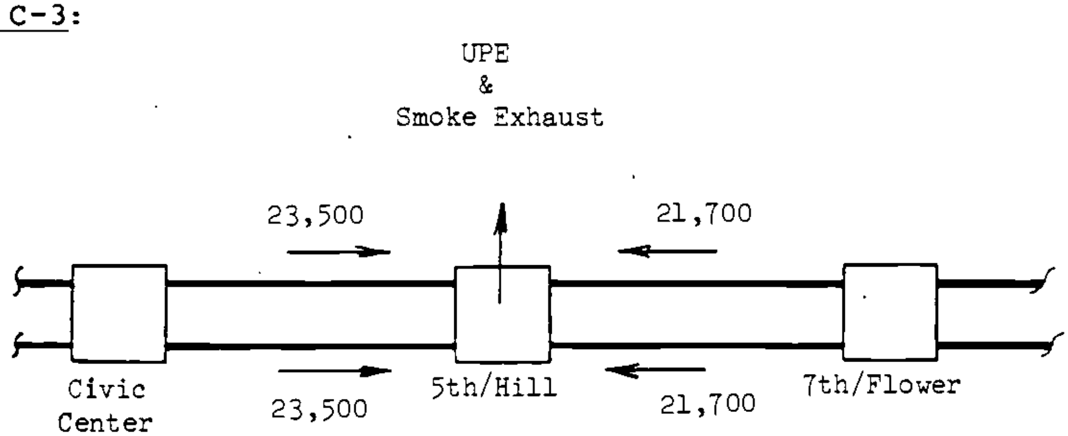
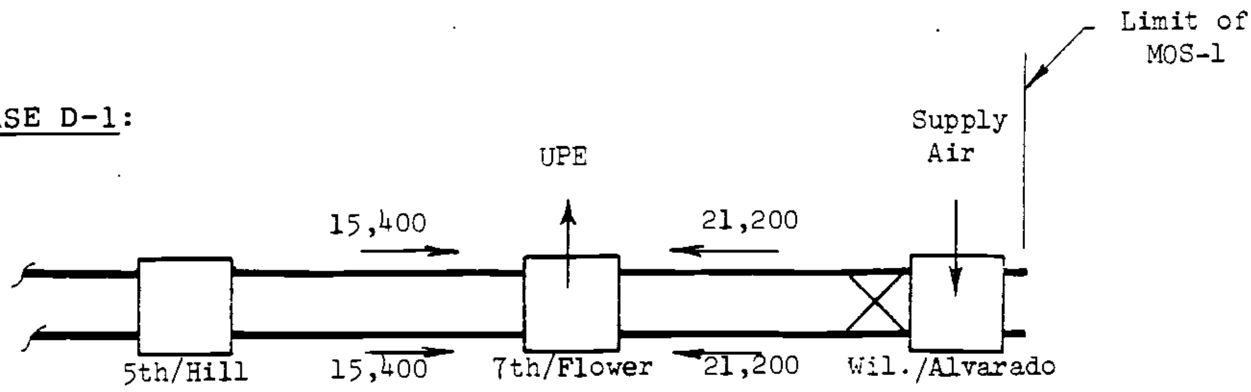
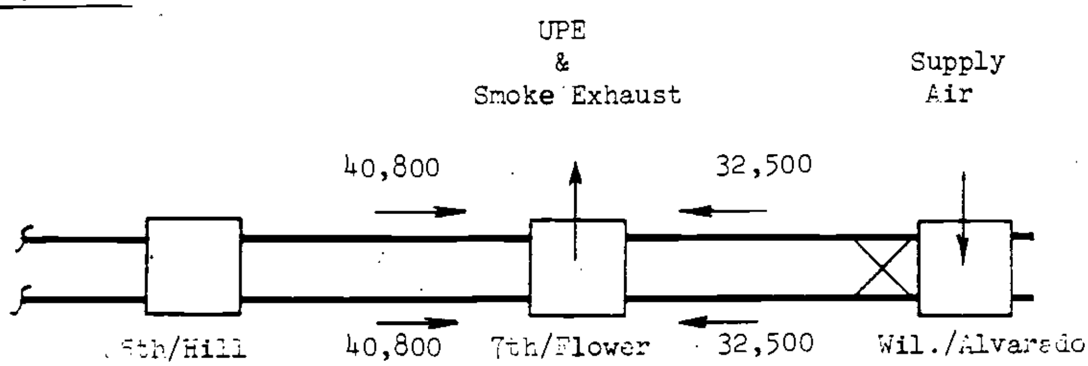


Figure IV-4 Results of Revenue Tunnel Purging Simulations for Cases D-1 through D-3

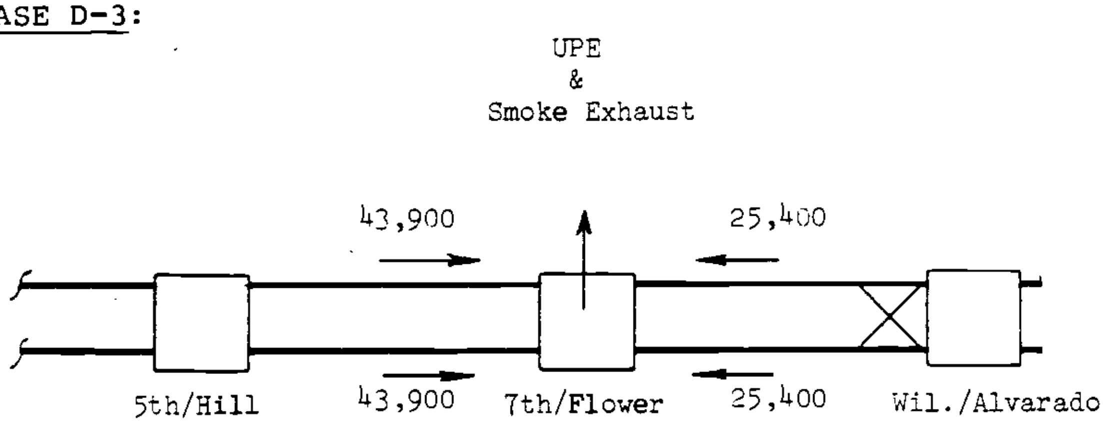
CASE D-1:

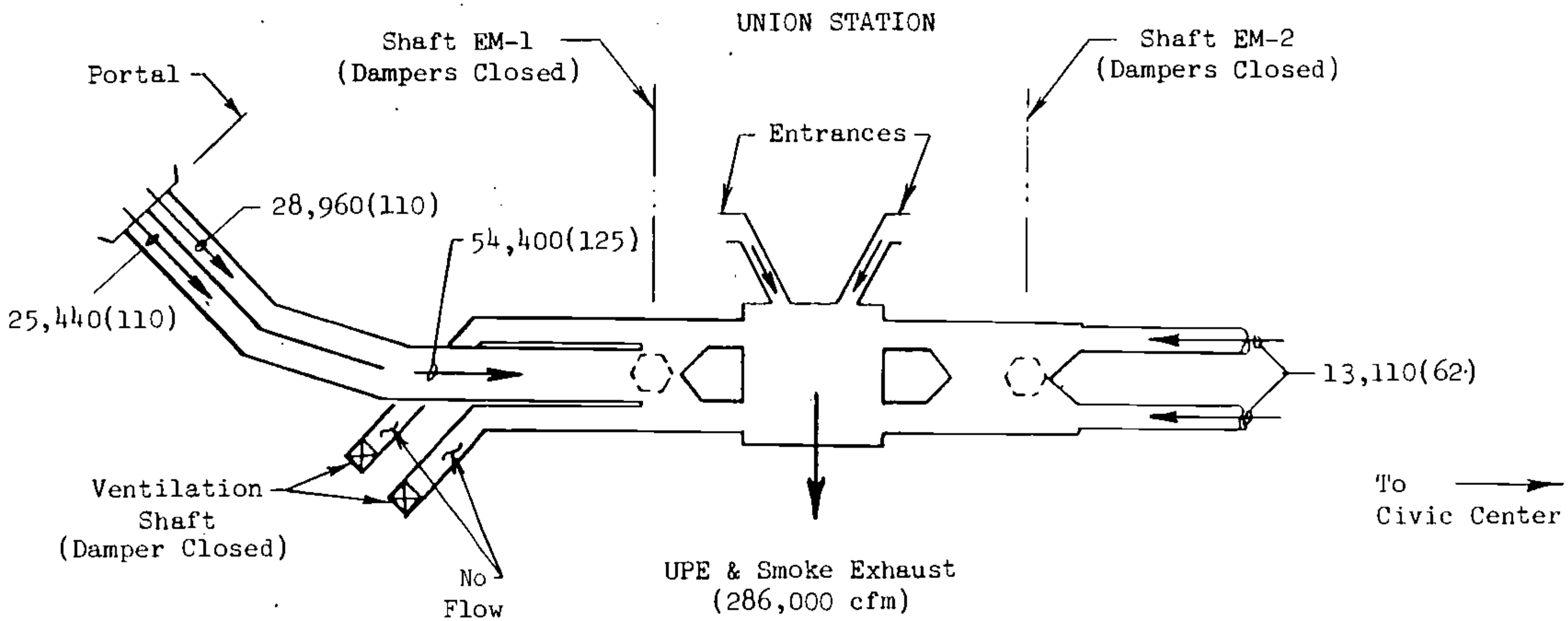


CASE D-2:



CASE D-3:





Note: 54,400(125) means an air flow rate of 54,400 cfm with an air velocity of 125 feet per minute.

