NATIONAL TRANSPORTATION SAFETY BOARD
Investigative Hearing
Washington Metropolitan Area Transit Authority Metrorail train 302 that encountered heavy smoke in the tunnel between the L'Enfant Plaza Station and the Potomac River Bridge on January 12, 2015

GROUP	H
EXHIBIT	
29	

Agency / Organization

Washington Metropolitan Area Transit Authority

Title

1988 Water Intrusion in Underground Structures Report

Docket ID: **DCA 15 FR 004**

U.S. Department
of Transportation
Urban Mass
Transportation
Administration

UMTA-DC-06-0374-88

WATER INTRUSION IN UNDERGROUND STRUCTURES

Washington Metropolitan Area
Transit Authority
Washington, D.C.

Mueser Rutledge
Consulting Engineers
New York, N.Y.

FINAL REPORT
OCT. 1988

UMTA Technical Assistance Program

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16. Abstract

This report summarizes an investigation of problems related to water intrusion in underground structures of the Washington Metropolitan Area Transit Authority. Design and construction of the system has been evolving continuously since 1966 and has included a number of innovative features as well as certain special problems related to control of leaking water. The assignment was to investigate four topics of water intrusion: (1) the build-up of hydrostatic pressures and measures for pressure relief; (2) waterproofing procedures in the Metro system and their effectiveness; (3) the special problem of calcification due to precipitation of carbonates in the drainage system of rock tunnels; and (4) special difficulties with the intrusion of acid water in Coastal Plain deposits. The assignment included contacting other rapid transit agencies to evaluate their methods of treating water intrusion. A field test of waterproofing compounds was performed at Dupont Circle and Rosslyn Stations to evaluate the possible effect of sealing of drains in those stations by calcareous precipitates. Studies of the effect of buildup of water pressures indicated little possibility of significant stress increase in the rock station structural lining. An on-going investigation of the effect of acid water intrusion disclosed the abatement of these problems by a natural process of groundwater flushing.

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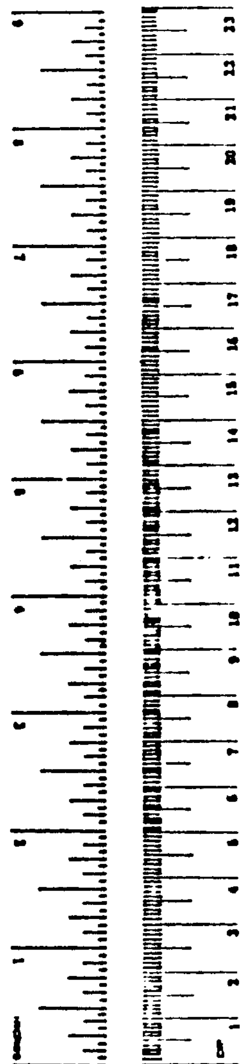
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
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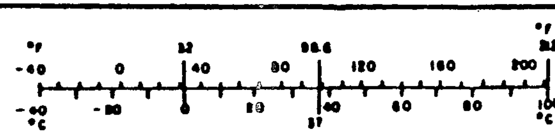
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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PREFACE

A study of water-related problems at the Washington Metropolitan Area Transit Authority (WMATA) under an Urban Mass Transportation Administration (UMTA) Technical Assistance grant (DC-06-0374) commenced in January 1983 with Mueser Rutledge Consulting Engineers (MRCE) as subcontractor. This study was given WMATA designation No. T17908 and constitutes Modification No. 1 to MRCE contract No. 3Z725U for general soil consulting services to WMATA for fiscal year 1982-3. It has been assigned the MRCE Job No. 5634 and that appears as the identification number on illustrations in this report. The work has continued in stages from January 1983 with active field work at intervals and submittals of summaries at various times. In a meeting of Feb. 9, 1984 which included UMTA project management, WMATA and MRCE representatives, the activities to that date were summarized. The study focused on water intrusion problems experienced by WMATA in certain portions of its system. Most of these problems are site-specific, specialized and local. Some portions of this study have wider implications to other rapid transit systems. A limited survey was also made of the experience of several other transit agencies. In this respect the study somewhat parallels other recent UMTA studies of seepage control in underground transit structures.

The active portion of the study was divided into four areas:

1. Water intrusion prevention;
2. Hydrostatic pressures and pressure relief;
3. Calcification, causes and effects;
4. Acid water, causes and effects.

These tasks utilized a number of specialist subconsultants plus a field test concerning calcification and hydrostatic pressure relief in two of WMATA's older rock stations. The purpose of the study was essentially problem solving, based on field observations and gathering of site information. While this study will by no means settle the general problems of subway leakage, certain specific difficulties encountered in the WMATA system are clarified and information of interest to other rapid transit properties has been obtained.

A number of WMATA staff members assisted MRCE in the investigation, a list too extensive to detail here. Mr. L.H. Heflin was Project Manager for WMATA. Those who were particularly helpful in the WMATA Department of Design, Construction and Facilities Maintenance include the following:

Office of Engineering and Architecture:

Larry H. Heflin, Design Manager/Senior Geotechnical Engineer.

Office of Construction:

Carl G. Bock, Senior Geologist/Geotechnical Engineer;
John Rudolf, Chief Civil/Structural Engineer.

Office of Facilities Maintenance:

Timothy L. Reed, Assistant Superintendent, Track and Structures.

Personnel of the General Engineering Consultant (GEC, DeLeuw Cather and Co.) who assisted include Messrs. Charles W. Daugherty, Engineering Geologist, and Mohammed Irshad, Chief Structural Engineer of the GEC subway project staff. Messrs Daugherty and Bock as active engineering geologists on the project over many years, were responsible for recognizing and elucidating certain of the water intrusion problems. Data collected and collated by them has been utilized extensively in the MRCE study.

Of particular assistance in providing information on their own experiences with tunnel leakage were Mr. Joseph P. Welsh of GKN Hayward Baker Co. and Mr. Henry A. Russell of Parsons, Brinckerhoff, Quade & Douglas, Inc.

Personnel of Mueser Rutledge Consulting Engineers (formerly Mueser Rutledge Johnston and DeSimone) who participated include:

James P. Gould, Partner-in-Charge;
Arthur M. Mayes, Resident Project Engineer;
Sergio L. Tello, Head of Office Engineering for Project;
Karl Westermann, Assistant Project Engineer;
Joseph Vigilante, Field Engineer.

The report is presented in two volumes. The first is the text with illustrations, followed by a list of references. This is intended to be complete and to stand alone. Detailed memoranda and reports by MRCE personnel relating to inspections and field operations are assembled in an Appendix volume intended for limited printing and distribution. Also included in that volume are the reports by subconsultants to MRCE.

CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Contract Provisions

This study was initiated by a WMATA proposal to UMTA, dated October 15, 1980. The proposed work was summarized as follows:

"A. PROJECT SUMMARY

This project will consist of a series of studies which will investigate and provide solutions to a number of structural problems occurring within Metro tunnels. These studies which are to be undertaken within this project are: Calcification Studies, Hydrostatic Pressure Relief Studies, Acid Water Studies and Water Leakage and Waterproofing Methods..."

"1. Calcification Studies

The original Metrorail tunnel design anticipated that groundwater pressures within the rail system would be reduced or nullified by allowing the groundwater to drain from behind the structural concrete into the tunnel drainage system and be pumped from the system. Subsequent to the construction of the tunnels various chemical reactions have allowed a precipitate of materials, referred to here as calcification, which severly reduces or totally prohibits the groundwater from flowing freely and results in pressure upon the structure.

This study anticipates an analysis of the clogging material and seeks to correlate its presence with those factors which may have occasioned its genesis in rock tunnel structures..."

"2. Hydrostatic Pressure Relief

Hydrostatic relief studies are the actual pressures now present and probable in the future on stations, structures, and running tunnels excavated in rock or rock like material. Such an effort would be two pronged. First, to see if our design for heavier structural loading because of the presence of groundwater is indeed called for in those areas where there is no hydrostatic pressure relief system and, secondly, to see if increased pressures are present in those areas where hydrostatic pressure relief system has failed; and, if present to what extent..."

"3. Acid Water Studies

An acid water study is needed to confirm that the Metro structures are not being attacked by water bearing acid as with the case on design Section G-2. In this area, acidic waters caused deterioration of steel ribs used as temporary supports as well as the metal flashing used for the forming of floating slabs. Subsequent investigations proved that the structure integrity of the liner was not damaged, the strength of the acid makes it imperative that the remainder of the system be investigated to ascertain if any other areas may be subject to possible structural weakening. This study will provide a basis for maintenance and any needed rehabilitation of the Metro system..."

"4. Water Leakage and Waterproofing Investigation

This section of the project will consist of an investigation of the causes of water leakage and waterproofing methods used to deal with and solve the problem of water intrusion. This study will include site visits to transit systems and other underground structures. This project will provide qualified Metro personnel familiar with Metrorail dewatering problems to investigate unfamiliar approaches to water control."

The practical significance of the water intrusion is to create the most costly, dangerous and annoying maintenance problem in the Metro system. The consequences include electrical arcing, shorting and malfunctions, icing, failure of steel track fastening and deterioration of neoprene rail pads and grout beds; clogging of drainage systems, fouling of pumps and impellers; and probably most significant, a safety hazard which has resulted in worker accidents. The earliest difficulties with leakage in cast-in-place concrete lining led to extensive and repeated grouting contracts for sealing leaks. More recently pre-cast, segmented, gasketed concrete lining stipulated in the detailed design has provided an economical method of controlling leakage. Leakage to underground rapid transit structures remains the chief problem in the operation of the system arising from the natural setting.

MRCE submitted a preliminary proposal for work as a subcontractor to WMATA on July 12, 1982 and a modified final proposal on October 22, 1982 which was accepted by WMATA on December 8, 1982 with active work commencing in January 1983. The technical work under the program was assigned to Modification No. 1 of MRCE Services Contract 3Z725U. A number of subconsultants and subcontractors were retained by MRCE as listed in Table No. 1. WMATA representatives participated in field trips to certain other transit systems in connection with water intrusion studies. WMATA staff accompanied many MRCE inspections to various parts of the Metro system, expedited access, oversaw safety arrangements and provided background information on construction conditions, remedial programs and experiences with water intrusion.

Generally this study has been concerned with water problems in rock tunnels and rock stations except for the acid water problem which occurred within Coastal Plain sediments. However, as water problems and construction experiences have evolved over the five years occupied by the study, the investigation has become more wide ranging. Because the control of water intrusion and hydrostatic excess pressures are general in nature, this report has been organized to cover these topics in Chapters 2 and 3, followed by treatment of the specific problems of calcification and acid water, Chapters 4 and 5.

1.2 Methods Employed in This Study

Essentially five different investigative procedures were employed in the various aspects of this study:

1. Search and study of background data, case histories and technical literature;

2. Field inspection trips and staff interviews both for WMATA sections and other transit systems;

3. Field tests and field data gathering and sampling, chiefly for the studies of acid water intrusion and calcification;

4. Laboratory testing of samples of groundwater, soil, precipitates, rock and concrete;

5. Data analysis, reduction and synthesis leading to this summary report.

The examination of background was focused chiefly on information collected by WMATA, Bechtel Associates, Inc. (the then General Construction Consultant) and DeLeuw Cather and Co. (then and now General Engineering Consultant (GEC)) for the WMATA system. Field inspection of WMATA facilities were confined chiefly to 1983 and 1984 and were carried out principally by MRCE engineer K. Westermann at WMATA and in New York City, and by J.P. Gould at London Transport. Field testing was performed by a group of subconsultants and subcontractors and was generally done under the direct inspection of Messrs. A.M. Mayes and K. Westermann. Data analyses were performed chiefly in MRCE offices in New York City, generally by S.L. Tello and K. Westermann.

The technical consultants and subcontractors assisted in or performed portions of the field tests, laboratory tests and data analyses. Table No. 1 summarizes the functions carried out by the subcontractors, whether professional or technical, and indicates the section of this report in which their work is described. They are listed in Table No. 1 simply in alphabetical order without making a distinction of type of organization or type of work.

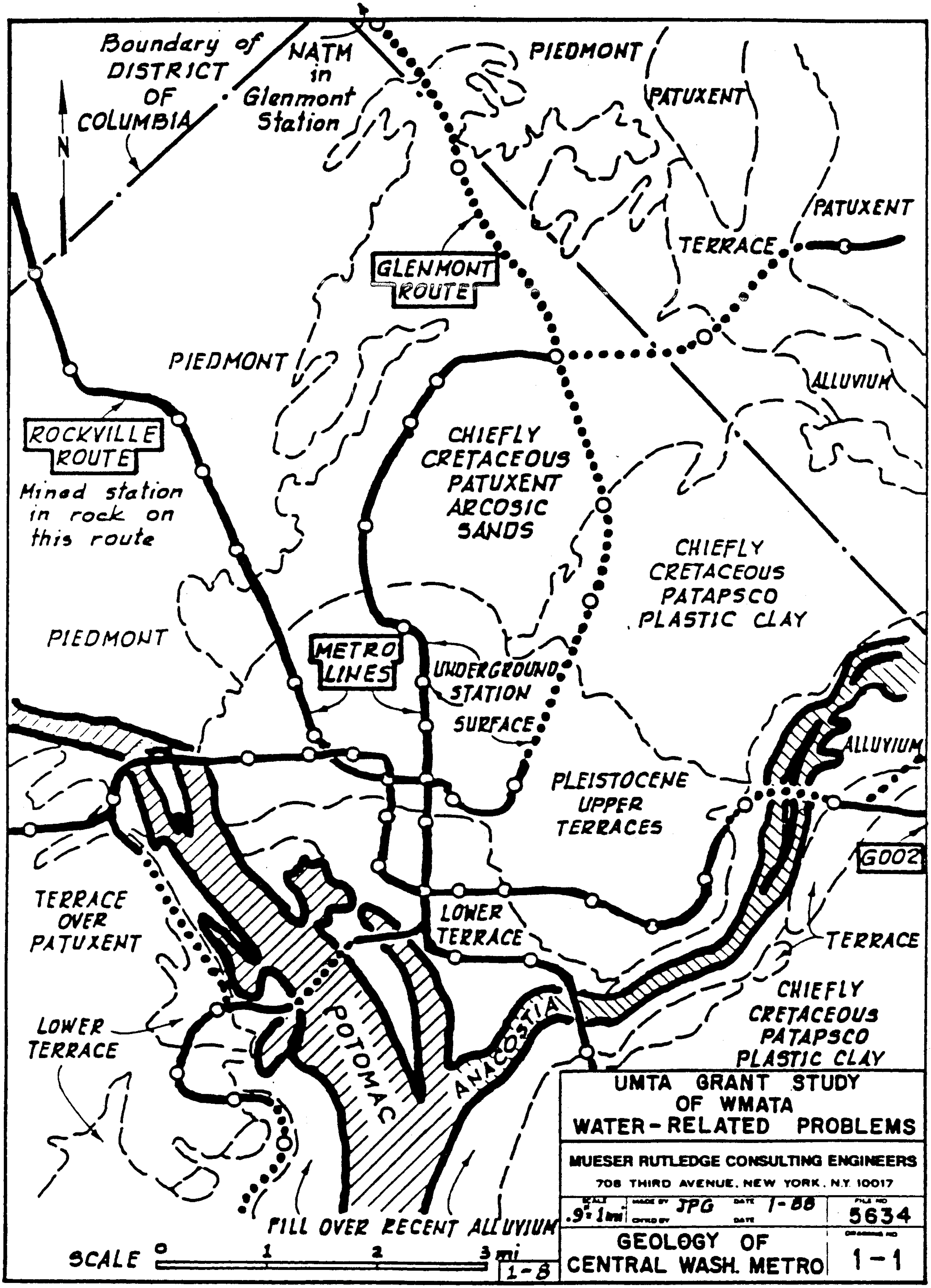
1.3 Geological Setting

The Washington Metro system is located in an especially interesting geological setting, about evenly divided by the "fall line." This separates the Piedmont province in the west and northwest consisting of relatively shallow crystalline bedrock from the Coastal Plain province of deep near-shore sediments on the south and east. Bedrock is a "metasediment" upgraded to schist and gneiss from the original clayey and sandy deposits by heat, pressure and igneous intrusion. Its sedimentary origin is manifested by extensive calcite filling in the rock joints, a greater proportion in the ordinary country rock than in the rock more altered by igneous intrusion. The Coastal Plain sediments consist of compact and heavily over-consolidated sands and clays of Cretaceous age dipping southeast. Because of the deltaic, lagoonal and back swamp origin of these deposits, numerous horizons contain carbonized organic material with associated pyrites. Among these pyrites are a finely crystalline form called "marcasite" which has high specific surface area. These two contrasting geological settings have created the two distinctive problems with underground water: solution and reprecipitation of calcium carbonate in the rock tunnels of the Piedmont and instances of acid water intruding tunnels in the Coastal Plain sediments.

The general geologic setting is shown in the simplified map of Drawing No. 1-1 which distinguishes major divisions of geologic materials below surface fill or residual soil with the lines of the principal underground sections of the central subway system. Attention was focused originally in this study on tunnels in bedrock since these involved certain structures which rely on drainage to eliminate exterior hydrostatic pressures. These have experienced difficulties with calcification as well as unwanted and unexpected water intrusion. The ordinary problems of waterproofing tunnels or cut-and-cover stations in soil were not part of the original study plan. However, as the studies evolved it became apparent that experiences with general water intrusion contained useful lessons for those specific problems that were the focus of the investigation.

TABLE NO. 1, SUBCONSULTANTS AND SUBCONTRACTORS

SUBCONSULTANT OR SUBCONTRACTOR	SCOPE OF SERVICES	REFERENCED IN THIS REPORT
WMATA Division of Maintenance	Cored concrete lining in G002 installed valves in these cored holes. Assisted in inspections G002 and Rockville Route.	Chap. 4, field tests and Chap. 5 G002 acid water.
Engineering Science, Inc. (Testing Laboratory)	Performed chemical tests of water samples from G002 and from Rockville Route Station leakage.	Chap. 4, field tests and Chap. 5 G002 acid water. Report in Appendix.
Technical Grouting Services Inc. (Grouting and Waterproofing Contractor)	Subcontractor for field test for brush-on capillary penetrating waterproofing compounds and water pressure build-up behind lining of two stations mined in rock.	Chap. 4, field tests of waterproofing compounds
Goldberg-Zoino & Assoc. (Geotechnical Consultants)	Designed, supplied and directed installation of instruments for measurement of water pressures outside of shotcrete lining and stresses in lining surface.	Chap. 4, field tests at DuPont and Rosslyn. Details in Appendix
DeLeuw Cather and Company (Project General Engineering Consultant)	Provided background data on acid water inflow and calcification. Analyzed effect of water pressures on stresses on rock station supports. Studied mechanism of calcite precipitation (by R.S. DeSanto).	Chap. 4, forms of calcite precipitation Two reports in Appendix.
W.B. White (Consultant in Geochemistry)	Sampled calcite and inflowing seepage and tested them for chemical constituents.	Chap. 4, character of inflowing water. Report in Appendix.
Division Two (Dewatering & Well Drilling Contractor)	Rehabilitated pumping wells previously installed in Section G002 and water sampling from these wells.	Chap. 5, G002 acid water study.
Warren George, Inc. (Test Boring Contractor)	Designed and supplied valves for water sampling and water pressure measurement in cored holes through concrete tunnel lining.	Chap. 5, G002 acid water study. Valve details in text.
Erlin, Hime Associates (Concrete-Cement Technology)	Performed petrographic study and chemical analysis of acid effects on cores of concrete lining taken at acid water seepage in Section G002.	Chap. 5, acid water study. Report in Appendix.
London Transport International	Provided data on London Transport experience with tunnel leakage and prevention of inflow.	Chapter 6



Boundary of DISTRICT OF COLUMBIA
NATM in Glenmont Station
PIEDMONT
PATUXENT
PATUXENT
TERRACE
GLENMONT ROUTE
N
PIEDMONT
ALLUVIUM
ROCKVILLE ROUTE
Mined station in rock on this route
CHIEFLY CRETACEOUS PATUXENT ARCOSIC SANDS
CHIEFLY CRETACEOUS PATAPSCO PLASTIC CLAY
PIEDMONT
METRO LINES
UNDERGROUND STATION
SURFACE
PLEISTOCENE UPPER TERRACES
ALLUVIUM
G002
TERRACE OVER PATUXENT
LOWER TERRACE
TERRACE
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LOWER TERRACE
POTOMAC
ANACOSTIA
FILL OVER RECENT ALLUVIUM
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MADE BY JPG
DATE 1-88
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DATE
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GEOLOGY OF CENTRAL WASH. METRO
DRAWING NO 1-1

CHAPTER 2: WATER INTRUSION PREVENTION

2.1 Significance of Water Intrusion in Transit Tunnels

"Guidelines for Tunnel Lining Design" (Reference 2-1), Page 39, "Influence of Water", contains an excellent review of the problems of leakage and waterproofing, portions of which are paraphrased herein. Infiltration to transit structures can interfere with electrical functions, create hazards for workers and patrons and unsightly conditions in public areas, and eventually cause deterioration of structural elements. Until the advent of the New Austrian Tunneling Method (NATM), it was not generally practical to build a truly "impervious" tunnel. Most transit tunnels operate with tolerable quantities of inflow that must be collected and removed.

The effects of tunnel leakage on the surrounding ground and adjacent facilities will depend on local geology and hydrology. Even moderate leakage can cause unacceptable exterior drawdown where compressible, normally-consolidated, fine grained soils are nearby. Leakage can accelerate solution of soluble sediments, those containing calcareous constituents or gypsum. Where fine sand or silt, such as New York City post-glacial lake deposits, surround the tunnel leakage can lead to piping of soil particles causing loss of ground and eventual settlement at the surface and of tunnel elements. Fortunately, in Washington, D.C., soils of significant compressibility are only rarely encountered within the radius of influence of the subway acting as a drain. Nor are there instances of damage to well water supplies or of subsoils highly vulnerable to piping. Infiltration problems associated with the Washington Metro System include the formation of calcareous precipitates in drainage systems of rock tunnels and the production of acid water within certain Cretaceous soils. These two special conditions are the subjects of Chapters 4 and 5 of this report.

2.2 General Experience With Tunnel Leakage

To assess the performance of various tunnel lining and waterproofing systems, data on allowable and actual leakage experienced have been summarized in Drawing No. 2-1 and detailed in Table No. 2. An instructive summary of case histories is presented in Reference 2-1, Appendix C, "Measured and Specified Tunnel Infiltration Rates." Experiences are summarized therein for a number of tunnels on land and subaqueous, used for a variety of purposes. The majority of cases are for segmented cast iron or concrete linings. The unit utilized to express the intensity of water infiltration is gallons per square feet of tunnel interior surface area per day. However, a more graphic measure of transit tunnel infiltration is used on Drawing No. 2-1 by converting to gallons per minute per 1000 lineal feet of single running tunnel, applicable to transit tunnels with an average inside diameter of 16 to 19 feet.

For transit tunnels, the infiltration permitted by specifications is usually stated in terms of leakage per 100 or 200 lineal feet of single tunnel. Typically, this allowable value is equal to about 0.1 gpm per 100 lineal feet, or, on the horizontal scale of Drawing No. 2-1, approximately 1 gpm per 1000 lineal feet of tunnel. Leakage given per 1000 lineal feet tends to average out exceptional local inflow created by individual large leaks.

There is overall similarity in the watertightness of particular lining types. For example, the Baltimore experience with segmented, gasketed concrete or cast-iron linings is similar to that of London Transport. In both cases the leakage averages out below the specified limit of 1 gpm per 1000 lineal feet after general contact grouting and local remedial grouting of heavy individual leaks. The two earliest sections of precast concrete liner on the Washington Metro have had similar low leakage rates. The least favorable experiences have been in all systems with cast-in-place concrete linings. Several of these systems show a worst case local leakage of more than 1 gpm of flow per lineal foot which averages out over a long section of tunnel to values of 200 to 500 gpm per 1000 feet.

The intensity of leakage in a transit tunnel is the result of various factors interacting: permeability of the surrounding ground, effective permeability of the lining, and basic groundwater conditions such as total head and effectiveness of recharge. This relationship is illustrated schematically in the upper panel of Drawing No. 2-2 and it is considered in more detail in Chapter 3 which concerns the magnitude of hydrostatic pressures acting on the exterior of the lining.

2.3 Factors Influencing Tunnel Lining Permeability

The effective permeability of the tunnel lining depends on its secondary permeability which depends in turn on the character of joints in segmented liner or of cracks in cast-in-place concrete. Segmented metal liner received its earliest applications in London subways which also pioneered precast concrete segments for transit tunnels. Favorable mining conditions in London clay and its low permeability led to their wide use of precast concrete which provided a high degree of watertightness. While segmented, bolted cast-iron liners have long been favored in the United States, the use of segmented concrete for subways was initiated under an UMTA demonstration grant in Baltimore Metro in 1978 (Reference 2-2). Since that application, the method has found increasing use, including two recently-completed WMATA tunnels. The experience in these systems and the range of cases given in Appendix C of Reference 2-1 indicate that average inflow over 1000 lineal feet can be kept well below 1 gpm after larger individual leaks are sealed by grouting or caulking.

Leakage experience with cast-in-place concrete in many systems has ranged from barely acceptable to highly unsatisfactory. It should be recognized that placing concrete for tunnel liner is inherently difficult, requiring long pumping lines with fluid mixes, difficult joint arrangements, reinforcing which impedes placement, high tunnel air temperatures on curing and fluctuations of interior temperatures during use plus the perturbing effect of train vibrations. Drawing No. 2-1 and Table No. 2 record the results of one of the more spectacular recent experiences with leakage of cast-in-place concrete lining on the Buffalo light rail system (Reference 2-3). This was an unusual case where porous limestone supplied unlimited recharge outside concrete liner of uncertain quality. Leakage which locally had reached as much as 250 gpm in 300 lineal feet was reduced by carefully engineered grouting to less than 1 gpm per 1000 lineal feet at the most troublesome locations.

2.4 Cracking of Concrete Lining

Obtaining quality concrete in cast-in-place tunnel lining is complex compared to above-ground concreting. Concrete slump at the mixing plant must be chosen to meet a four or five-inch slump commonly specified at placement. This can be achieved by including additives such as super-plasticizers and flyash. The slump at mixing must take into account the distance and mode of transportation, concrete behavior under high-pressure pumping and the constrictions behind the forms created by the initial tunnel support. The maximum size of aggregate should be reduced for lining having dense reinforcement and closely spaced initial supports. Concrete lining expands during curing due to the heat of hydration. Subsequent cooling causes contraction and longitudinal cracking totalling roughly one half inch in a 100 foot length. Subsequent lineal changes due to external temperature variation is additive. The distribution of cracks in the cast, unreinforced lining depends in part on the roughness of the surface against which the concrete is placed. At one extreme, a smooth circular opening cut by a tunnel boring machine in rock will facilitate slip of the concrete and will integrate many potential small cracks into fewer larger cracks. The inevitable cracking of cast concrete lining reduces the effectiveness of waterstops at formed joints in controlling leakage. Longitudinal reinforcement does not greatly alter the total contraction but it tends to distribute it in numerous smaller cracks. The inclusion of flyash as a partial cement replacement tends to reduce the amount of cracking by reducing the heat of hydration while at the same time it enhances the pumpability of concrete.