Figure IV-5 Purging Nonrevenue Tunnels Leading to Yards

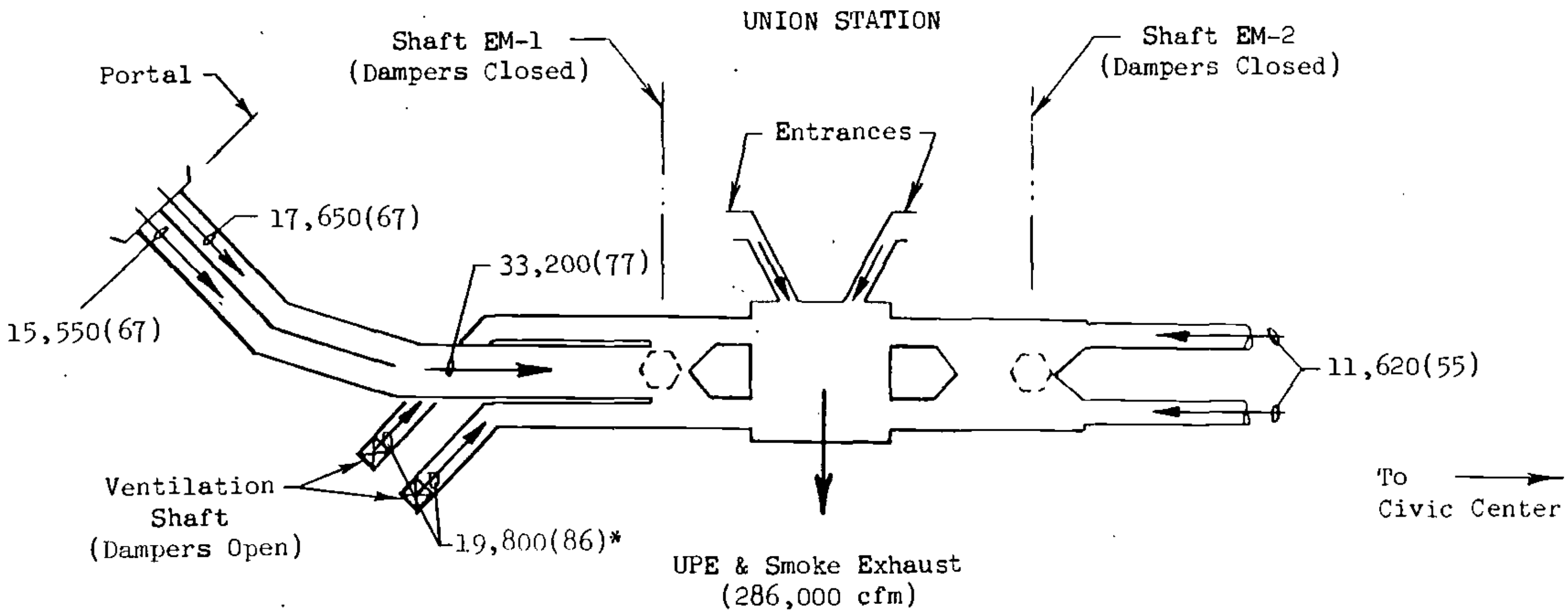


Figure IV-6 Purging El MOnte Nonrevenue Stub Tunnels

By operating the station smoke exhaust to supplement the UPE system, the tunnel air flow between Union Station and Civic Center can be increased from about 10,200 cfm to about 22,500 cfm. In the other tunnel segments, air flows in excess of 30,000 cfm can be achieved.

By using the station exhaust systems only, tunnel air flows range from 19,700 cfm between Union Station and Civic Center to a high value of 43,000 cfm between 5th/Hill and 7th/Flower.

The nonrevenue tunnels east of Union Station can be purged by operating the UPE and smoke exhaust systems at Union Station. Air flows ranging from 25,400 to 54,400 cfm can be achieved in the tunnels leading to the yards with corresponding air velocities in excess of 100 fpm. By opening the ventilation shaft dampers, about 19,800 cfm with an air velocity of 86 fpm can be expected in each bore of the El Monte stub tunnels. The above air flows and corresponding air velocities can be increased by 16% by also operating the station exhaust systems at Civic Center.

f) Discussion

For the MOS-1 segment, the highest predicted air flow rates in most tunnel segments are obtained with the "augmented exhaust" concept (Cases A-2 through D-2) and the lowest flow rates are predicted with the supply/exhaust "push-pull" concept (cases A-1 through D-1).

The "exhaust" concept (cases a-3 through d-3) can produce equal or better results in most MOS-1 tunnel segments without the use of station supply air fans. Furthermore, this mode of operation can be used to purge multiple tunnels simultaneously as shown in Figure IV-7 by operating the exhaust systems at every other station.

g) Analyses Outside MOS-1

Three sections have been examined: between Wilshire/La Brea and Wilshire/Fairfax; between Wilshire/Fairfax and Fairfax/Beverly; and between Fairfax/Santa Monica and La Brea/Sunset.

Notes:

1. Numbers represent air flow rates in cfm.

2. For station exhaust system capacities, refer to Table 3.10

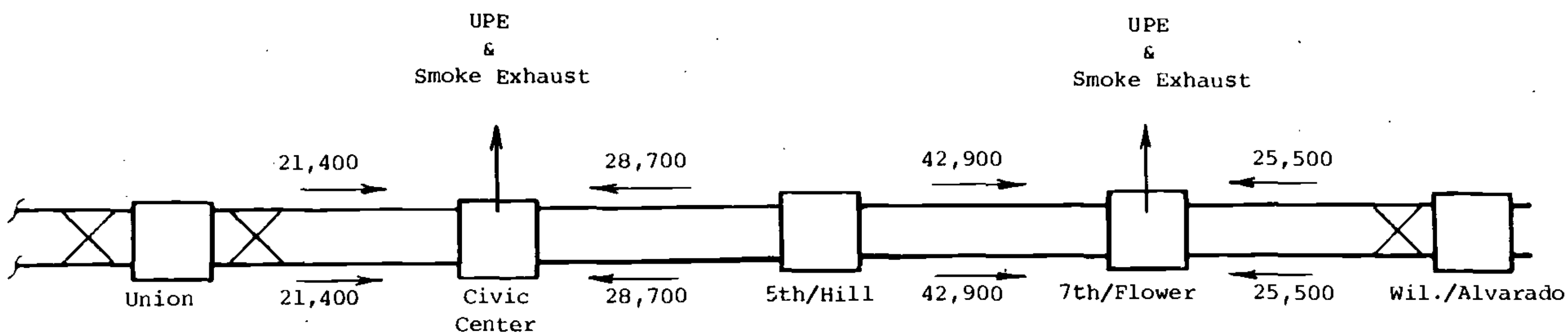


Figure IV-7 Purging Multiple Tunnels Simultaneously

The section between Fairfax/Santa Monica and La Brea/Sunset is one of the longest tunnel sections without a mid-tunnel shaft and bounded by typical, single-level center platform stations. Hence, the results obtained for this case give an indication of the minimum air flow attainable in other, shorter tunnel sections that have not been simulated.

Results are based on purging the tunnels with station supply air systems and UPE systems ("push-pull" concept). In each case, operation of the supply air systems (150,000 cfm) at one station and the UPE systems (128,000 cfm) at one adjacent station has been simulated. The bypass dampers in the ventilation shafts adjacent to the stations whose ventilation systems were operated have been assumed closed. Also, it has been assumed that train operations had ceased and that no trains were present in the tunnel sections examined. The adverse effects of discharging the supply air at a high velocity toward the center of the station and away from the tunnels, as well as the added resistance to tunnel air flow imposed by segmented steel liners, have not been assessed.