The natural advance of the poured lining creates a slope at its leading face. A sloping construction joint on this face is acceptable and may be preferable to formed vertical joints if properly cleaned and consolidated. It should be recognized that no joint control measures eliminate the difficulty with cracking under tunnel placing conditions. An interesting study was undertaken of unreinforced cast linings for Detroit sewer tunnels, reported in Reference 2-4. The marked influence was observed of the build-up of heat in the tunnel due to rapid placement of successive lengths of concrete lining. Despite the necessary ventilation measures, continued rapid placement can build up and sustain an air temperature in the tunnel above 90°F. This increases total contraction when the tunnel concrete returns to normal ambient temperatures.

There are two basic components in concrete cracking: one relates to both drying and curing shrinkage, which is influenced by the water-cement ratio of the mix; the other is thermal contraction responding to changes in the ambient air temperature. It has been suggested that a continuously maintained humid atmosphere will restore much of the contraction due to drying shrinkage, just as increasing ambient temperature will cause thermal cracks to close. However it should be recognized that cracks once having opened will not precisely reseal. The effects of both drying shrinkage and thermal shrinkage are accentuated in an atmosphere such as Washington, D.C., where high temperatures and high humidity occur in summer and low temperatures with dry air in the winter. This characteristic seasonal change aggravates cracking in tunnel sections near open portals.

Drawing No. 2-3 illustrates the general influences on cracking of cast-in-place concrete expressed as total width of circumferential cracks occurring in a 100-foot length of tunnel.

The lower diagram from standard texts illustrates the drying or curing shrinkage versus cement and water content. For a good quality mix producing a 28-day compressive strength of 4500psi, drying shrinkage is about 3/8 inch in 100 feet. The upper diagram of Drawing No. 2-3 shows the variation in total crack widths of this tunnel concrete in Washington from dry winter conditions to humid summer conditions. The use of light reinforcing has little influence compared to seasonal temperature changes. Contraction in winter is double the magnitude of the original curing shrinkage. Expansion in summer reduces it by half. The influence of crack width and spacing on permeability of cast concrete is treated in Chapter 3 in analyzing the effect of tunnel leakage and drainage on external hydrostatic pressures.

2.5 General Waterproofing Methods

A useful summary of measures for permanent infiltration control in tunnels is presented in Table 6.2 of "Guidelines for Tunnel Lining Design" (Reference 2-1). There are five categories of methods: drainage, grouting, waterstops and gaskets, sealants, and impervious membranes. However, the measure for infiltration control is attention to the basic quality of cast-in-place concrete. Recent UMTA-sponsored research has reviewed waterproofing methods at great length. One of these studies by Paul Parks and Associates (Reference 2-3) concerns experiences with leakage and leakage control in five major eastern transit systems, Atlanta, Boston, Buffalo, New York and Washington.

Particularly instructive case histories are the treatment of major infiltration in the Niagara Frontier Transit Authority of Buffalo and for the Lenox Avenue line in New York City. The latter is covered in some detail in an independent review by MRCE in Chapter 6 of this report. This report will not summarize the broad subject of infiltration control, but rather will focus on the experiences gained from WMATA cases and from data gathered specifically for this study.

The two most important WMATA developments have been the advent of segmented concrete liner and the New Austrian Tunnel Method (NATM). Waterproofing methods considered in this chapter include crystallizing capillary coatings, grouting for crack sealing and utilization of waterproof membranes. For practical reasons, brush-on coatings are more frequently used on the negative side, that is, on the interior surface of the tunnel final lining. Membranes are more frequently used on the positive side, that is, the exterior surface of the final lining.

2.5.1 Crystallizing Capillary Compounds A variety of products have been developed which can be categorized as brush-on, negative side, intergral surface coatings with penetrating characteristics (Reference 2-5). They are compounded with Portland cement, fine quartz or silica sand, organic or inorganic sodium and/or calcium salts and/or stearates. There are two alternative concepts of the function of these penetrating coatings. When seeping water interacts with the sodium silicate it forms a crystal on the concrete surface. By osmosis, the sodium silicate lodges in pores of inner concrete surfaces, thus filling pores and reducing permeability. When leakage becomes active, crystal growth is sustained and fine cracks supposedly are sealed. Alternatively, it may be that the brush-on compound applied on a concrete surface coming into contact with moisture and unhydrated lime forms insoluble fiber crystals. The fibers are formed in voids and capillary tracts of the concrete. Whatever the mechanism, these compounds are receiving widespread use as a simple and inexpensive means of waterproofing by brushing on the interior surface of concrete basements and underground structures. A useful summary is given by Anderson in Reference 2-5 which includes his evaluation of the supposed advantages and the deficiencies. Examples of successful use by WMATA are presented in Reference 2-6. Five of these compounds were utilized in the field test of water pressures and waterproofing in two WMATA rock stations, described in Chapter 4.

A difficulty with all "cementatious" coatings is their incompatibility with the basic concrete shrinkage. As explained in Section 2.3, concrete shrinkage from summer to winter may involve a linear strain of one unit in 2,500; while cementatious compounds exhibit linear strains of one in 100 to one in 500. In general, it appears that when shrinkage of the concrete liner continues because of wide seasonal temperature variations, the surface coating of crystallizing penetrating compound will also crack. Continuing train vibrations create another disturbing influence on healing of shrinkage cracks in transit tunnels. As a rough indication, where the situation is unfavorable enough to produce cracks greater than about 0.02 to 0.03 inches, the brush-on compound will eventually crack at the same location. However, experience in the Atlanta subway (Reference 2-7) indicates that crystallizing penetrating compounds can substantially reduce the total water seepage through concrete whether it is intact or contains fine cracks. Its use has satisfactorily decreased humidity in ancillary rooms held at relatively constant temperature which are also free of train vibrations.

2.5.2 Grouting for Crack Sealing A detailed summary of grouting methods for correcting water intrusion in transit tunnels was presented by Baker in Reference 2-3. WMATA procedures for crack sealing observed in this study at Section A009 of Rockville route have utilized acrylate chemical grout. Instead of relying on injection to permeate directly within the crack itself, this was injected into holes drilled through the cracks to the outside of the cast concrete lining for the purpose of spreading an impervious coating on the exterior surface of badly cracked concrete. The procedure involves drilling successive holes through the section along the crack until the sealing is accomplished.

Water-reactive polyurethane gels have been used for crack sealing with success in the Atlanta and Boston systems. The usual method is to drill holes angled into the crack with the position and sequence of holes adjusted during the work as indicated by the pattern of grout take.

2.5.3 Membrane Waterproofing Systems Increasing awareness of leakage difficulties with cast-in-place concrete linings led to the use of membranes for positive side waterproofing of concrete final linings. The most recent development in the United States is the advent of the New Austrian Tunneling Method (NATM) which includes a drainage filter fabric or "fleece" placed outside a PVC waterproofing membrane, both secured to the initial lining and against which the final lining is poured. The fleece is a non-woven polypropylene about ¼ inch thick. The 60 mil PVC membrane is spliced by heat welding and attached by heating against plastic-headed nails driven through the fleece and into the initial shotcrete lining. The fleece facilitates drainage of exterior water and cushions the PVC membrane against damage. The lowest edge of the fleece encircles the embedded longitudinal drain at the base of the tunnel sidewall, as shown in Drawing No. 2-4. The longitudinal side drains feed laterals which connect through a junction box to the centrally placed invert drain. The junction box affords access to the system for inspection and clean-out.

This drainage feature is an important element of the NATM scheme, first utilized in Section B010 of Glenmont Route of Washington Metro. In the three years since completion of the first sections of the poured-in-place final lining, there has been no evidence whatsoever of leakage through the final tunnel lining. The contrast is striking between that section of Glenmont Route and the conventional cast concrete lining of adjacent Section B009.

A particularly helpful feature of the NATM system is the fact that the filter fabric and the waterproofing membrane can be extended continuously from tunnel or station up shafts, escalatorway or other penetrations. Thus the intersection of the penetrating structure with the underground tunnel is entirely shielded from surface infiltration. It is at the intersection of penetrating structures with the underground opening that the most troublesome leakage has occurred in WMATA rock tunnels.

In contrast, the Los Angeles subway (SCRTD) is utilizing a heat-welded, 100 mil thick, high-density polyethylene (HDPE) for an exterior waterproofing membrane. This is to be hydrocarbon-resistant since the tunnel will pass into gassy or petroleum-impregnated ground. The membrane is nailed to a smoothed surface on the initial lining of ribs and lagging. Drainage cannot be provided because of the anticipated presence of hydrocarbons in the ground. Therefore the final lining is designed to fully resist exterior fluid pressures.

A similar arrangement has been employed to waterproof WMATA cut-and-cover stations in soil. No drainage fleece has been provided in order to avoid exterior drawdown. The membrane wraps completely over the sides and top of the station concrete but terminates under the invert slab near its exterior edge. As construction has advanced, leaks have appeared in shrinkage and construction joints of the cast concrete lining. This illustrates the inherent problem of a stiff separate waterproofing membrane punctured at numerous locations for attachments or utility penetration, and thus vulnerable to the intrusion of water into the surface between the membrane and the final concrete lining. The very continuity and stiffness of the plastic membrane encourages a pattern of communicating spaces to develop on the back of the concrete which can spread water from any opportunistic leak to any available crack in the concrete, defeating the waterproofing function.

2.6 Leakage to WMATA Rock Stations

The WMATA Rockville Route from Dupont Circle to the encircling Beltway included eight stations excavated by tunneling in bedrock. These stations have experienced water intrusion accompanied by calcification in varying degrees, as discussed in Chapter 4. The stations' cross section includes a wide circular arc roof, typically 60 feet between supports and 45 feet high at the center of the arch, with vertical side walls and flat invert. Inside the final structural support was placed the architectural concrete arch forming the train room interior. The space between the structural support and the architectural lining is typically eight feet high at the crown and was utilized for ventilation, passage of utilities and for maintenance of waterproofing coatings on the exterior of the architectural concrete.

The wide, clear interior span offered aesthetic and operational advantages but involved special design and construction problems of grand scale. Surrounding rocks are metamorphosed sedimentaries of the Wissahickon formation which exhibited strong structural control, striking north paralleling the stations' axes and dipping steeply west. Dip slip shears, slickensides and thin gouge or mylonite occur along the foliation, controlling rock movements and loading. Excavation has required a variety of staging procedures with temporary support provided by rock bolts and initial shotcrete. The final structural lining consisted of successive layers of shotcrete on 14-inch, wide-flange ribs. A typical cross section of the main train room 600 feet in length is presented in Drawing No. 3-4.

Rock loads were represented by a symmetrical tent loading acting across the arch with lateral rock reaction modeled by springs resisting deformation of the structural lining. Hydrostatic pressures were not included. The symmetrical tent load was checked by applying discrete rock blocks moving in a direction controlled by the rock attitude at the station. Drainage was accomplished by small diameter weep holes, primarily inherited from those placed in the original tunneling to control the flow of water through the rock surface to be shotcreted. Shotcrete placed as lagging between the heavy ribs has cracked extensively in most of the stations, exhibiting reflection cracks along the edges of the interior flange of the rib.

As a consequence leaks have developed in many stations through the cracked shotcrete, producing extensive deposits of calcium carbonate at the point of exit of the leaking water. Drain lines have been clogged by calcium carbonate precipitates. The hazard of developing hydrostatic pressures on the exterior of the lining is discussed in Chapter 3. Leakage in five of the rock stations is described in the following text. The stations are the oldest of those constructed in rock, including Dupont Circle, Woodley Park, Van Ness, and Cleveland Stations of Rockville Route and Rosslyn Station of Huntington Route. They are shown in simplified plan and profile by Drawings Nos. 2-5 through 2-9.

2.6.1 Dupont Circle Station (Drawing No. 2-5). It is characterized by the least thickness of rock cover in this group of stations and by a series of prominent foliation shears striking nearly parallel to the station axis. Groundwater and the water-carrying utilities flow across the station from east to west. The water table is near the base of the underpass structure on Connecticut Avenue, lying 35 or 40 feet above the tunnel crown. Total leakage into the 600 foot length of station is of the order of 5 to 10 gpm. A prominent leak is concentrated at the northeast corner of the train room near the train room's vertical wall. Probably this leakage was promoted by the presence of the Q Street vent shaft at this corner plus two large sewers that cross along the line of Q Street. Extensive grouting was carried out behind this headwall which reduced this leakage to acceptable amounts.

2.6.2 Woodley Park-Zoo Station (Drawing No. 2-6). Rock is deeply weathered with extensive jointing and shearing. A chloritic shear zone was mapped striking north in the north half of the station and northwest in the south half and dipping steeply westward. Groundwater is about 80 feet above the tunnel crown. The most annoying leakage occurred at the intersection of the entrance escalatorway with the west side of the train room. A collection pool was installed to contain the substantial inflow and prevent it from intruding the train room. The upper portion of the entrance escalatorway was built in cut-and-cover excavation. It is likely that water obtained access along the upper surface of the escalatorway where rock was loosened in blasting. The mechanical room at the north end of the station has been the location of other leaks which were treated extensively by grouting. It is probable that these were fed by flow down the exterior of the north vent shaft.

2.6.3 Cleveland Park Station (Drawing No. 2-7). Cover rock consists of 40 to 55 feet of blocky, massive, hard and relatively sound diorite gneiss. Groundwater is 50 to 60 feet above the crown of the train room and descends at both ends of the station into relatively deep fills. The entrance on the north was placed in a deep cut-and-cover. Leakage into the station was concentrated just at the base of the sloping top of the escalatorway where it intersected the north end of the train room. Backfill of the cut-and-cover excavation provided a pervious communication downward. There is no indication that utilities aggravated the leakage except that there are two sewers and a water line placed centrally in Ordway Street which intersects the south corner of that former open excavation.