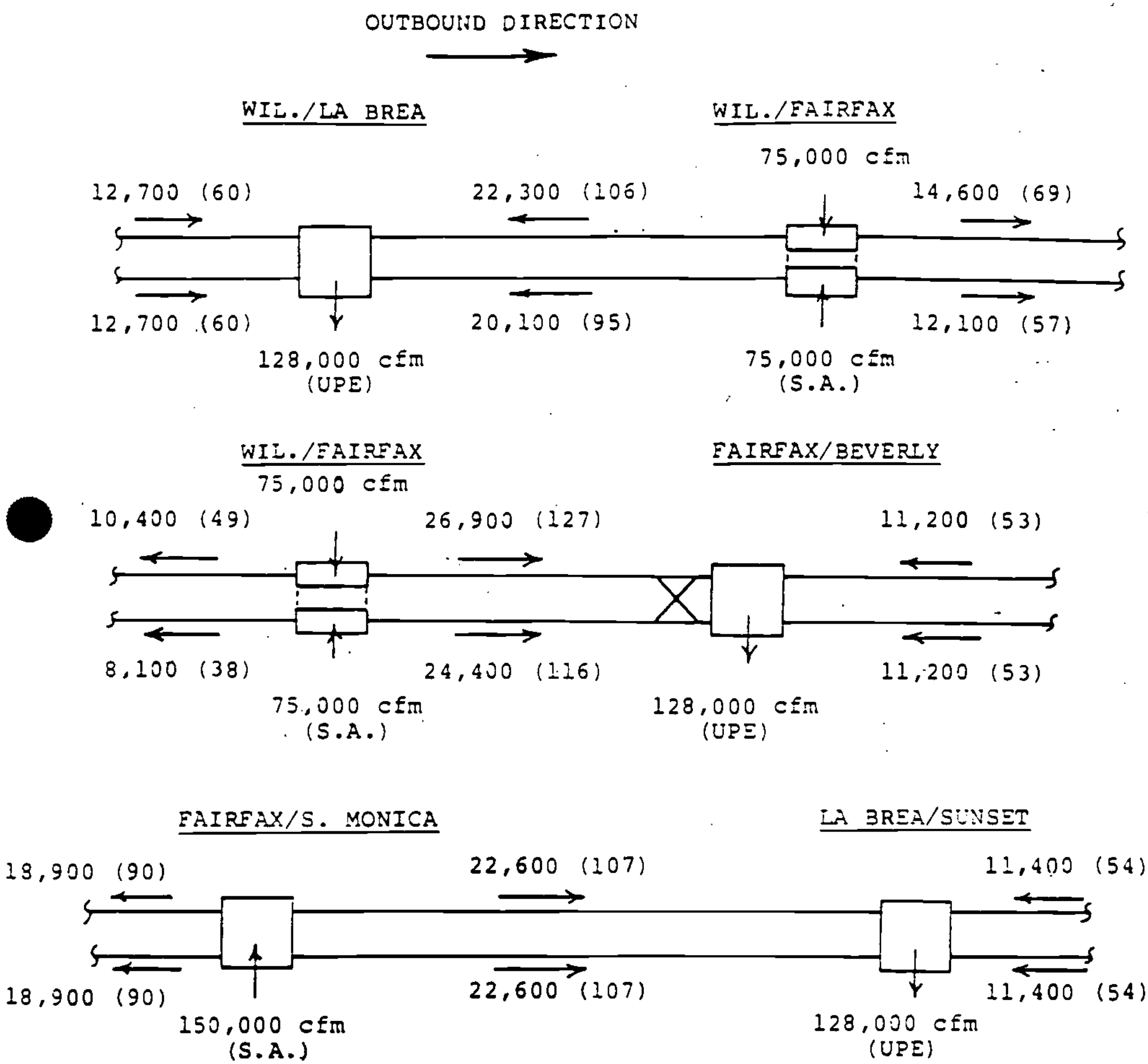
h) Results of Tunnel Purging Simulation Outside MOS-1

The results for the three cases simulated are shown schematically on Figure IV-8. The air flow rate in cubic feet per minute and the air velocity in feet per minute (shown in parentheses) are indicated for each tunnel section.

The maximum methane infiltration rate which can be diluted to a methane concentration of 0.25% by the predicted tunnel air flow rates are shown on Table IV-4. The air flow rate in cubic feet per minute and the air velocity in feet per minute (shown in parentheses on Figure IV-8) are indicated for each tunnel section.

The results show that tunnel air flow rates ranging from 20,100 to 26,900 cfm can be achieved by operating the station ventilation systems in a "push-pull" mode. These air flow

Figure IV-8 Results of SES Simulations Using Station Ventilation Systems for Tunnel Purging Outside MOS-1



Note: 22,600 (107) means a tunnel air flow rate of 22,600 cfm at an air velocity of 107 feet per minute.

Table IV-4 Maximum Methane Infiltration Rates Handled by the Predicted Ventilation Rates

Tunnel Section	Tunnel Length (ft)	Allowable Predicted Air Flow Rate (cfm)	Methane Infiltrati Rate (cfm)*
Wil./La Brea to Wil./Fairfax (Outbound)	4,550	20,100	50
Wil./La Brea to Wil./Fairfax (Inbound)	4,550	22,300	56
Wil./Fairfax to Fairfax/Beverly (Outbound)	3,870	24,400	61
Wil./Fairfax to Fairfax/Beverly (Inbound)	3,870	26,900	67
Fairfax/S. Monica to La Brea/Sunset (Outbound	6,650	22,600	57
Fairfax/S. Monica to La Brea/Sunset (Inbound)	6,650	22,600	57

*Computed based on a maximum methane concentration of 0.25% by volume.

rates correspond to an air velocity range of 95 to 127 fpm, based on a tunnel cross-sectional area of 221 sq ft. In the tunnel with the lowest predicted air flow rate (i.e., 20,100 cfm of fresh air), the ventilation can handle up to 50 cfm of methane gas infiltration, which is equivalent to 72,000 cfd. The predicted tunnel air velocity is marginally below the criterion (95 fpm vs. 100 fpm) in one of the six tunnel sections examined (i.e., in the outbound tunnel between Wilshire/La Brea and Wilshire/Fairfax).

As described under the subsection titled "Discussion" and shown in Figure IV-7, continuous ventilation of the entire 18.6-mile system may be required and can be accomplished in final design by one of the following two alternatives:

(1) Increase the smoke exhaust system capacity in the post MOS-1 stations

(2) Replace one of the emergency fans with a mid-tunnel type fan

i) Station Ancillary Room Ventilation

Station ancillary rooms and passageways that are beyond the train room and mezzanine areas are force ventilated by a system of fans and dampers to meet the criterion of a minimum of 10 air changes per hour for each room. Room exhaust air is ducted to station ventilation shafts where it is monitored for gas content. Ancillary room as well as tunnel and train room ventilation and gas monitoring are controlled from the Central Control Facility (CCF).

4. Gas Monitoring Subsystem

a) Background

The gas monitoring subsystem provides for the detection and annunciation of methane and hydrogen sulfide infiltration. Using industrial-grade very sensitive gas measuring instruments, air flows are continuously monitored for deviations above the normal atmospheric concentrations of these gases. The sensitivity (less than 1.0 ppm) of these instruments allows the sampling probes to be located in shafts venting air from the station, each tunnel, and midline ventilation shaft structures, rather than throughout the structures. The resulting monitoring system is less complicated, yet it detects gas intrusions of a significantly lower flow rate than a system using equipment typical of mine gas monitoring systems.

The subsystem will have 21 central analyzers, one at each station and the midline ventilation shaft structures, for the 18.6-mile Metro Rail System. Each analyzer will be microprocessor-controlled for automatic operation, including automatic calibration and self-diagnostic capabilities.

SCADA will provide for two-way communication between the CCF and each central analyzer. Information sent to CCF includes gas measurements and annunications (gas level warnings/alarms and equipment failure). Personnel at the CCF can select sampling points and have the gas measuring instruments calibrated. The SCADA subsystem enables the data received from the monitoring subsystem to be stored in short-term memory and a permanent record to be made at the CCF. SCADA also provides special CRT displays when warning, alarm, or trouble annunciations are received.

b) Purpose of the Gas Monitoring Subsystem

The gas monitoring subsystem of the Communications System is capable of functioning continuously to provide early detection and annunciation of gas infiltration before a hazardous condition can develop. Annunciation of an increase in the gas level above the normal ambient range will serve as notification to initiate gas control procedures and to investigate the source of the intrusion.

c) Description of the Gas Monitoring Subsystem

The gas monitoring subsystem as presently designed consists of 21 central analyzers, one in each station and each midtunnel ventilation shaft structure. Samples of air are extracted from every exhaust shaft and tunnel segment in the system and analyzed for methane and hydrogen sulfide content. This equipment can detect concentrations of these gases of 1.0 ppm or less. When abnormal concentrations of either gas are detected, the CCF operators will be alerted. Normal operation of the analyzer equipment is completely automatic; however, provisions have been made to allow some equipment functions to be controlled remotely from the CCF. The high sensitivity, reliability, and simplicity of the equipment make it the best system available for monitoring gas concentrations in the Metro Rail subway.

d) Considerations Leading to the Selection of the Gas Monitoring Sybsystem

(1) Hazardous Gases - General

The hazardous gases found along the alignment fall into two categories: combustible gas and toxic gas.

The principal combustible gas encountered is methane. On occasion, traces of other combustible hydrocarbon gases are mixed with the methane. The degree of dominance of methane over other combustible gases permits the use of methane-specific gas measuring instruments for combustible gas monitoring even when the other hydrocarbon gases are present. If hydrocarbon gases other than methane are found in appreciable quantities during construction, an appropriate analyzer to monitor these gases can be provided.

Hydrogen sulfide is the only toxic gas found in significant amounts along the alignment. Aside from a few instances of elevated concentrations, this gas was found in only trace amounts.

(2) Methane

Methane is colorless in pure form, odorless, and nontoxic. Its hazardous characteristic is flammability. When mixed with air, methane has a lower flammability limit (LFL) of 5% (50,000 ppm) and an upper flammability limit (UFL) of 15% (150,000).[1] An underground facility is classified as gassy by Cal-OSHA when 0.25% (2,500) ppm or more of methane or other flammable gas is detected. This classification mandates that strict procedures are to be followed prior to construction, during construction, and during operation for occupied facilities such as mines and tunnels.

[1]The flammability limit values vary slightly among various authorities. For example, Matheson (TM), a division of Searle Medical Products USA Inc., reports methane flammability limits of 5.0 to 15.4% by volume while the International Technical Information Institute reports a lower limit of 5.3.

Two pertinent examples of these procedures are: (1) under USBM regulation, all personnel must be withdrawn from a mine when 1.5% (15,000 ppm) methane is detected in the air exhausted from a working area, and (2) the working area must be continuously ventilated with an airflow of at least 60 fpm.

(3) Hydrogen Sulfide

Hydrogen sulfide is colorless, odiferous, toxic, and flammable. Although its flammability range, 4 to 44% in air, is wider than that of methane, the primary danger from hydrogen sulfide is its toxic nature. As little as 0.10% (1,000 ppm) can cause death in a few minutes. The odor of hydrogen sulfide can be detected by the human nose when the concentration is as low as 0.025 ppm. However, the olfactory nerves are desensitized in a very short period of time, and therefore, the nose cannot be depended upon to warn of dangerous concentrations. The limit for exposure set by Cal-OSHA is the threshold limit value - time weighted average (TLV-TWA) of 10 ppm adopted by the American Conference of Government Industrial Hygienists.

(4) Gas Mixture Characteristics

The minimum specified ventilation rates will so thoroughly mix the hazardous gases that the constituents will not separate out of the mixture even though their specific weights vary considerably. Threrfore, if these gases infiltrate into a segment of the Metro Rail system, both heavy and light gases may be collected by a single sample probe in the exhaust ventilation stream of the affected segment. Separate gas analysis instruments will be provided for each central analyzer system to measure the methane and hydrogen sulfide content of the sample, or other gases that may be encountered in significant amounts during construction.

(5) Ambient Atmospheric Gas Levels

In the Los Angeles area, the normal atmospheric methane concentration is 1.5 ppm and is relatively stable. In contrast, the total hydrocarbon concentration in the atmosphere ranges from approximately 3 to 9 ppm and varies significantly throughout a single day. The total hydrocarbon concentration includes methane and other combustible hydrocarbons. The use of methane-specific gas measuring instruments provides a more stable background than instruments to measure total hydrocarbon combustible gas.

The ambient atmospheric level of hydrogen sulfide in the Los Angeles area averages less than 0.001 ppm.

(6) Ventilation

The Cal-OSHA Tunnel Safety Orders of Title 8, CAC, are among the most stringent and respected in the world. A feature that helped earn that respect is the emphasis on anticipating and preparing for hazardous conditions rather than reacting to an incident. In known gassy areas, for example, ventilation is given first priority and gas detection (monitoring) is given second priority, instead of vice versa, as in older codes. The ventilation serves to dilute gases to below hazardous levels, whether LFL or TLV-TWA, and to remove the gases from the area. In the Metro Rail System, ventilation provides the additional function of conveying the infiltrated gas to the sampling probes of the gas monitoring subsystem.

Metro Rail System design includes provisions to ensure adequate ventilation of all spaces during system operation. In the stations, ventilation is provided by the climate control ventilation systems. The ventilation in the tunnels is provided by the piston effect of the trains during revenue service and by a combination of smoke exhaust and UPE fans at stations during nonrevenue hours. These methods of ventilation provide more air flow than the 60 fpm mandated by Cal-OSHA for tunnel construction. The air velocity criterion ensures good dilution and conveyance of the infiltrating gases. However, with low infiltration rates, the resulting gas concentrations require sensitive instruments for gas detection and measurement.

(7) Development of the Gas Monitoring Subsytem

Although the design of the Metro Rail System includes state-of-the-art provisions to prevent incidents such as gas infiltrations, the possibility of a leak has been a design consideration since the Preliminary Engineering Phase. Initial activities included reviewing the types of gas monitoring systems used in the mining industry, particularly coal mining, where much of the gas monitoring technology was developed. The local sensor equipment used in the mining industry was not readily adaptable for extensive gas monitoring on a rail transit subway project. The local sensors are devices that are located within the area to be monitored and that depend on gas diffusion in air or on ventilation to transport the gases to the sensor for detection. This design would have required that hundreds of these devices be located throughout the system. This would add to the cost and complexity of the SCADA subsystem and CCF equipment, as well as the gas monitoring subsystem. In addition, the sensitivity of the local sensors (1,000 ppm) means that only relatively large leaks would be detected. For example, a methane leak would have to flow into a tunnel section at a rate of 21 cfm or more to be detected by local sensors if an airflow of 100 fpm was maintained in the tunnel (tunnel cross-sectional area is approximately 210 ft). These complications were compounded by the substantial maintenance requirements of the local gas sensors, indicated by information on failure rates and calibration requirements. The combination of tunnel length and the need to perform much of the sensor maintenance in the tunnel during the daily 4-hour period of nonrevenue service would add significantly to the number of maintenance technicians needed.

Discussions with engineers familiar with practices in heavy industry revealed that significant advances have been made in industrial grade central analyzer gas monitoring equipment and systems. Federal and state requirements to monitor for stack emissions and toxic fumes, as well as the demands for better process control, have necessitated the advances. Particular advances involve types of service provided, sensitivities available, and reliability and availability of automatic controls. The sensitivity of the central analyzer equipment to be used means that, with the same 100 fpm airflow as previously considered for the local sensors, gas infiltration at a rate of 0.021 cfm (versus 21 cfm for local sensors) is within the sensitivity range of the analyzer. This 0.021 cfm corresponds to about half of the gas flow rate of a typical outdoor decorative gas light.

The central analyzer type of gas monitoring equipment consists of gas analysis instruments at a centralized location with sampling probes (tubes) extending from the instruments to the locations to be monitored. Air samples will be extracted from the exhaust ventilation shafts and tunnel segments throughout the Metro Rail system for measurement of gas concentration levels. Air samples are drawn through sample probes to a vacuum pump, from the pump to a selector valve, and from the valve to either the atmosphere or to the gas measurement instruments. Then the sample leaving the instruments is exhausted to the atmosphere. Whether a sample is exhausted to the atmosphere immediately or goes to the measuring instruments prior to being exhausted is dependent on the position of the sample stream selector valve. The selector valve switches the tube supplying the air sample to the measuring instruments after a preset time interval. In this manner, a sample from one tube at a time is routed to the gas measurement instruments. While one tube supplies the sample being analyzed, samples are continuously drawn through the remaining tubes. This sample stream switching operation continues in a cyclical manner, performing analyses of each sample once per cycle, and allows each central analyzer to monitor the gas levels at multiple vent-shaft locations. The continuous sample draw on all tubes ensures that a fresh sample, which is representative of current conditions, is delivered to the instruments.

Each central analyzer will have two gas measuring instruments, one for methane and the other for hydrogen sulfide. Additional instruments may be added if other gases are encountered during construction. The methane measuring instrument will be an infrared analyzer having a minimum sensitivity limit of 1.0 ppm. The hydrogen sulfide measuring instrument will probably be an ultraviolet, pulsed fluorescent analyzer having a minimum detection limit of 0.002 ppm, although other equipment is being investigated.

Each gas measuring instrument within a central analyzer has two adjustable set points for annunciation of elevated gas levels. The first is called the warning set point, and the second, the alarm set point. The set point for the warning annunciation will probably be established during the construction phase, or shortly thereafter because on-site gas measurements are needed. Data regarding ambient levels of methane and hyrodgen sulfide will be evaluated as construction progresses. Once the normal range for a structure is determined, the warning set point can be established. For example, area as "gassy." The hydrogen sulfide value is the threshold of odor. More consideration will be given to the effects of dilution, tunnel length, point-of-source concentration versus detected concentration, and other aspects before the alarm set point is established.

Gas concentrations exceeding a set point will be annunciated at the CCF, which is manned 24 hours per day.

The performance of the central analyzer equipment will be monitored constantly. The equipment is furnished with self-diagnostic capability and will report trouble conditions to the CCF.

Calibration of the measuring instruments is performed daily to ensure accurate gas level readings and proper system operation. Calibration is an automatic feature of the equipment and does not require the participation of personnel.

if ambient methane in a tunnel segment is found to have a normal range from 5 to 10 ppm while being ventilated, the warning set point might be established at 20 ppm to allow for fluctuations in atmospheric (outdoor) methane levels and in the ventilation system.

A warning level annunciation will advise the CCF that an unusual influx of methane or hydrogen sulfide has occurred. Procedures for CCF reaction to the annunciation are to be prepared. It is anticipated that the procedures will include the use of portable gas detector units to locate the area/point of infiltration so that corrective measures can be taken.

Criteria for alarm level set points have not yet been established. For discussion purposes, concentrations of 2,500 ppm for methane and 0.025 ppm for hydrogen sulfide have been mentioned. The methane value corresponds to 0.25% in air, the level at which Cal-OSHA classifies an

Power for each central analyzer is 48 Vdc from the communications system. This power supply has a battery backup that is floating on-line so that changeover is instantaneous if there is a power failure in the main supply.

Each central analyzer has a micro-processor-based control unit to control functions, ensure warning/alarm integrity, perform diagnostic checks, and communicate with the CCF through SCADA. The microprocessor allows control of some central analyzer functions from the CCF.

A study comparing the two monitoring methods - local vs. centralized - recommended that industrial grade central analyzer technology be applied. Based on this study, a centralized gas monitoring subsystem has been developed for Metro Rail. This gas monitoring subsystem design is based upon equipment and systems developed for continuous operation in some of the most difficult of industrial conditions, e.g., carbon monoxide monitoring inside dust collectors of coal-fired processes (for explosion prevention). Other users of central analyzer gas monitoring equipment include environmental agencies (atmospheric and emission monitoring), chemical industries (process control), factories and powerplants (stack gas emission monitoring), and petroleum and other industries (toxic gas monitoring).