2.6.4 Van Ness Station (Drawing No. 2-8). Bedrock is quartz-diorite gneiss with 20 feet of rock above the station crown of moderately jointed, occasionally highly jointed, unweathered, hard, blocky gneiss with prominent foliation. Groundwater slopes from a high of about 55 feet above the tunnel crown to a low of 30 feet on the north. The north entrance structure was placed in cut-and-cover in a manner similar to Cleveland Park Station, also with leakage concentrated at the point where the slope of the entranceway intersected the north end of the station.

2.6.5 Rosslyn Station (Drawing No. 2-9). Bedrock is generally hornblende gneiss, more massive and with less evidence of shears than any of the other four stations. The distinctly favorable rock conditions permitted a broad opening to be made with a full face excavation in the upper part of the station. There is typically 45 or 50 feet of relatively sound rock cover over the entire station with groundwater close to the top of rock. The direction of groundwater flow is eastward, nearly at right angles to the station axis. The entranceway on the west was in cut-and-cover for the upper portion, then passing into a mined tunnel. A particularly annoying leak occurred precisely at the point where the entranceway structure joined the train room with a persistent leak directly over the path of entering patrons. Undoubtedly this was caused in a manner similar to the other station entrances by a direct path of flow from the backfill of the cut-and-cover excavation down the top of the sloping entranceway.

2.6.6 Conclusions on Leakage to Rock Stations These cases demonstrate that the most troublesome leakage to the stations mined in rock frequently is created by penetrations from the surface to the underground opening. Usually the most permeable zone below the water table is the jointed upper portion of the rock. A sloping, penetrating structure intersects the pervious horizon and transmits water downward where it is dammed by the station lining. Leakage occurs precisely at the least desirable location where the public passes from the escalatorway into the train room. Since such leaks cannot be tolerated, an intensive grouting or sealing effort has been necessary.

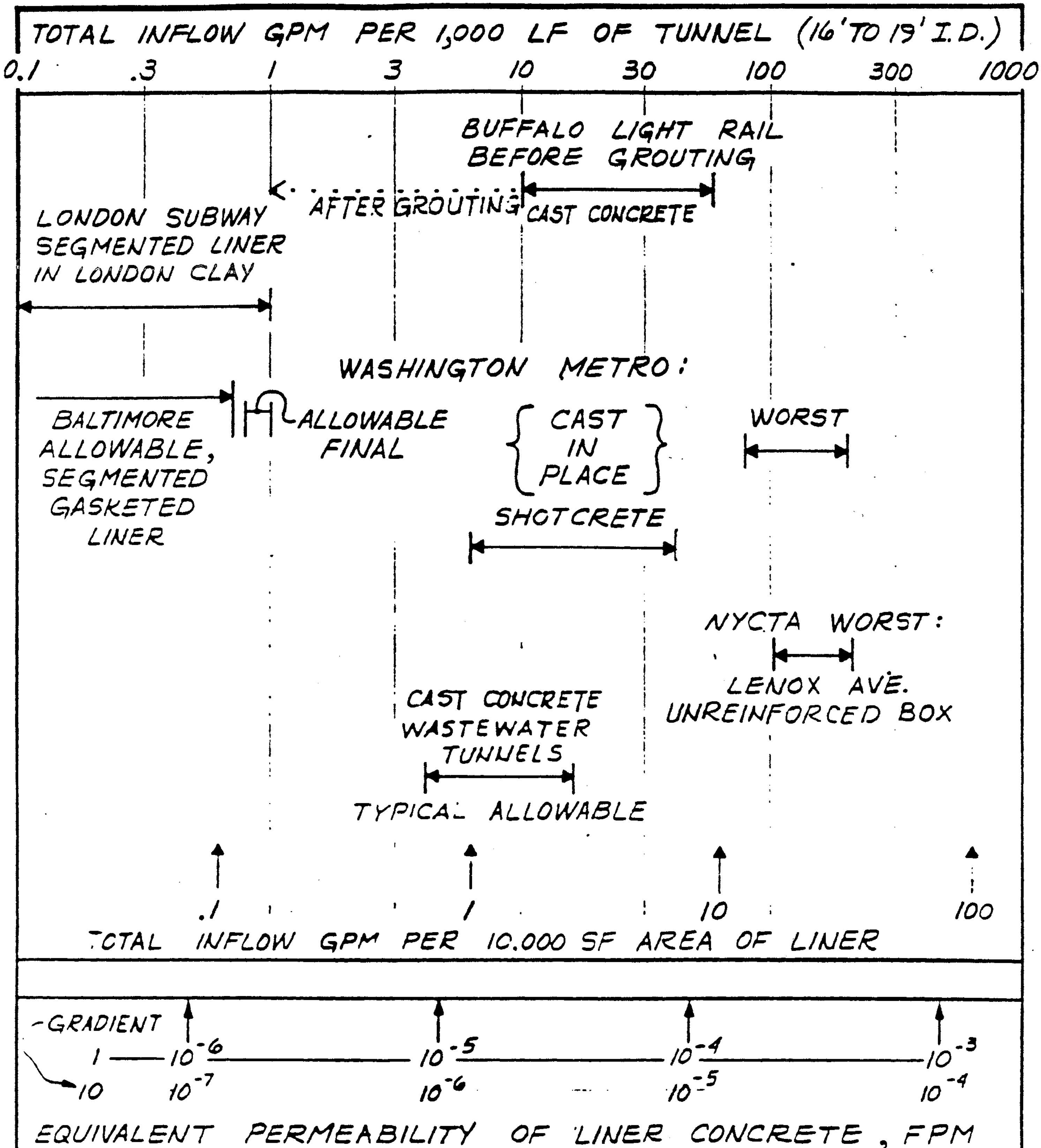
The NATM scheme provides a nearly ideal solution by continuing the drainage fleece and the waterproof membrane from the deep station structure up the escalator shaft. This guarantees that even if groundwater infiltrates from above it will merely pass along the drainage fleece into the track drains and not intrude the structure. At Wheaton Station of Glenmont Route the NATM waterproofing was applied in such a manner that it eliminated the need for the vault between the structural lining and the interior architectural concrete.

Before the NATM waterproofing procedure evolved, MRCE made recommendations for a cutoff collar for shafts which penetrated through weathered rock to a station in impervious rock at depth, as illustrated on Drawing No. 2-10. It consists of a concrete ring with grout holes and waterproofing membrane positioned near the top of relatively sound rock. Grouting would be done above the collar in more jointed rock with secondary grout holes extending laterally into better quality rock. The construction joint between the shaft concrete lining and the collar contains an elastomeric membrane plus waterstops at top and bottom of the collar. This scheme has not been implemented and would be redundant where the NATM waterproofing procedure is invoked. However, such a provision should be considered in a situation such as the Washington rock profile where a deep structure in essentially impervious rock is connected to a source of water by the presence of the penetrating shaft.

TABLE NO. 2, TUNNEL LEAKAGE CASE HISTORIES

SYSTEM	TYPE OF TUNNEL LINING	PERMISSIBLE LEAKAGE	LEAKAGE EXPERIENCE
Wash. D.C. Metro WMATA	Cast concrete and shot-crete on ribs	0.2gpm per 250lf or 0.1gpm in any 100lf	Worst condition found in shallow rock with extensive re-charge, max. about 100gpm/1000lf.
	Segmented pre-cast concrete		Appears to meet specification limitation in first two sections completed.
Baltimore Subway	Segmented pre-cast or metal liner	.07gpm per 100lf	Reported "as no measurable infiltration "in segmented gasketed liner. Extensive grouting of cast concrete required to meet specification limitation.
Buffalo Light Rail NFTA	Cast concrete	0.9gpm per 1000lf or .05gpm in any 30lf	Local maximum 250gpm in 300lf. Typically 10 to 60gpm per 1000lf. Reduced to specified limit by cement grout outside lining and by acrylamide grout in cracks in cast concrete.
London Transport	Segmented pre-cast concrete or metal liner	Not stipulated	Generally 0.1 to 1gpm per 1000lf. Metal liner used for modern sub-aqueous tunnels. Tunnels in London clay usually yield insignificant leakage.
Typical Waste-Water Tunnel	Typically cast-in-place concrete	4 to 12gpm per 1000lf	Exceptional cracking can occur when high internal water pressures deform the lining outward against yielding ground.

Note: For transit tunnels of approximate 18 feet inside diameter, divide the value of leakage as gpm per 1000 lineal feet by 40 to obtain approximate leakage in gallons per square foot of tunnel surface per day. Leakage in liters per square meter per day is approximately equal numerically to the value of leakage in gpm per 1000 lineal feet.



"GRADIENT" IS TAKEN AS THE RATIO OF HEAD ACTING ON THE EXTERIOR OF THE LINER CONCRETE TO THICKNESS OF THE LINER. SEE DWG. NO. 2-2

$$\text{GRADIENT} = \frac{\Delta h}{t}$$

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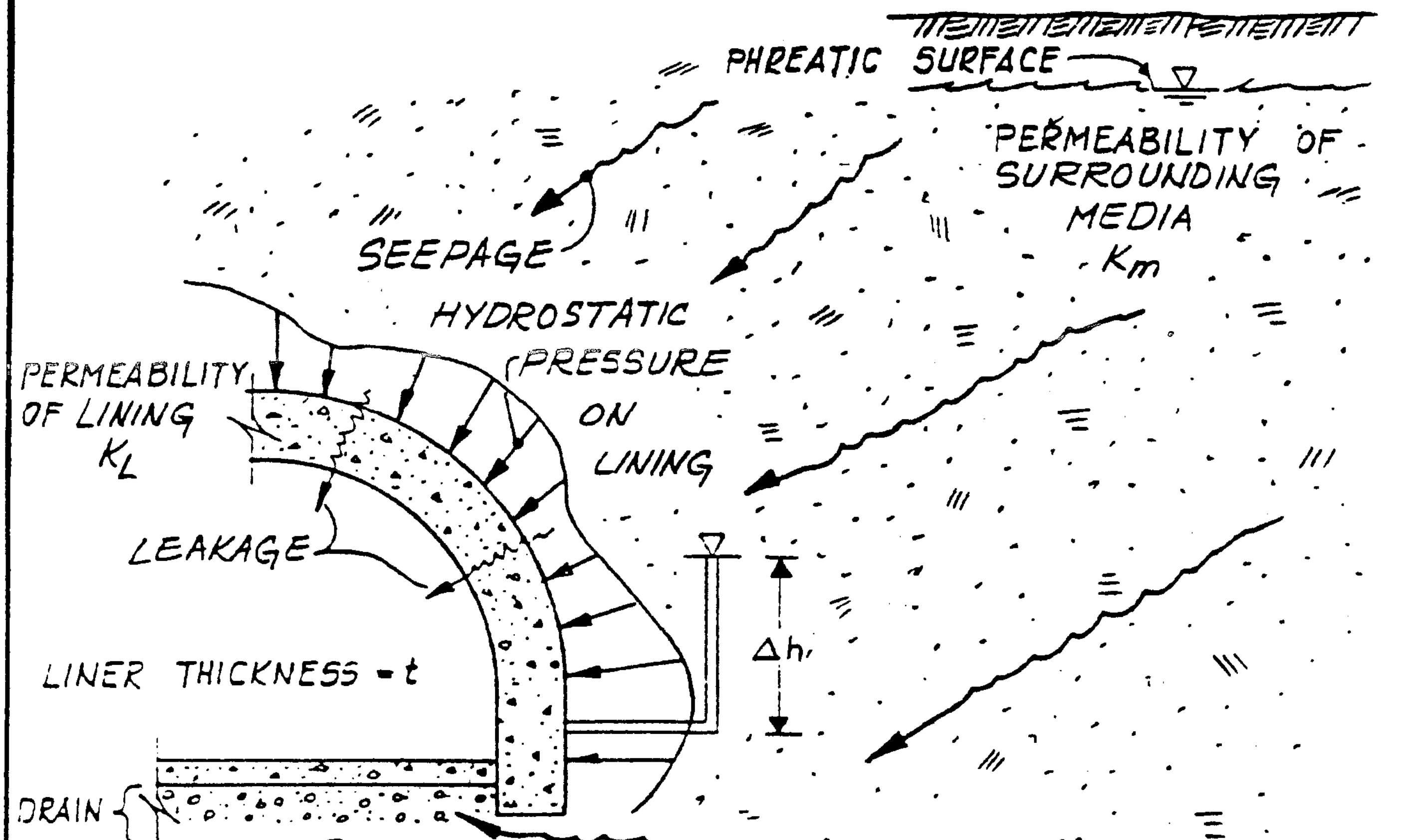
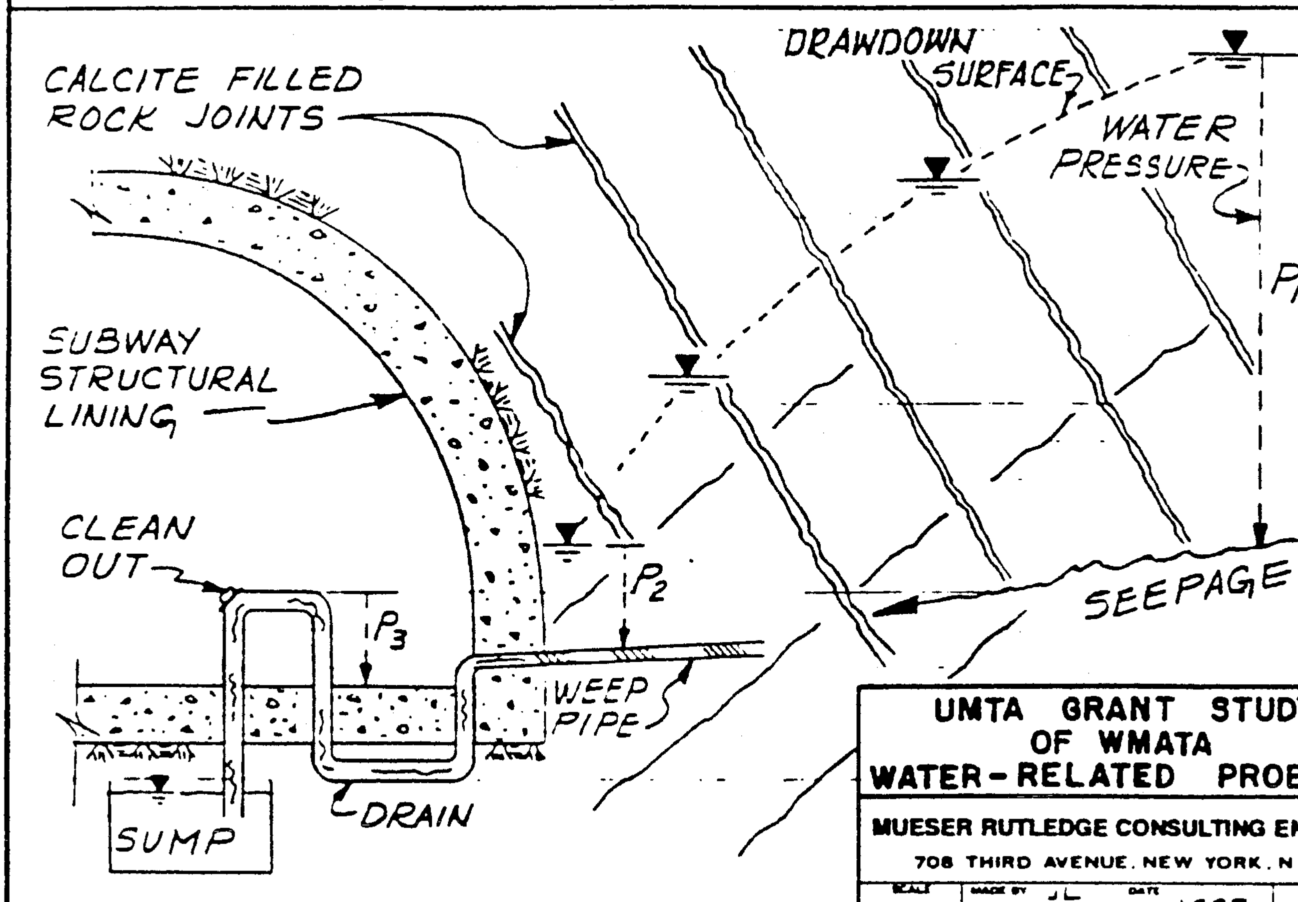
—	JL / CHKD BY JPG	1987	5634