(8) Central Control Facility

Each central analyzer automatically communicates to the CCF the following:

- Methane measurement of each sample
- Hydrogen sulfide measurement of each sample
- Warning annunciation
- Alarm annunciation
- Trouble annunciation

As previously mentioned, some central analyzer functions can be controlled from the CCF. Each central analyzer will respond to CCF requests for:

- Selection of next sample to be analyzed
- Calibration of methane gas measuring equipment
- Calibration of hydrogen sulfide gas measuring equipment

Equipment in the CCF will perform the following function:

- Record all gas measurements on a 24-hour active memory
- Record the highest gas measurement of sample line, each day, on a 30-day memory
- Record the 30-day memory data on microfilm
- Make a hard copy of all warning, alarm, and trouble annunciations
- Provide a CRT display of each warning/alarm and trouble annunciation

B. Selection of Tunnel Liners

The selection of tunnel liners for the Metro Rail Project includes consideration of a number of factors. The presence of gas was one major factor in selecting liners and membranes. Other factors include, for example, construction at depths of approximately 100 ft in the tar sands and construction across potentially active fault zones. Conceptual and preliminary design studies considered a number of possible lining gas-proofing schemes, but the selection was narrowed to fabricated steel segments and an alternative of CIP concrete with hydrocarbon-resistant membrane or precast concrete segments with a hydrocarbon-resistant coating. These linings are discussed further in the following paragraphs.

1. Fabricated Steel Segments

The lining most impervious to gas flow is fully welded steel. Cost estimates, however, indicated that a fully welded and grouted steel lining would cost at least twice that of any other acceptable alternative. However, a lining of fabricated steel segments is required in some areas for construction considerations and for crossing fault zones. Such fabricated linings are impervious to gas except at the joints. Because of the quality control possible during fabrication and installation, and especially because of the machining of the joints, the seal on steel will be better than that in the concrete segments. A conservative estimate of the water flow rate through the joints is to apply the average rate given in the "Guidelines for Tunnel Lining Design" for cast-iron linings (0.015 gal/ft^2/day). For calculation purposes, this value was rounded to 0.02 although it is likely that good caulking techniques will significantly reduce the inflow rate.

2. Precast Concrete Segments

Where fabricated steel is not required, contractors will have the option of using precast concrete or CIP concrete lining. A standard design of precast concrete segments has been developed for the Metro Rail Project ("Design Documentation Structural Requirements for Concrete Tunnel Liners," Hansmire, 1985). These segments are 4 ft wide, 8 in. thick, and have an inside diameter of 17 ft 10 in. The concrete specified for precast segments will have admixtures and a low water/cement ratio to increase density and reduce permeability. The outside of these segments adjacent to the ground will be coated with 60 mil of a liquid-applied, hydrocarbon-resistant coating to virtually eliminate flow through cracks and by diffusion.

Tests have indicated that this coating eliminates approximately 99% of the gas flow through the concrete. However, to allow for some imperfections in the coating and an occasional "ding" during construction, an efficiency factor of 90% has been applied to the coating on the completed segments.

3. Cast-In-Place Concrete Lining

An alternative lining design has also been prepared should the contractor elect to use reinforced, CIP concrete ("Design Documentation Structural Requirements for Concrete Tunnel Liners," Hansmire, 1985). For this alternative, it is envisioned that the contractor will use steel ribs and wood lagging as initial support with the CIP final lining placed later. Between the initial support and final lining will be sandwiched a hydrocarbon-resistant membrane of high density polyethelene (HDPE). The CIP concrete specifications provide for admixtures and a low water/cement ratio in the concrete. Both of these provisions provide a denser, less permeable concrete.

With a CIP lining, there are no joints but there will still be diffusion and flow through cracks. MRTC reviewed available literature and practice and found: (1) no inflow data for transit tunnels with this type of construction, and (2) a difference of opinion among knowledgeable engineers about the severity of cracking of CIP compared to precast linings. It is believed reasonable to assume that the gas flow through CIP segments would be approximately equal to that through the precast segments. As with the precast concrete segments, it is estimated that the hydrocarbon-resistant membrane eliminates 90% of the flow by diffusion and through cracks.

C. Membranes

1. Products Considered

After initial screening, 14 products were submitted to Matrecon, Inc., for permeability, abrasion, and chemical resistance. The details of those product samples are shown on Table IV-5.

2. Laboratory Tests

a) Permeability

The barrier materials were tested in accordance with ASTM D1434, Gas Transmission Rate of Plastic Film and Sheeting, Procedure V, with the exception that duplicate specimens of each sample were tested. The tests were conducted at a nominal temperature of 23°C and at a nominal pressure differential of 50 psi. This pressure was found necessary to obtain enough flow through the products to obtain usable data. Complete details of these tests are found in Matrecon's report "Methane Transmission Rate Through Various Barrier Materials for Tunnel Construction" January 17,

Table IV-5 Inventory of Samples

Application Method	Supplier	No.	Trade Name	Amount	General Description
Prefabricated membranes	Schelgel Lining Technology	1	HDPE	2 rolls of 135 ft^2 each	100-mil high density polyetheylene.
	Cooley, Inc.	2	CPE	1 roll of 150 ft^2	37-mil reinforced chlorinated polyethylene.
	Grace Construction Products	3	Bituthene GRM-120	1 roll of 200 ft^2	58-mil[a] soft deformable membrane, one side adhesive other side a nonadhesive film. Tested bonded to primed filter paper.
		4	Bituthene BIT-300	1 roll of 180 ft^2	72 Mil[a], remaining description as above.
		5	Bituthene Primer P-3100	5 gal	Liquid primer to be used with Bituthene membranes.
	Burke Industries	6	LLDPE	2 rolls of 80" x 10'	30-mil polyolefin.
	Huber and Suhner (Sample received from Plymembranes, Inc.)	7	PVC	1 roll of 6 1/2' x 13'	80-mil PVC laminate backed with nonwoven fiber geotextile.
Field applied coatings; spray brush, etc.	Pentagon Plastics	8	Soladex	1 gal	1-component solvent based liquid containing Hypalon (CSPE). Tested as a 7-mil single layer supported on filter paper.
		9	Flexcrete ST	8 kg	2-component curable system, epoxy.
	Fox Industries	10	Hydroester FX-498	2 gas	2-component curable system, system, epoxy. Tested as a 25-mil single layer.
	Ameron, Inc.	11	Americoat 330	5 gal	2-component curable system, coal-tar epoxy resin. Tested as a 45-mil double-layer supported on filter paper.
		12	Amerthane 480	6 sheets, 4' x 4'	2-component system, cures to form elastomeric polyurethane. Can be built to desired thickness. Tested as received, a 45-mil layer.
	Keel Corporation (Sample received from IPA Systems, Inc.)	13	Farbertite	5 gal	1-component aqueous system; an emulsion containing coal-tar, mineral filler, and rust inhibitor. Tested as a 40-mil double-layer supported on filter paper.
	Fulbright and Rodrigues Systems, Inc. (Sample received from Liquid Boot, Inc.)	14	Liquid Boot	3 ft^2	2-component polymer modified asphalt. Soft and deformable. Can be fabric reinforced. Tested as received a 100-mil layer.
	Silikal North American, Inc.	15	....	2 sheets, 2' x 2'	Fiberglass reinforced methyl methacrylate laminate. Tested as received, 60-mil layer.

[a]Thickness includes release sheet.

1985. Results of the Matrecon tests on permeability characteristics are summarized in Table IV-6.

Pending the outcome of abrasion and chemical resistance tests, products in Table IV-6 with a gas transmission rate of two digits or more are eliminated.

b) Chemical Resistance

The following material is quoted from "Swelling in Hexane of Various Barrier Materials for Tunnel Construction," Matrecon, Inc. February 28, 1985:

"Fourteen barrier materials prospects were submitted for testing. Six were prefabricated membranes supplied in roll or sheet form, and the remainder were liquid coating materials intended to be applied in the field by spray or brush. The samples cover a range of compositions including polymeric sheets, asphaltic sheetings, laminates, one-component liquids and two-component curable liquids. An inventory of the test samples with suppliers and descriptions is given in Table IV-5.

Table IV-6 Calculated Methane Transmission Rate Through
A 60-mil Barrier at a 7.5 psi Pressure Differential

Type of Barrier	Sample ID	Gas Transmission Rate (GTR)[b], mL(STP)·day^{-1}·m^{-2} Best Estimate	Precision
Prefabricated membranes	Schlegel HDPE	5.7	±1.7
	Cooley CPE	2.5	±1.2
	Bituthene GRM-120	6.2	±3.3
	Bithuthene BIT-300	100	±10
	Burke LLDPE	27	±2
	Huber PVC	290	±80
Field applied coatings; spray, brush, etc.	Soladex	8.6	±0.8
	Flexcrete ST	11	±1
	Hydroester FX-498	0.78	±0.31
	Amercoat 330	12	±1
	Amerthane 480	6.1	±0.8
	Farbertite	3.9	±1.6
	Liquid boot[b]	≤4.1	±0.8
	Silikal	5.1	±1.3

aThe values are calculated assuming:
1) that the GTR is directly proportional to the pressure differential and
2) that the GTR is inversely proportional to the specimen thickness. The "Best estimate" is the average of four values; the "Precision" is the standard deviation of the four values.

[b]The GTR is reported the "Best estimate" of two determinations. "Precision" is the range of the values.

The swelling of each sample in hexane was determined in accordance with ASTM D471. Out of the thirteen samples tested, eight showed a net gain in weight (swelling) and the remaining five a net loss. The material showing the least swelling throughout the test period was Hydroester FX-492. This sample underwent a weight gain in the range of 0.35%-0.37% over the two-week period, but had not reached its equilibrium swell at the end of the test. The final weight gains of the remaining seven swollen samples ranged between 1% and 8%.

Five of the test samples showed a net weight loss at the end of the test. The extreme cases were the two Bituthene materials which (with the exception of a thin protective layer) were totally soluble. Two additional materials, although not showing net losses in weight, did show a trend toward further weight loss as exposure continued.

The test data are given in Table IV-7. The numbers in the "Comment" column attempt to objectively evaluate the effect of hexane immersion on the test specimens. Samples designated "4" or "5" which indicate the immersed specimens either softened and fragmented or completely dissolved, respectively, are unacceptable and should not be considered further. The materials designated "3" are questionable as they contain extractable constituents. There is also some concern regarding those materials designated "2" which continue to increase in weight."

Pending evaluation of abrasion tests, it is MRTC's evaluation that all materials with comment level 3 or greater in Table IV-7 should be eliminated from further consideration.

c) Abrasion Resistance

The following material is quoted from "Durability of Various Barrier Materials for Tunnel Construction," Matrecon, Inc., June 6, 1985:

Table IV-7 Weight Percent Swell of Barrier Materials on Exposure to Hexane

		Weight, % Swell Following Exposure for[a]					
Type of Barrier	Sample I.D.	1-day	2 days	7 days	14 days	21 days	Comment[b]
Prefabricated Membranes	Schlegel, HDPE	2.1-2.3	3.5-3.7	5.1-5.2	5.1	...	1
	Cooley, CPE	8.9-9.2	9.5-9.7	8.4-8.6	7.5-7.8	7.5-7.9	3
	Bituthene, GRM-120	32-73	(100)[c]	(100)[c]	(100)[c]	...	5
	Bituthene, BIT-3000	(29)-73	(100)[c]	(100)[c]	(100)[c]	...	5
	Burke, LLDPE	6.3-6.4	6.2-6.5	6.2-6.3	6.4-6.5	...	1
	Huber, PVC	Not Tested					
Field Applied Coating:	Soladex	5.3-5.7	5.1-5.7	5.1-5.2	5.0-5.2	...	1
	Flexcrete ST	3.8-3.9	4.1-4.2	4.3-4.4	4.2	...	1
	Hydroester FX-498	0.10-0.15	0.16-0.21	0.21-0.23	0.35-0.37	0.35-0.38	2
	Amercoat	(1.2)-(1.0)	(1.8)--(1.5)	(3.7)-(3.2)	(4.3)-(4.2)	(5.4)-(4.9)	3
	Amerthane 480	1.0-1.2	1.7-1.9	3.5-3.9	5.3-5.8	6.9-7.1	2
	Farbertite	(6.1)-(5.3)	(7.8)-(6.6)	(8.7)-(8.2)	(7.7)-(7.8)	...	4
	Liquid Boot	10.1-28.8	(1.6)-6.8	(5.0)-0.3	(8.2)-(3.5)	...	4
	Silikal	4.2-4.8	3.5-4.5	2.1-3.3	1.3-3.1	1.4-2.8	3

[a] The values reported are the range of the percent weight gains determined for triplicate specimens. Weight losses are indicated by parentheses ().

[b] 1 - The sample was at equilibrium within 2 weeks of exposure; the last two swell determinations did not differ significantly.

2 - The Sample had not yet reached equilibrium following 2 or 3 weeks of exposure.

3 - The sample and/or test liquid showed evidence of extraction of the sample. The weight percent of extract residue recovered from the Cooley, Americoat, and Silikan Materials at 14 days was 6%, 11%, and 12%, respectively.

4 - The sample showed evidence of significant softening and fragmentation.

5 - The sample was almost completely soluble in the test solvent.

[c] Both Bituthenes are multi-layer sheets. The topmost layers, thin protective films, did not dissolve but represent an insignificant portion of the sample mass.

"Nine of the original fourteen candidate barrier materials submitted by the supplier were subjected to testing. Three were prefabricated membranes supplied in roll or sheet form, and the remaining six were liquid coating materials intended to be applied in the field by spray or brush. The samples cover a range of compositions including polymeric sheetings, asphaltic sheetings, laminates, one-component liquids and two-component curable liquids. The nine chosen for durablilty testing are indicated in Table IV-8.

Five sets of durability related test data were collected and evaluated. The tests applied were chosen with the input and approval of MRTC, and admittedly did not duplicate exactly the conditions which would be encountered in a real construction environment. The tests were laboratory simulations of some of the destructive forces which are expected to occur within a tunnel construction environment, and their purpose was to provide information for the preliminary screening of a range of candidate barrier materials.

Table IV-8 Summary of Durability Test Scores

Application Method	Supplier	Individual Test Scores[a]: Sliding Friction Test	Gouge/ Scratch Test	19.0 cm Drop Impact test	Penetration, Crack Test	Average Score
Prefabricated Membranes	Schlegel HDPE	8	12	13	0	8
	Cooley CPE	58	100	54	100	78
	Burke LLDPE	0	24	100	100	56
Field Applied Coatings; Spray, Brush, etc.	Flexcrete ST	60	6	0	4	18
	Fox Hydroester FX-498	18	0	52	0	18
	Silikal	30	14	34	23	25
	Amerithane 480	23	7	57	100	47
	Americoat 330	30	62	85	100	69
	Soladex	100	66	56	100	81

[a]The individual test scores are scaled from 0, the least and best score, to 100, the greatest and worst.

The tests were:

(1) The sliding friction of an abrasive-coated sled moving across the samples at a fixed rate. The results of this test were expected to correlate with the damage the barrier layer would encounter during the concrete segment placement process. Placement requires pushing the segment through a steel shield which might be partially covered with sand or small gravel, subjecting the barrier coating to abrasion and friction.

In this context, the work correlate means that the order of the laboratory test results, from best of worst sample, will match the order of sample performance in the field. This does not mean that the degree of damage in the laboratory test will be the same as that encountered in a field environment.

(2) The width of the scratch caused by a point gouging the sample sample at a fixed rate. The results of this test

were also expected to correlate with barrier layer damage occurring during the placement process discussed in number 1.

(3) The penetration depths resulting from 19.0 cm and 27.2 drop impacts of a rounded point onto the barrier layer. This data was expected to correlate with the damage to the barrier layer which would result from impacts between segments, or between segments, rock, and construction equipment.

(4) A score based on the number of penetrations and cracks noted on microscopic observation of the drop impact craters. This was expected to correlate with damage from the construction impacts discussed in number 3.

Table IV-8 reports the experimental data for all tests on a scale from 0 (best value) to 100 (worst value). This table also reports the average score for each sample. For the flexible membrane samples, these values ranged from 8 for the Schlegel HDPE to 78 for the Cooley CPE; for the field applied coatings, values ranged from 18 for both the Flexicrete ST and Fox Hydroester FX-498, to 81 for the Soladex.

The single test which predicted the overall performance for the samples most reliably was that based on the number of microscopically observed cracks and penetrations. Samples surviving this test unpenetrated consistently performed reasonably well on the other tests. The Schelegel HDPE flexible membrane sample as well as the Flexcrete ST, Fox Hydroester FX-498, and Silikal field applied coating samples all performed well in the penetration/crack test and other test procedures."

It was decided that any product scoring below 20 on the average durability score would be considered to have successfully passed the durability test.

3. Membranes Selected

Based on the three sets of tests discussed above, it was concluded that the HDPE, Flexcrete ST, and Hydroester FX-498 would be acceptable barrier materials. Of these, the HDPE is a sheet and would be used with CIP concrete linings and the liquid-applied Flexcrete and FX-498 would be used with precast segments.

V. FINAL DESIGN

A. Tunnel

Structural design of the tunnel linings is documented in the MRTC reports "Tunnel Liner Rationale" (August 7, 1984) and "Structural Requirements for Concrete Tunnel Liners SCRTD - Metro Rail Project" (Hansmire, 1985). Final selection of a tunnel liner system must be based on structural, construction, and gas considerations, as summarized in the following paragraphs.

1. Design Assumptions

Estimates of potential gas inflow into the tunnels have been made based on the calculation methods outlined in Section III and the following assumptions:

a) Segmented Steel Liners

(1) Gas inflow at joints only.

(2) Gas inflow corresponding to specified water inflow of 0.02 $gal/ft^2/day$, or

twice the measured inflow through joints reported in "Guidelines for Tunnel Lining Design," adjusted to existing pressure conditions.

(3) Gas concentration of 100%.

(4) Gas pressure taken as the average groundwater (perched or true water table) pressure at tunnel springline.

(5) Tunnel length for each reach taken as centerline of station to centerline of station.

b) Precast Concrete

(1) Gas flow through concrete, cracks in concrete, and joints.

(2) Gas inflow corresponding to specified water inflow of 0.02 gal/ft^2/day.

(3) Gas concentration and pressure as above.

(4) Coating efficiency of 90% - applies to flow through concrete and cracks.

c) CIP Concrete

(1) Gas flow through concrete and cracks in concrete.

(2) Gas inflow corresponding to specified water inflow of 0.02 gal/ft^2/day.

(3) Gas concentration and pressure as above.

(4) Membrane efficiency of 90% - applied to all flow.