EXPERIENCE OF TUNNEL LEAKAGE — DRAWING NO 2-1

RELATION OF PERMEABILITY, LEAKAGE AND PRESSURE



DRAINAGE OF TUNNELS IN SOIL



DRAINAGE OF STATIONS IN ROCK

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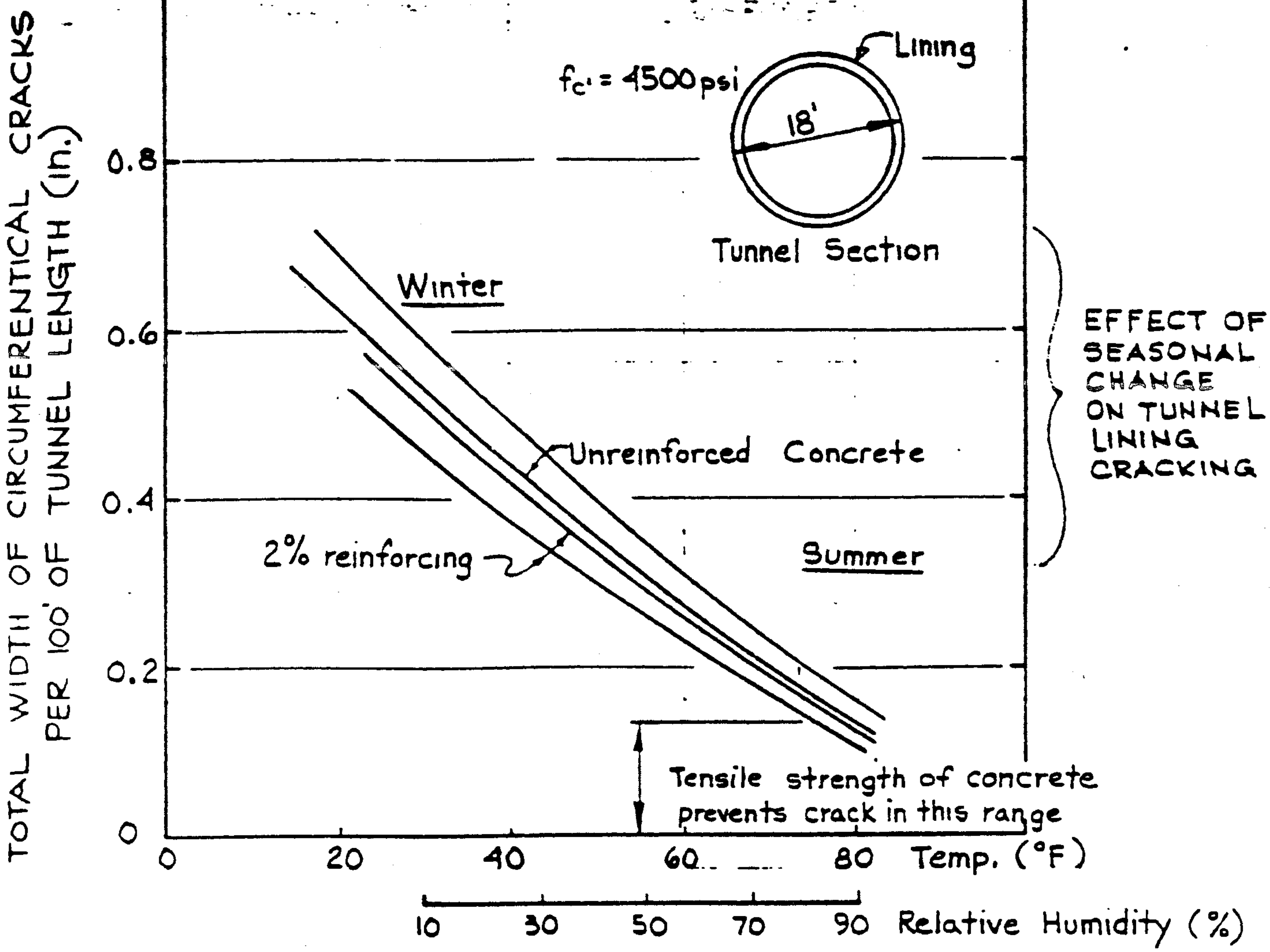
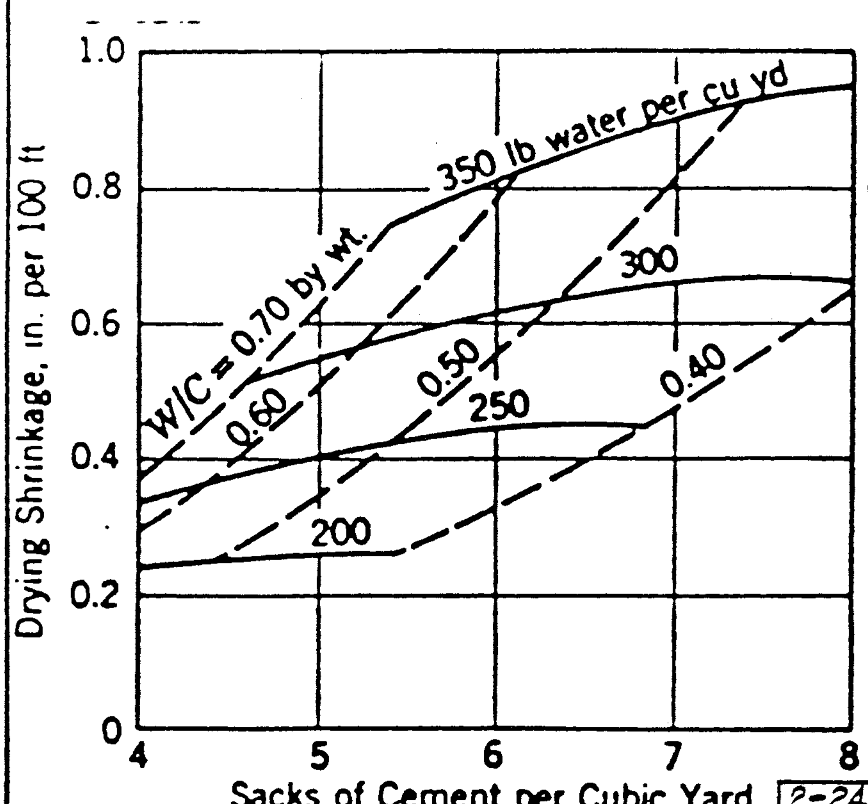
SCALE —	MADE BY JL CHKD BY JPG	DATE DATE 1987	FILE NO. 5634
ILLUSTRATION OF TUNNEL LEAKAGE			DRAWING NO. 2-2





EFFECT OF WATER AND CEMENT ON TUNNEL LINING CRACKING DUE TO CURING DRYING

2-24

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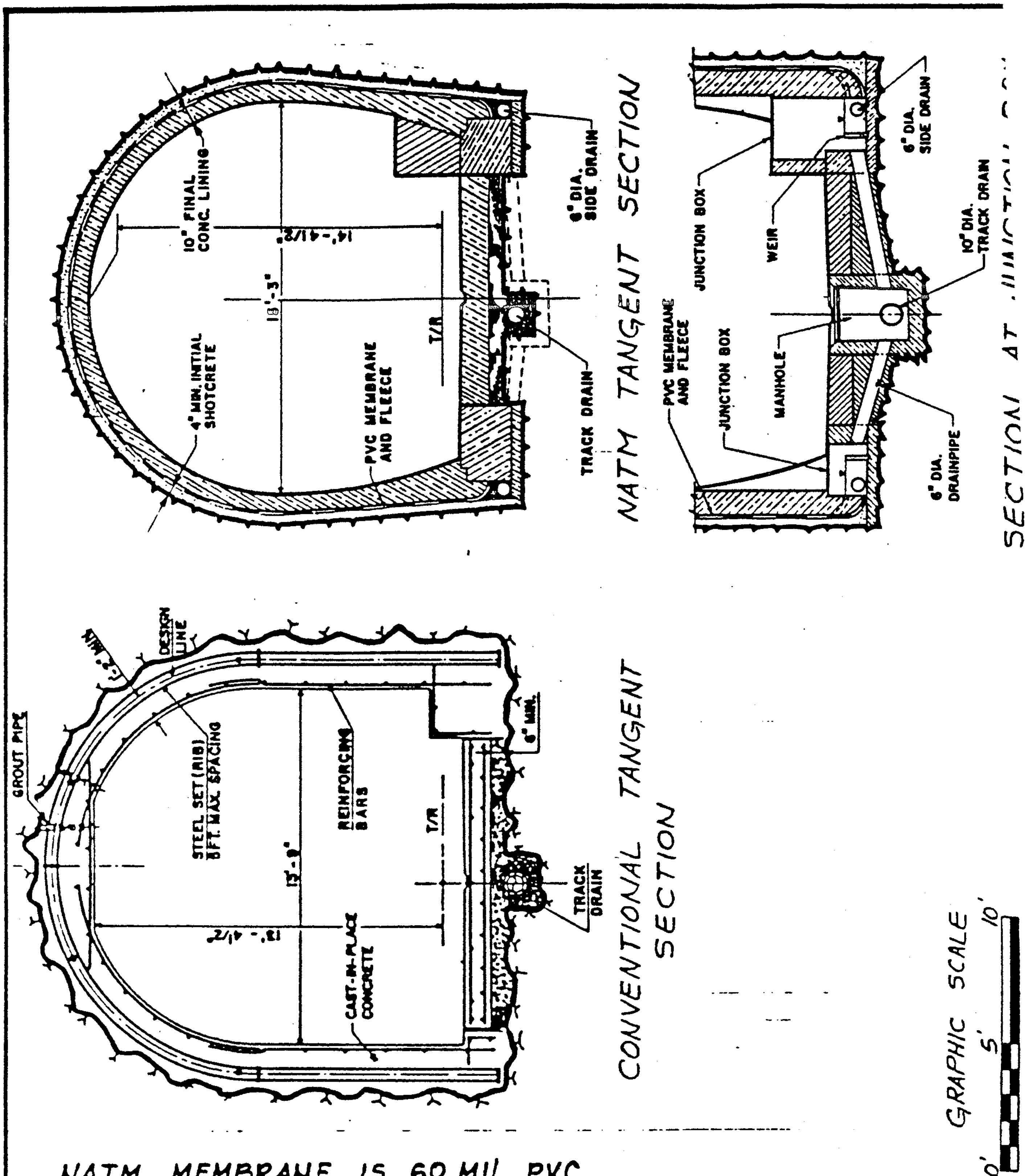
COMPONENTS OF TUNNEL LINING CRACKS

DRAWING NO 2-3



NATM MEMBRANE IS 60 MIL PVC HEAT WELDED AT JOINTS. FLEECE IS 1/4" POLYPROPYLENE ATTACHED TO INITIAL LINING BY HEAT WELDING TO PLASTIC HEADED NAILS.