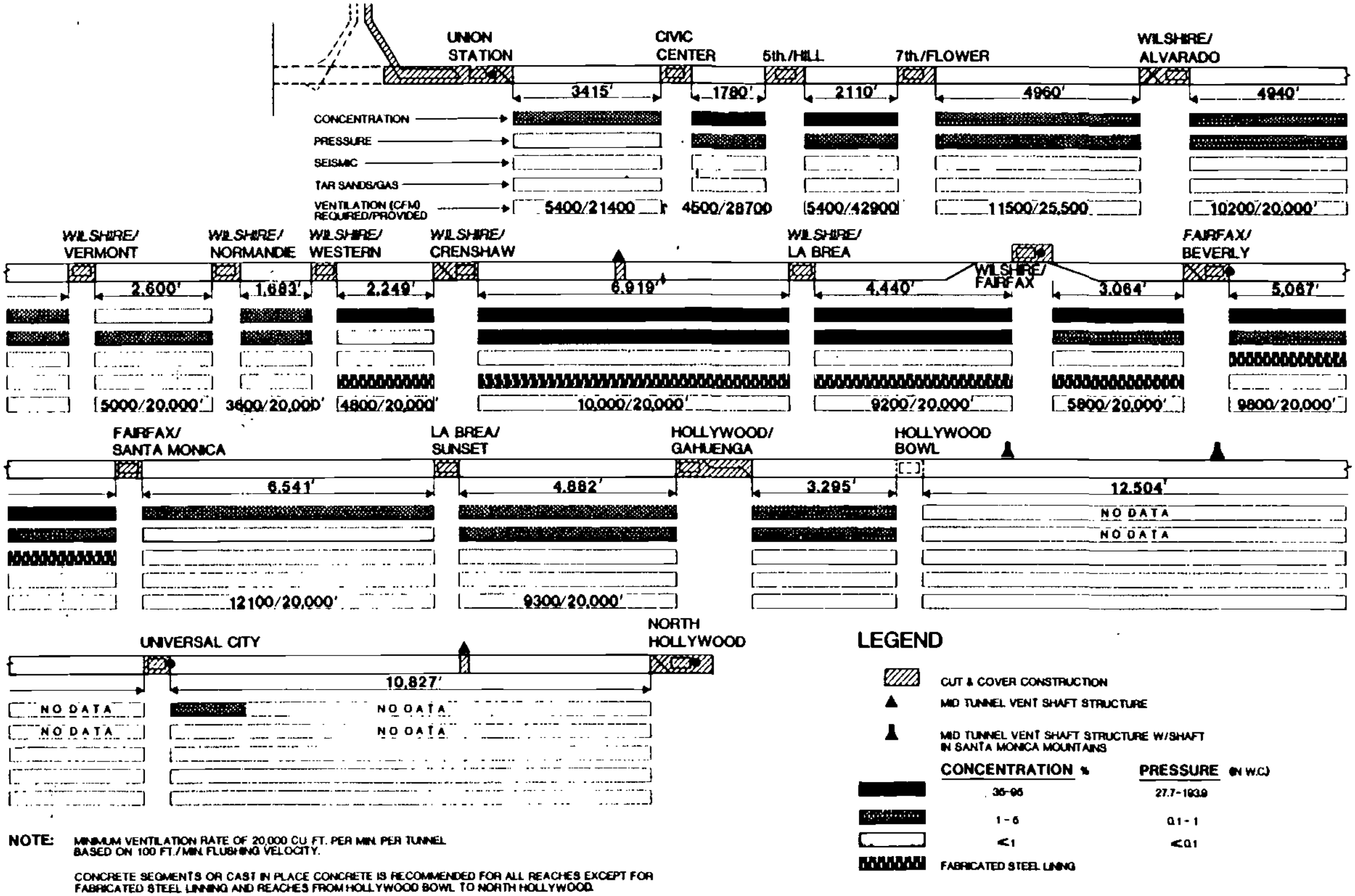
The tunnel lining designs for each reach of the project are summarized in Table V-1. The reasons for the design selected for each reach are summarized in the Discussion column. Figure V-1 shows the same information and it also shows, on the last line under each reach, a comparison of required versus provided ventilation.

The first of these numbers, the required ventilation, is that ventilation needed to dilute the gas inflow to 0.25% in air, or 1/20 of the

Table V-1 Summary of Tunnel Design

Tunnel Reach	Lining	Length	Avg. Water Head	Ventilation Required	Ventilation Provided	Discussion
Union Sta.-Civic Center	Concrete	3415 ft.	20 ft.	5420 CFM	21400 CFM	No special considerations.
Civic Center-5th/Hill	Concrete	1780 ft.	40 ft.	4460 CFM	28700 CFM	No special considerations.
5th/Hill-7th Flower	Concrete	2110 ft.	45 ft.	5430 CFM	42900 CFM	No special considerations.
7th/Flower-Wil./Alvarado	Concrete	4960 ft.	50 ft.	11460 CFM	25500 CFM	No special considerations.
Wil./Alvarado-Wil./Vermont	Concrete	3940 ft.	40 ft.	10180 CFM	20000 CFM	No special considerations.
Wil./Vermont-Wil./Normandie	Concrete	2600 ft.	30 ft.	5050 CFM	20000 CFM	No special considerations.
Wil./Normandie-Wil./Western	Concrete	1685 ft.	30 ft.	3590 CFM	20000 CFM	No special considerations.
Wil./Western-Wil./Crenshaw	Steel	2250 ft.	30 ft.	4820 CFM	20000 CFM	Clean sand with high water pressure i invert. Use steel for a daptability o construction.
Wil./Crenshaw-Wil./La Brea	Steel	6920 ft.	20 ft.	9980 CFM	20000 CFM	Highest measured pressure and concentra tion of gas.
Wil./La Brea-Wil./Fairfax	Steel	4440 ft.	40 ft.	9160 CFM	20000 CFM	Deep, over-under tunnel in tar sands Use steel for adaptability of construc tion.
Wil./Fairfax-Fairfax/Beverly	Steel	3065 ft.	25 ft.	5770 CFM	20000 CFM	Deep, over-under tunnel in tar sands Use steel for adaptability of construc tion.
Fairfax/Beverly-Fairfax/S. Monica	Steel	5065 ft.	35 ft.	9840 CFM	20000 CFM	Tunnel crosses Santa Monica Fault. Us steel for ductility.
Fairfax/S. Monica-La Brea/Sunset	Concrete	6540 ft.	35 ft.	12070 CFM	20000 CFM	No special considerations.
La Brea/Sunset-H.Wood/Cahuenga	Concrete	4880 ft.	30 ft.	9260 CFM	20000 CFM	No special considerations.

Figure V-1 Summary of Tunnel Design



LEL. For comparison, the second of these numbers (i.e., the ventilation provided)is for the amount of ventilation provided in the system for other reasons. It is important to note that provided ventilation is twice or more than required for all reaches of MOS-1. Thus, for those reaches, the dilution is to 1/40 or less of the lower explosive limit.

d) Conservatism in Flow Calculations

The flow calculations do not include consideration for the following factors, all of which tend to make the flows lower, i.e., make the calculations conservative:

(1) Fabricated Steel Segments

- o Quality joint sealants and caulking are specified.
- o Void space behind the lining will be grouted.
- o CIP invert and walkway will cover approximately one-quarter of the lining.

(2) Precast Concrete Segments

- Concrete is specified to have lower water content and high density to reduce cracking and permeability.
- Quality gasket material and caulking are specified.
- Void space behind the lining will be grouted.
- CIP invert and walkway will cover approximately one-quarter of the lining.
- Curing of segments in the yard and inspection before taking them to the tunnel will eliminate cracked or otherwise faulty segments.
- Surface hairline cracks probably do not propagate through the segments but, in any case, will be filled with the coating.

(3) Cast-in-Place Concrete

- Concrete is specified to have lower water content and high density to reduce cracking and permeability.
- Curing of concrete will minimize shrinkage and temperature cracking.

- o Surface hairline cracks probably do not propagate through the segments.
- o Contains only occasional construction joint.

2. Recommendations

Structural calculations show that any one of three tunnel lining schemes can be used for each tunnel reach; however, for other reasons, it has been judged prudent to use steel lining for some reaches and concrete for others. Those reasons include crossing of fault zone, construction deep in tar sands, and construction with clean sand under high water pressure in the tunnel invert.

B. Stations

Inflow may also occur into the system through the walls of the station and other structures, i.e., crossovers. These structures have a larger periphery (area) exposed to the ground, but thicker walls than the tunnels. The first factor increases potential flow, the second decreases it.

An approximate calculation has been made of the impact of these two factors on inflow into the system. The calculation indicates that inflow from the station can be approximated by adding a length to each tunnel equal to the station length. Thus, for calculation purposes, the length of the tunnel was taken as the centerline of station to centerline of station. Table V-1 includes this approximation.

C. Concrete

(1) Tightening - Experience in Baltimore has shown that bolt tightening, recaulking, patching, and grouting can significantly reduce leakage through precast concrete segments.

(2) Interior Membranes - Resins and epoxies can be investigated and tested to try to find products to use on the inside of tunnels to seal leaks.

(3) Steel Lining - A relatively thin steel lining can be installed and grouted into place inside the concrete tunnel lining (similar to the steel lining of a penstock) to provide a gas-proof lining.

(3) Add Sensors - Additional sensing points can be provided throughout the tunnels to better identify and isolate those areas where leaks are occurring so they can be fixed.

(4) Grouting and Injecting - Contact and area grouting can be conducted around the structures to reduce gas flow.

(5) Cast-Iron Segments - Cast-iron segments (not manufactured in the United States) could be used in lieu of concrete linings to reduce inflow. Such segments are apparently used successfully in England and elsewhere, but this cost and use in the United States are untried.

B. Steel Segments

(1) Tightening - Experience in Baltimore has shown that bolt tightening and recaulking can be performed on segmented linings to significantly reduce leakage.

(2) Welding - All joints can be welded tight to provide a gas-proof lining.