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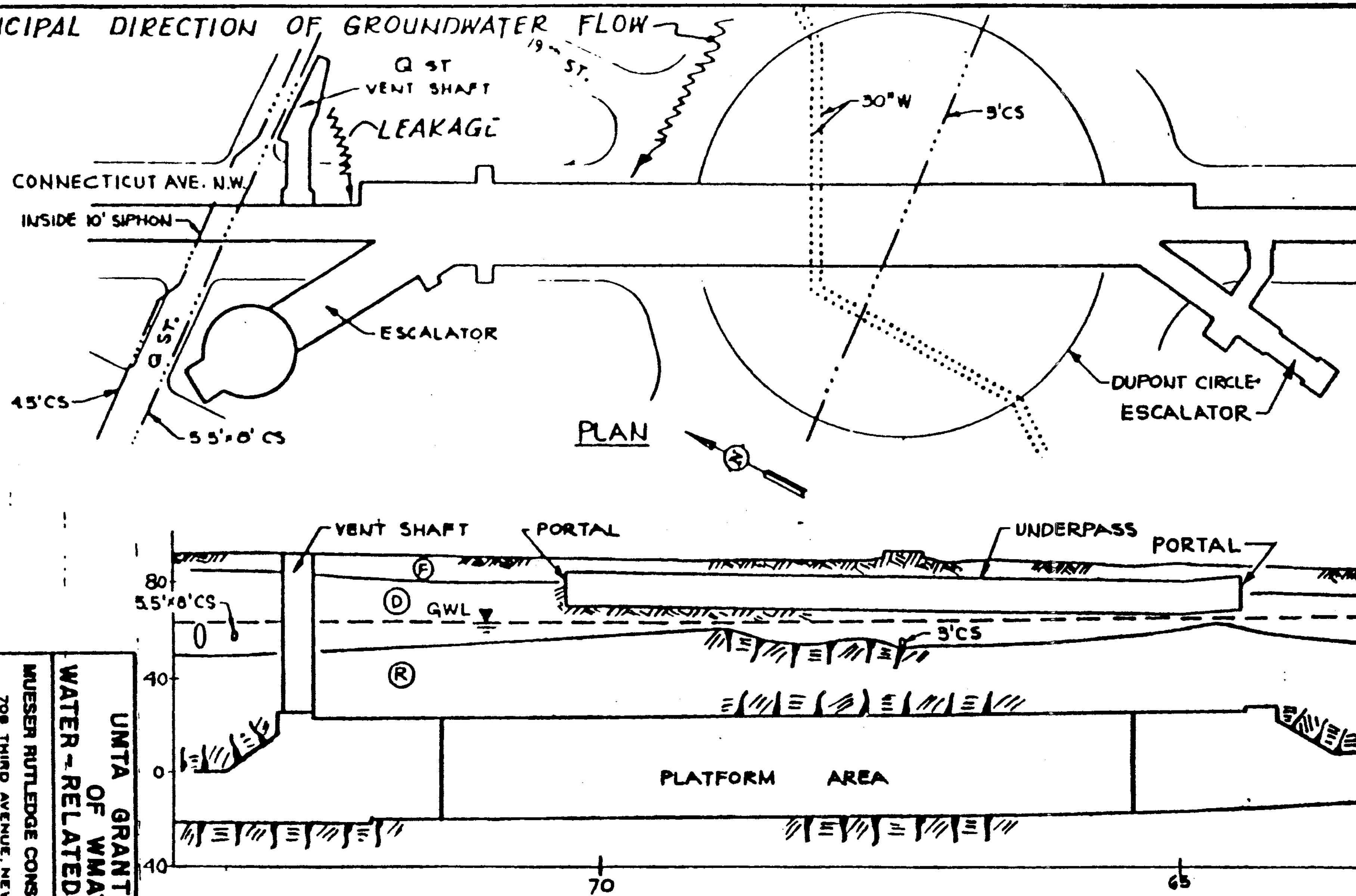
SCALE: AS NOTED	MADE BY: SL. / CHKD BY: JPG	DATE: 1987	FILE NO: 5634
NATM WATERPROOFING AND DRAINAGE			DRAWING NO: 2-4



SECTION

Note: In the schematic sections on Dwg. No. 2-5 to 2-9, the following symbols refer to subsurface features: (F) = Man-made fill. (D) = Decomposed rock. (R) = Bedrock, generally weathered at surface becoming less jointed and sounder with depth.
GWL = Groundwater level, shown as dashed line.

2-26

SCALE
HORIZ: 1" = 120'
VERT: 1" = 60'

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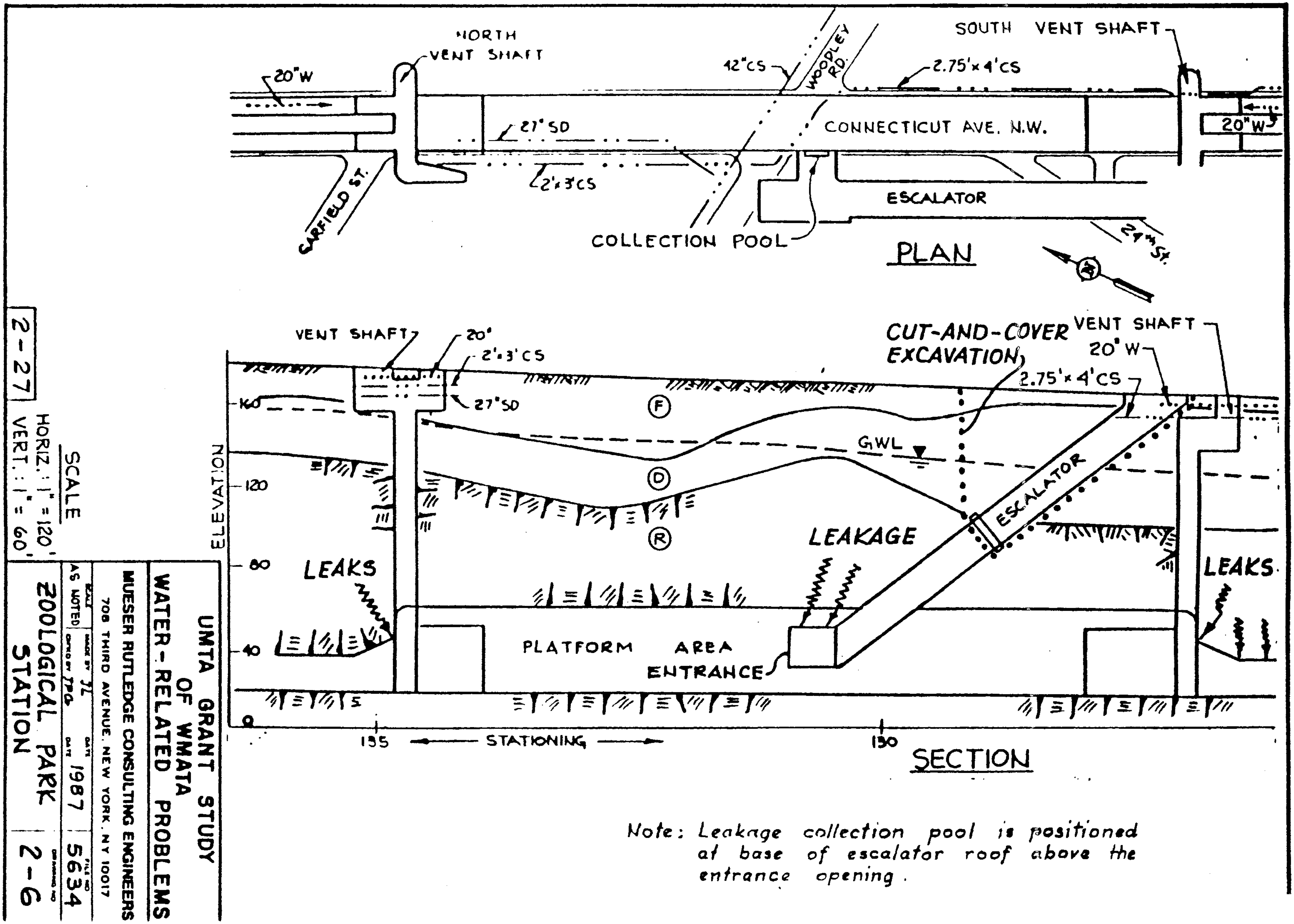
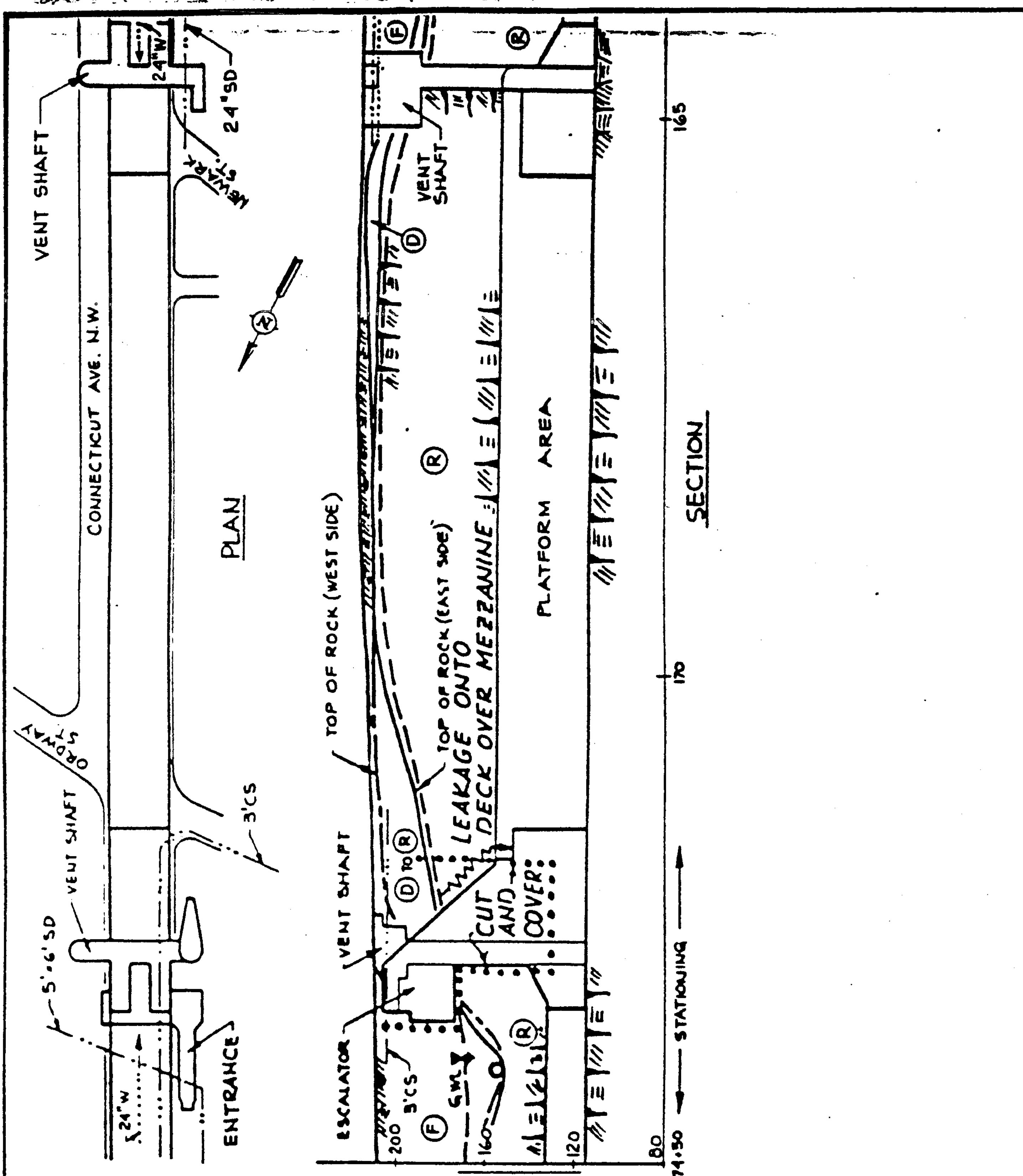
SCALE: AS NOTED | MADE BY: JL | CHECKED BY: TG | DATE: 1987 | FILE NO: 5634
DUPONT CIRCLE STATION
DRAWING NO: 2-5



Note: Leakage collection pool is positioned at base of escalator roof above the entrance opening.



SCALE
HORIZ. : 1" = 120'
VERT. : 1" = 60'

2-28

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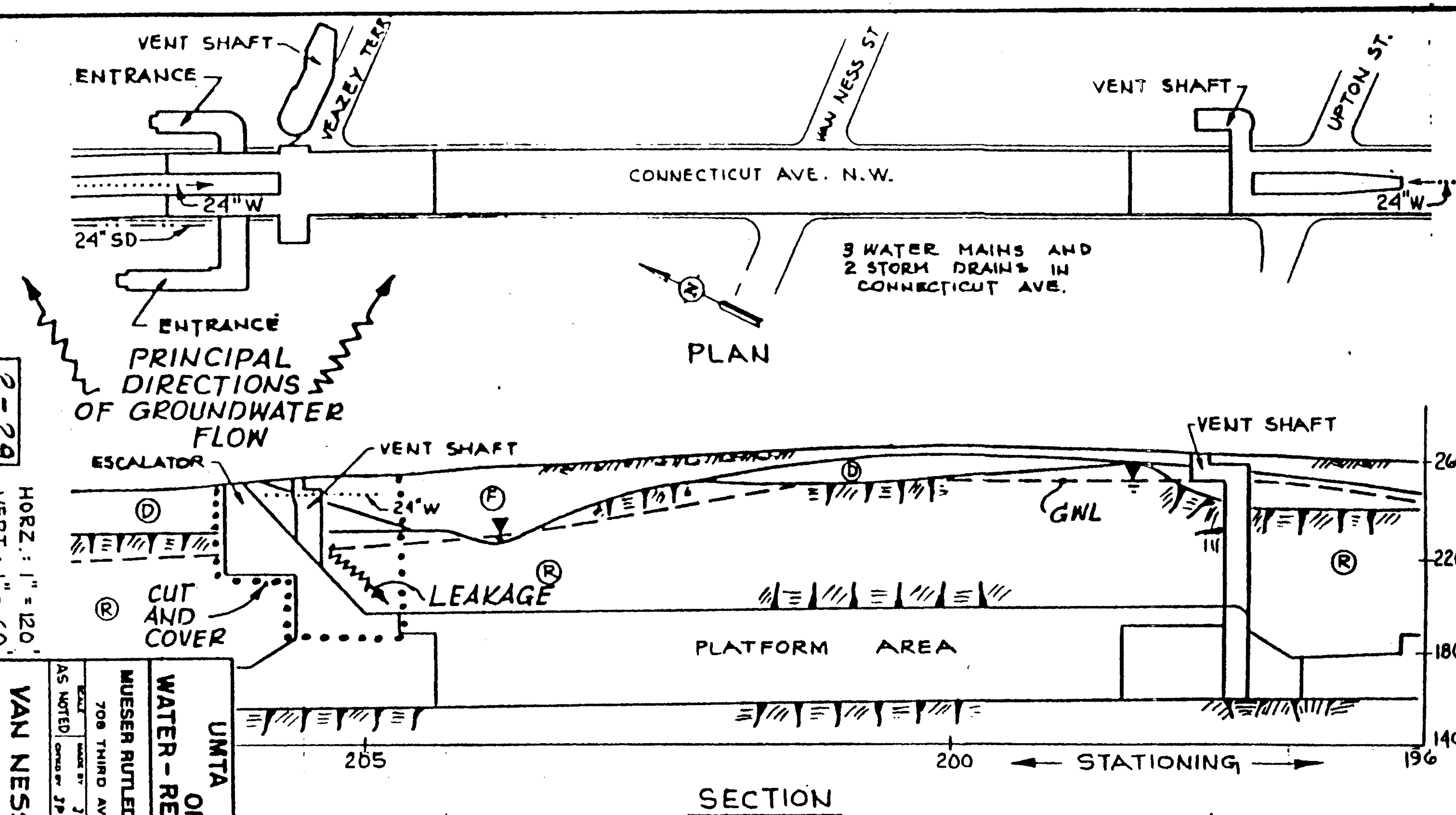
CLEVELAND PARK
STATION

DRAWING NO. 2-7



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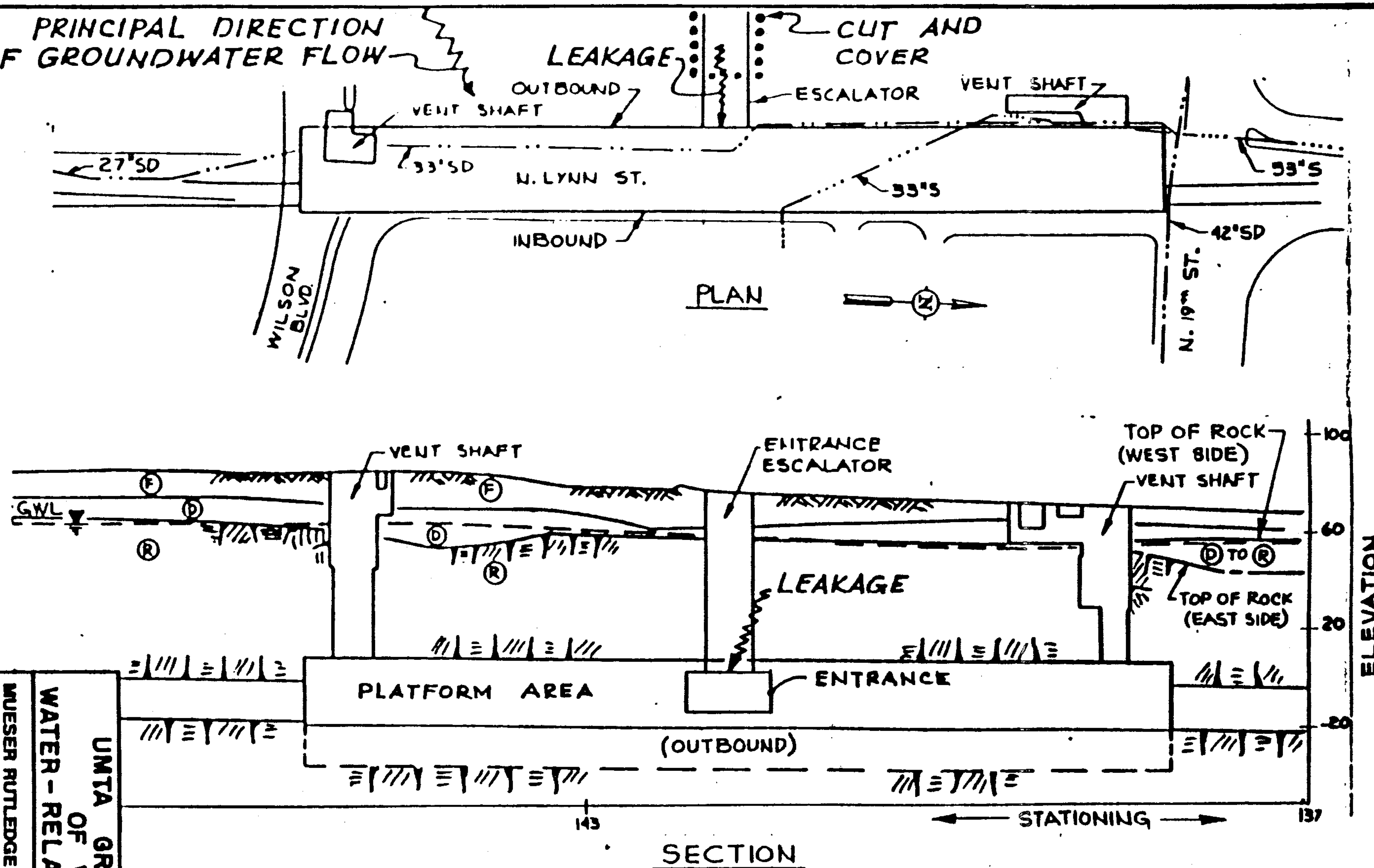
SCALE	MADE BY	DATE	FILE NO
AS NOTED	JL	1987	5634
	CHKD BY JPG.	DATE	

VAN NESS STATION | DRAWING NO 2-8



2-30

SCALE
HORIZ.: 1" = 120'
VERT.: 1" = 60'

UMTA GRANT STUDY OF WMATA
WATER-RELATED PROBLEMS

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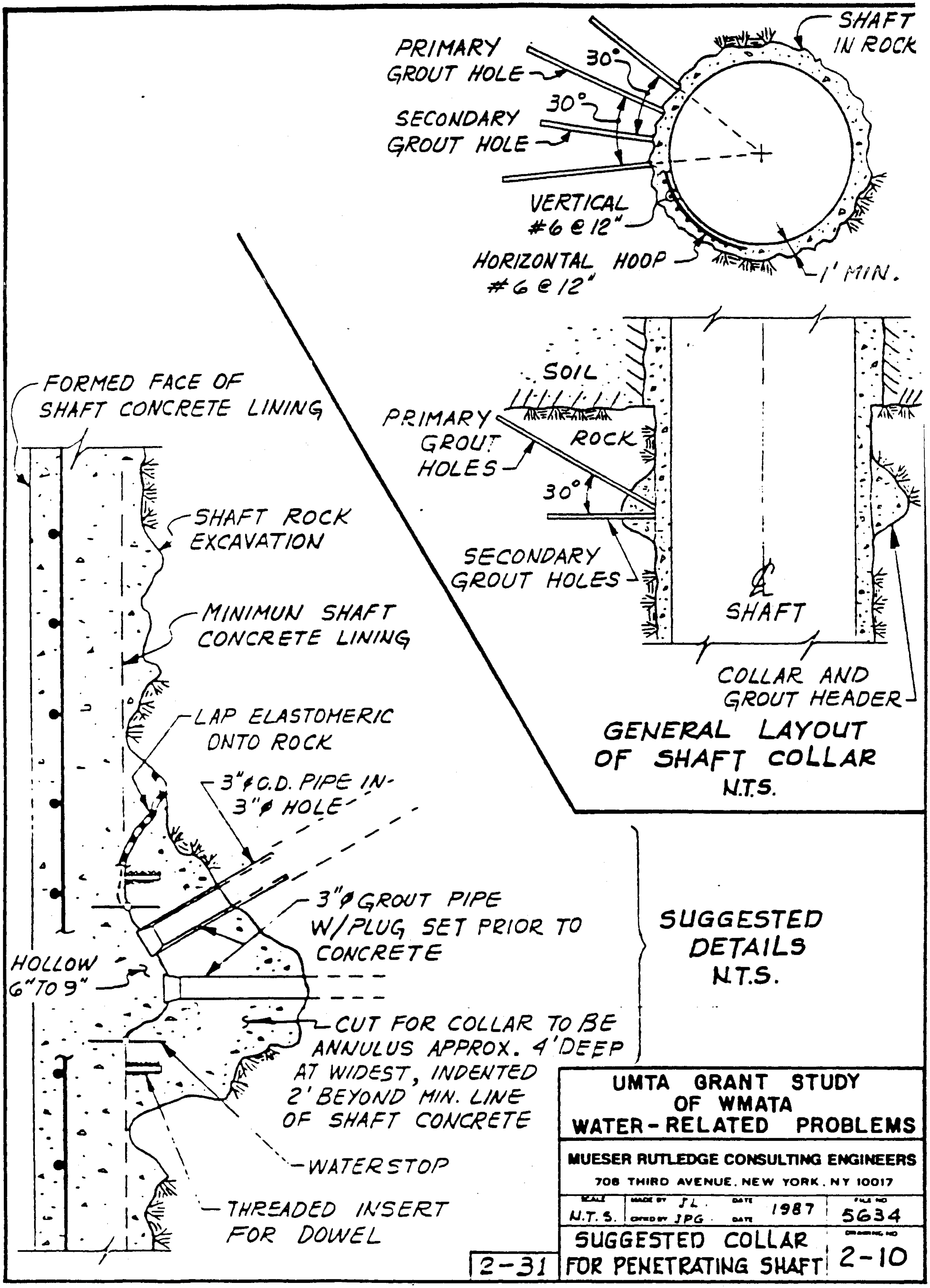
SCALE	MADE BY	DATE	FILE NO.
AS NOTED	JL		5634
	CHKD BY JPG	DATE 1987	

ROSSLYN STATION

DRAWING NO. 2-9


SHAFT IN ROCK
PRIMARY GROUT HOLE
30°
30°
SECONDARY GROUT HOLE
VERTICAL #6 @ 12"
HORIZONTAL HOOP #6 @ 12"
1' MIN.
SOIL
ROCK
PRIMARY GROUT HOLES
30°
SECONDARY GROUT HOLES
℄ SHAFT
COLLAR AND GROUT HEADER
GENERAL LAYOUT OF SHAFT COLLAR
N.T.S.
FORMED FACE OF SHAFT CONCRETE LINING
SHAFT ROCK EXCAVATION
MINIMUN SHAFT CONCRETE LINING
LAP ELASTOMERIC ONTO ROCK
3"φ O.D. PIPE IN 3"φ HOLE
3"φ GROUT PIPE W/PLUG SET PRIOR TO CONCRETE
HOLLOW 6" TO 9"
CUT FOR COLLAR TO BE ANNULUS APPROX. 4' DEEP AT WIDEST, INDENTED 2' BEYOND MIN. LINE OF SHAFT CONCRETE
WATERSTOP
THREADED INSERT FOR DOWEL
SUGGESTED DETAILS
N.T.S.
UMTA GRANT STUDY OF WMATA WATER-RELATED PROBLEMS
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SCALE N.T.S.
MADE BY JL
CHKD BY JPG
DATE 1987
FILE NO 5634
SUGGESTED COLLAR FOR PENETRATING SHAFT
DRAWING NO 2-10
2-31

CHAPTER 3: HYDROSTATIC PRESSURES AND PRESSURE RELIEF

3.1 Introduction

This chapter concerns hydrostatic pressures acting on WMATA tunnels from groundwater sources, and the relation between pressure relief and leakage into WMATA tunnels. It is not intended to be a general treatment but rather to reflect WMATA specific experience with groundwater problems with particular emphasis on rock tunnels and stations. The ASCE-UTRC, "Guidelines for Tunneling Design" (Reference 2-1) has the following advice on resisting external water pressures.

> "In many instances, it is not necessary to design the concrete linings of rock tunnels to resist full hydrostatic pressure. Neither is it necessary to provide hydrostatic pressure relief or external drainage unless it is desired to channel water leakage through the lining or collect it in an external drainage system. Tunnel shape has a strong impact on the lining stresses resulting from external water pressure. Moments in circular tunnel linings from hydrostatic loading will be limited to those caused by elevation changes between the crown and invert. The thrust from water pressure in a circular lining may even increase its capacity by compensating for tensile stresses associated with bending."

Since the earliest designs of 1966, WMATA procedures for resisting water pressures and providing drainage or watertightness have evolved in stages and a summary of those developments follows. It should be recognized that both in rock or soft ground the external water pressures acting on the lining and leakage through the lining are produced by an interaction of the following factors:

1. Permeability of the surrounding ground and of the tunnel lining;

2. Provisions for systematic drainage to the tunnel or inadvertent leakage through the lining;

3. Tunnel head acting from the groundwater source, divided in two components: head loss in the surrounding ground and increment of head loss causing flow through the lining.