VII. ADDITIONAL ALTERNATIVES THAT COULD BE CONSIDERED

As discussed earlier in this report, a number of alternatives have been considered during the various stages of design of this project. This section will not consider all those alternatives in detail, but it will set forth the ones that might still be used to augment or modify the existing tunnel design. None of these alternatives are now believed necessary, but they could be further investigated and adopted if the need becomes apparent.

A. General

General design changes include some concepts that have been discussed earlier and are summarized as follows:

(1) Area Venting - Installation of vents or collection wells on a specified pattern throughout the affected area(s) could draw down the general level of gas.

(2) Ventilation - Augmenting ventilation can be accomplished by increasing the number or capacity of existing fans, converting emergency fans to continuous-duty tunnel ventilation fans, or providing additional mid-tunnel fans.

contingency plans, used as necessary and if necessary to ensure that a safe operating environment is provided for passengers and Metro Rail personnel.

The Operational Plan will also include areas of concern regarding:

- o Alert levels for each sensor position and each operating condition.
- o Responsibilities of various staff persons.
- o Reporting requirements - internal and external.
- o Equipment operating instructions.
- o Evaluation criteria.
- o Step-by-step instructions for source identifications.
- o Repair action procedures.

This Operational Plan is intended to be an evolutionary one, continously updated during construction and prerevenue operations, based on the actual gas environment and site-specific conditions.

F. Other Information

As an additional contingency, an Emergency Preparedness Plan is under development to clearly define all necessary measures to be taken in the event of a rare, but potential, gas intrusion into a localized area of the Metro Rail System. It should be understood that these operational plans are hour, and exhaust air will be continuously monitored for gas content.

D. Nonrevenue Operations

Nonrevenue operations normally occur during periods when the Metro Rail System is "closed" to passenger service (typically 4 hours per day, 1-5 a.m.). Station ventilation systems will be used during this period to provide sufficient air movement for gas sampling purposes and simultaneous dilution of gas, if present. As in the case of revenue operations, several additional ventilation systems are available for use, if needed.

E. Operating Plans

A Comprehensive Operational Plan is presently under development to provide instructions for:

- o Immediate actions for train movements, ventilation systems, patrons, employees, and operating equipment.
- o Ensuing action for source identifications and system repair actions, when required.

ventilation and gas detection procedures up to and including installation of Metro Rail's many ventilation and gas monitoring systems. Plans are presently being developed to provide continous monitoring during this period to ensure a safe environment for installation and testing.

C. Revenue Operations

Prior to the start of revenue operations (carrying passengers), all ventilation systems and the CCF, which provides the focal point of continous monitoring for the presence of gas, will be fully on-line.

Normal movement of trains (headways varying from 2-1/2 minutes during peak periods to 15 minutes during off-peak periods) provide substantial movement of air throughout the tunnels and stations. This "indirect ventilation" is a major resource for ensuring very low levels of gas, should gas be present. Additional ventilation capability, if needed, can be provided by actuating any of the available ventilation systems.

As previously stated, all station ancillary areas will be ventilated at a rate of 10 air changes per of trains in the tunnels (typically during revenue operations).

(2) Direct Ventilation - achieved by using the forced air action of numerous station and tunnel fans.

In addition, fans and vent systems are available throughout station's ancillary areas to ensure positive movement of air at all times.

Design considerations for the three operational periods are discussed below.

B. Prerevenue Operations

More specific information and data obtained during Stage I and II construction shall determine the degree of necessity for instituting the alternatives available during this interim period where the Metro Rail System is not completely ready for revenue operations, but is beyond the point of "rough construction." Typically, this is the period where the many system elements are installed and checked out and when integrated systemwide tests are performed. The available gas buildup safeguards range from extending the use of construction concentrations is the use of ventilation. The ventilation systems (part of the current Metro Rail design) are capable of ensuring a safe environment for passengers and personnel throughout the underground system. The ventilation systems perform two distinct, but complementary, objectives:

(1) A means of ensuring that excessive levels of gas are not attained. This is accomplished by diluting the gas, if present, to levels substantially below hazardous levels.

(2) A transfer mechanism for moving air to the sampling devices of the Metro Rail's gas monitoring system.

The gas monitoring system is designed to continuously provide early detection and annunciation of gas intrusion before a hazardous condition can develop, and to identify the magnitude and general location of the gas intrusion.

Two distinct categories of ventilation are available during Metro Rail operations:

(1) Indirect Ventilation - achieved by the movement

VI. DESIGN CONSIDERATIONS FOR OPERATIONS

A. General

This section addresses the activities, plans, and alternative measures that can be instituted during prerevenue, revenue, and nonrevenue operations to mitigate the intrusion of excessive levels of methane gas. For a clear understanding of these operational periods, the following definitions apply:

- Prerevenue Operations - The period of the Metro Rail system's life cycle commencing with the completion of Stage II construction and ending with the start of revenue service.
- Revenue Operations - The period commencing with the initiation of revenue passenger service and continuing throughout the Metro Rail system's operational life.
- Nonrevenue Operations - The period of each day of the system's operating life during which it is not open for passenger service, and the system is down for either preventive or corrective maintenance.

As in construction, the best means of preventing possible gas buildup from reaching excessive

APPENDIX A

ACRONYMS AND ABBREVIATIONS

API	American Petroleum Institute
ASTM	American Society for Testing Materials
Cal-OSHA	California Occupational Safety and Health Administration
CCF	Central Control Facility
CRWQB	California Regional Water Quality Board
cfd	cubic foot per day
cfh	cubic foot per hour
CIP	cast-in-place (concrete)
cm	centimeter
CRT	Cathode Ray Tube
CWDD	Converse Ward Davis Dixon
DIS	California Division of Industrial Safety
DOSH	California Division of Occupational Safety and Health
DWP	Los Angeles Department of Water and Power
EPA	Environmental Protection Agency
ES	Engineering-Science, Inc.
fpm	foot per minute
ft	foot
ft^2	square foot
gal	gallon
gpd	gallon per day
gpm	gallon per minute
HDPE	high density polyethylene
hp	horsepower
ID	inside diameter
in.	inch
LACFCD	Los Angeles County Flood Control District
LDPE	low density polyethylene
LEL	lower explosive limit
LFL	lower flammability limit
M	magnitude (on the Richter Scale)

MOS-1	Minimum Operable Segment One
MRTC	Metro Rail Transit Consultants
MSHA	Mine Safety and Health Administration
MWD	Metropolitan Water District of Southern California
OD	outside diameter
PBQD	Parsons Brinckerhoff Quade & Douglas, Inc.
PDCD	Parsons, Dillingham Construction, De Leuw
ppm	part per million
psf	pound per square foot
psi	pound per square inch
psig	pound per square inch (gauge)
PVC	polyvinyl chloride
SCADA	Supervisory Control and Data Acquisition
TBM	tunnel boring machine
TDS	total dissolved solids
TLU-TWA	threshold limit value - time-weighted average
UFL	upper flammability limit
UPE	under platform exhaust
USBR	U.S. Bureau of Reclamation

APPENDIX B

LIST OF STUDIES AND REPORTS AVAILABLE TO THE BOARD OF REVIEW

1. Geotechnical Investigation Report, Volumes 1 & 2, Converse Ward Davis Dixon, November 1981.

2. Geotechnical Engineering Report for Design Unit A-250, Converse Consultants, May 1984.

3. Geotechnical Engineering Report for Design Unit A-140, Converse Consultants, October 1983.

4. Methane Transmission Rates Through Various Barrier Materials for Tunnel Construction, Miedema and Haxo, January 17, 1985.

5. Durability of Various Barrier Materials for Tunnel Construction, Miedema and Haxo, June 6, 1985.

6. Swelling in Hexane of Various Barrier Materials for Tunnel Construction, Miedema and Haxo, February 28, 1985.

7. Report of Subsurface Gas Investigation, Engineering-Science, January 1984.

8. Report of Subsurface Gas Investigation, Engineering-Science, May 1985.

9. Title 8 Tunnel Safety Orders, Cal-OSHA, revised August 23, 1973.

10. Task Force Report on the Methane Gas Explosion and Fire, Department of Building and Safety of the City of Los Angeles, June 10, 1985.

11. Map locating oil wells, Division of Oil and Gas, Department of Conservation, State of California, January 5, 1985.

12. Construction Safety and Security Manual, PDCD, February, 1985.

13. Feasibility of Tunneling in Gassy Ground, R. J. Proctor, June 28, 1985.

14. Route Alignment Drawings, Contract A-250, Bechtel Civil & Minerals, Inc., April 8, 1985.

15. Route Alignment Drawings, Contract A-141, A-146, and A-147, DeLong Hampton & Associates, July 9, 1985.

16. Gas Monitoring System Review and Design Recommendations, MRTC, January, 1985.

17. Methane Control Program Theory of Operation (Draft).

18. Shield Driven Tunnels, Specification Section 02311, July 5, 1985.

19. Hydrocarbon-Resistant Membrane for Cast-In-Place Concrete, Specification Section 07101, June 10, 1985.

20. Hydrocarbon-Resistant Coating, Specification Section 07121, June 24, 1985.

21. Summary letter, Hammond to Crawley, June 25, 1985.

22. Tunnel liner rationale, letter, Hammond to Murray, August 7, 1985.

23. Environmental Control System (Draft), PBQD, July 1, 1985.

24. Abandoned oil well casings, letter, Proctor to Crawley, September 17, 1984.

25. Cal-OSHA classification of Metro Rail tunnels, letter, Larson to Monsees, December 18, 1984.