These factors are illustrated diagrammatically in Drawing No. 2-2. Briefly, as the liner itself becomes less pervious or if systematic drainage is omitted, the head retained outside the liner is maximized and water within the tunnel is a minimum. On the other hand, either systematic drainage or inadvertent leakage will decrease the surrounding water pressures acting outside the lining.

3.2 Hydrostatic Pressures in WMATA Designs

In WMATA design procedures, circular running tunnels have been taken as resisting full hydrostatic pressures, whether the lining has been cast-in-place concrete or pre-cast segmented lines. Horseshoe running tunnels in rock were originally considered to be fully pressure relieved by drainage lines and invert drains at their base. The earliest WMATA stations in rock were large single vaults supported by shotcrete, rock bolts and heavy steel ribs. These were designed to be fully pressure-relieved by the individual drainage lines positioned at leaks and placed during construction and before completion of shotcrete applications. The earliest piezometer observations near running tunnels and stations in rock suggested that drainage or leakage was creating very substantial drawdown, almost complete relief of water pressures in the rock joints immediately surrounding these mined openings. This appeared to be occurring even though the uppermost piezometric levels in the shallow water table remained near the original unaltered water levels. This is suggested by the data plotted in Drawing No. 3-1 showing the actual drawdown observed in piezometers which have intake points isolated in rock near the tunnel openings.

These observations represent the typical condition where permeability decreases substantially with depth in the profile of rock weathering. In some locations it is likely that piezometric levels near tunnels would be low in any case because of lack of communication through rock joints with a source of recharge at shallow depth. The usual condition in WMATA deep rock tunnels is to encounter water pressure after construction much lower than values hydrostatic with the surficial groundwater level in overburden soils.

One exception to the general rule of extensive drawdown is Piezometer No. VR-1 near running tunnel in rock in Section A006, which shows only roughly 50% drawdown at a point within a few feet of circular tunnels. As it became apparent that systematic drainage in rock tunnels was being influenced by the problem of calcification, concern developed that the assumption of complete hydrostatic pressure relief at rock stations was not conservative enough to allow for the progressive clogging and restricting of the drainage function.

The general effect of drainage on water pressures can be readily assessed by the flow net procedure. The pattern of flow usually can be estimated to the extent required in practical problems by the graphical construction. Accuracy of the prediction of quantity of flow is limited by the accuracy of knowledge of the permeability of the surrounding ground which is usually poor to mediocre. Two flow net examples are shown on Drawing No. 3-2. These assume two-dimensional seepage to concrete-lined horseshoe tunnels in isotropic ground and are examples of approximate procedures available for a design estimate. The upper diagram reflects the combined effect of a drainage slot representing an array of weep holes on a single line through the liner above the springline plus a pervious underdrain across the base of the invert.

The lower diagram of Drawing No. 3-2 illustrates the effect of the invert underdrain alone. The plot at the left of the tunnel cross section in both these sketches shows the hydrostatic pressures acting outside the liner while the drains are active and compares this to the original full head of water. In this case original head is taken at 60 feet at tunnel crown and 80 feet at tunnel invert. With both the weep holes and invert underdrain functioning, hydrostatic pressures on the straight leg of the liner average a maximum of about 13% of the original pressure. If only the invert is drained, hydrostatic pressures vary from about 50% at the tunnel crown to 10% at the outside base of the sidewalls.

The purpose of these studies was to assess the effect of plugging of small weep hole drains caused by calcification, as observed in the rock stations and in certain horseshoe-shaped running tunnels. On the basis of such studies, it was recommended in 1979 that for design of the horseshoe cast-in-place concrete liner at normal working stress, water pressures be assumed at 25% of the original height of static groundwater at the crown and 10% of the full height at the base of the straight leg. It was additionally required that the tunnel liner designed on this basis be checked for 100% of full hydrostatic acting against the straight leg, requiring a safety factor just greater than unity on the stresses produced. This later condition ordinarily controlled flexural reinforcing in the legs of the horseshoe liner.

As a design with the New Austrian Tunneling Method (NATM) was being developed in 1984 in a value engineering change proposal for Section B010 of Glenmont Route, there were protracted discussions of the effect of water pressure transferred from the drainage fleece onto the interior final lining. Eventually it was concluded that the effect of plugging of the drainage fleece could be accounted for by applying a water pressure equal to five meters of head upon the interior cast-in-place liner of the NATM design. This amounted to about one-fourth to one-fifth of the original groundwater pressure. Piezometer observations to Autumn 1988 indicate extensive drawdown of piezometric levels produced in the rock surrounding the B010 tunnels and acceptable stresses within the interior concrete liner.

3.3 Analysis of Hydrostatic Pressure Effects on Horseshoe Tunnel

To take advantage of the experience of DeLeuw Cather & Co. (DCCo) as General Engineering Consultant for the WMATA system, they were retained as special investigator for this study to distinguish the effects of water pressures acting on running tunnels and stations in rock. Two separate problems were considered: the effects in a horseshoe tunnel with an invert drainage layer, and the effects on a typical station mined in rock supported by shotcrete and steel ribs.

Basic results for the horseshoe section are summarized on Drawing No. 3-3. The tunnel is taken as a simple frame of constant cross section with the conservative assumption of pin support at the base of the straight legs. Moments at crown and springline are compared for cases which combine the basic rock load with four different distributions of lateral water pressures. If the invert drain is functional, the horizontal water pressure diagram on the straight leg decreases to zero at its base. In that case negative moment produced at springline is acceptable; moment at the crown is small. The safety factor with respect to a moment balance ranges from two to three. If the invert drain does not function properly, water pressures on the straight leg are taken as a uniform rectangular diagram. Then the negative moment at the crown can become relatively large and safety factors drop below 1.5. If the drain is completely plugged and water pressures became hydrostatic with the original groundwater, the safety factor for crown moments decreases to about one. Thus, the continual functioning of the invert drain is important and deserves maintenance attention. This analysis is conservative since the rock load was not decreased to reflect buoyancy acting on the wedge of overbreak rock as water pressures are increased.

3.4 Analysis of Hydrostatic Pressure Effects on Rock Stations

A report by DCCo was submitted to MRCE in November 1983 titled, "Effect of Hydrostatic Pressure on Stresses in WMATA Rock Station Structural Linings" (Reference 3-1). The WMATA mined rock stations of Rockville Route are caverns, typically 60 to 65 feet in width, opened by multiple headings with structural support by several layers of shotcrete applied behind and around steel ribs spanning the entire cavern arch.

Hydrostatic pressures were to be eliminated by drainage holes installed outside the shotcrete plus underdrains beneath the station invert slab. The general arrangement of the cavern support and the drainage are shown on Drawing No. 3-4. The station arch was designed using symmetrical roof rock loading and an initial small horizontal loading, then permitting an increase in horizontal pressures as the support deflects against rock engaging an assumed horizontal rock modulus by the outward deflection. The capacity of the supporting section was checked by applying discrete rock blocks whose magnitude and orientation were determined by the attitude of the joints in the surrounding rock.

Structural support in three rock stations were studied by DCCo: Forest Glen, Bethesda and Medical Center. For Forest Glen Station adding a water pressure diagram equal to 20% of the total head decreasing to 10% at the base of the side wall caused a 50% increase in compressive stress compared to the original design of a dry rock load without water. Addition of this water pressure caused a 3.5 times increase in concrete compressive stress if the interaction of the tunnel liner and the supporting rock on the side wall was not considered.

For Bethesda and Medical Center Stations, adding a full hydrostatic pressures at the crown of the station arch created a 61% increase in maximum compressive stress in concrete. This produced only a 5% overstress in the structure due to the reserve capacity of the arch section. In fact, a field investigation with piezometric measurements outside the shotcrete lining, indicated the buildup of only a few feet of water pressure on the shotcrete lining despite efforts made in this UMTA investigation program to seal the shotcrete liner. The shotcrete contains numerous reflection cracks, generally one along each outstanding flange of the steel arch ribs. Although this method of pressure relief by unplanned drainage can create an annoying maintenance problem and leaks damaging the architectural finish, it also ensures that hydrostatic pressure will not develop on the structural lining of the original rock stations. Thus, while Rockville Route stations might appear to be potentially vulnerable to the buildup of water pressures, neither the structural analysis nor the realities of the in situ condition suggest a long term threat to structural integrity of the lining. No investigation has been made of the corrosion of the steel ribs or rate of loss of structural section. However, pH values in leaking water in the rock stations are near neutral or slightly alkaline and are buffered by calcite within the bedrock joints.

Strain gauge measurements were made by the University of Illinois investigation team on the steel ribs of the lining of a number of the earlier Rockville Route stations mined in rock (Reference 3-2). Those observations have been analyzed to determine thrust and moment in the composite cross section of ribs and shotcrete and compared to the locus of failure combinations of thrust and moment. These analyses indicate that the stress level measured in situ is about 20% to 30% of yield point values for the design composite section of ribs and shotcrete. However, it is only about 15% of the actual yield point for the as-built cross section which incorporated a substantially greater thickness of shotcrete than was planned.

3.5 Relation of Tunnel Leakage and Water Pressures

The study of Section 3.2 concerned drainage to a tunnel where exterior water pressures were controlled by planned drainage arrangements. Experience with leaking cast-in-place concrete liners indicates liner permeability can be as high as 1×10^{-3} to 1×10^{-4} feet per minute. Where a leaky concrete liner is constructed in waterbearing ground, leakage to the tunnel and water pressures on the liner are a function of the relative permeability of ground and liner. The factors involved in this relationship are explored in Drawings Nos. 3-5 and 3-6. Drawing No. 3-5 is a simple flow net drawn for a tunnel in sand where horizontal tunnel dimensions are reduced by one half to account for anisotropic permeability of the surrounding sand. The flow pattern is symmetrical about the tunnel centerline. This analysis yields a "shape factor" which defines the efficiency of flow in the ground surrounding the tunnel, equalling 1.6 in this case.

Shape factor is an insensitive parameter and variations in tunnel shape or soil stratification have little effect on it. Therefore, this flow net can be used to demonstrate the factors that influence tunnel leakage and water pressures developed on the exterior of the liner. In the computations of Drawing No.

3-5 the flow through the sand stratum is then set equal to flow through the tunnel liner. These quantities depend on the values of permeability of the surrounding ground and the liner itself. Head loss across the liner can then be expressed in terms of the ratio of these two permeabilities. On Drawing No. 3-6 that fact is utilized to demonstrate the quantity of flow into the tunnel in the upper diagram and the potential head loss on the exterior of the liner in the lower diagram.

The upper diagram shows that acceptable leakage on the order of 1 gpm per 1000 feet of length can be expected whenever liner permeability is 1×10^{-7} feet per minute or less. If the liner permeability is as great as 1×10^{-6} fpm, the permeability of the ground must then be not more than about 2×10^{-6} fpm in order to meet acceptable standards for leakproofing. This is the situation experienced in many London Transport tunnels mined in London clay where leakage to the tunnel is restricted by permeability of the clayey ground. Then segmented pre-cast liners with no great attention to joint tightness have been notably successful. On the other hand, the worst WMATA experiences with leakage to running tunnels have combined the unfavorable circumstances of a cast-in-place concrete tunnel near a portal surrounded by jointed rock and continuously recharged from a stream overhead. That combination of conditions probably involved permeability both of the ground and the liner in the range of 10^{-3} to 10^{-4} fpm, leading to average inflow of 100 to 200 gpm per 1000 foot of tunnel.

The lower diagram of Drawing No. 3-6 uses the same information to establish a relationship between the two permeability values and the increment of head acting on the exterior of the tunnel liner. This, of course, is the water pressure that has to be resisted in the liner design. In this analysis there is no significant effect on the magnitude of these external pressures from the shape of the liner, whether circular or horseshoe. However, the shape of the tunnel has a large influence on the magnitude of its flexural stresses.

The lower diagram shows that if liner permeability is two orders of magnitude greater than permeability of the surrounding ground, 2/3 to 3/4 of the total head is preserved to act on the tunnel liner. Where tunnel liner permeability is only one order of magnitude less than that of the surrounding ground, only about 1/3 of the total head remains to act on the liner. Of course when the surrounding ground and the tunnel liner are of equal permeability then the liner is no more effective than an equivalent several feet of the surrounding ground itself, and the head remaining to act on the liner is negligible. It is assumed that the permeability of the liner is distributed as an equivalent concrete section of uniform porosity.

It should be recognized that these solutions are site specific and that the conclusions vary somewhat depending on flow pattern in the ground and also on the manner in which the head loss is concentrated around individual larger cracks in the tunnel liner. However, these simple computations illustrate the overall relationship between leakage and exterior water pressures.

3.6 Influence of Crack Width on Concrete Permeability

Drawing No. 3-7 illustrates a brief study made for this report to quantify those factors in the cracking of concrete which influence the equivalent average permeability of the tunnel liner. In the upper diagram, a relationship between flow gradient and thickness of an individual crack is shown for an ideally smooth crack and a crack so rough that it is equivalent to flow through granular soil wherein the crack's average width is taken as one-fifth of particle diameter. The flow in the smooth slot is taken as an upper bound, whereas flow in the equivalent irregular soil pores is the lower bound. Probably, as the crack width increases, the flow tends to approach the upper bound of the smooth slot. For very small cracks, the flow approaches that of the path through granular soil. That assumed median condition is translated in the lower diagram to equivalent concrete liner permeability versus crack width and crack spacing. Permeability and crack width are related exponentially and cover a range in this analysis similar to the actual permeability range evidenced in the field for cast-in-place concrete lining, between 1×10^{-4} and 1×10^{-7} feet per minute.

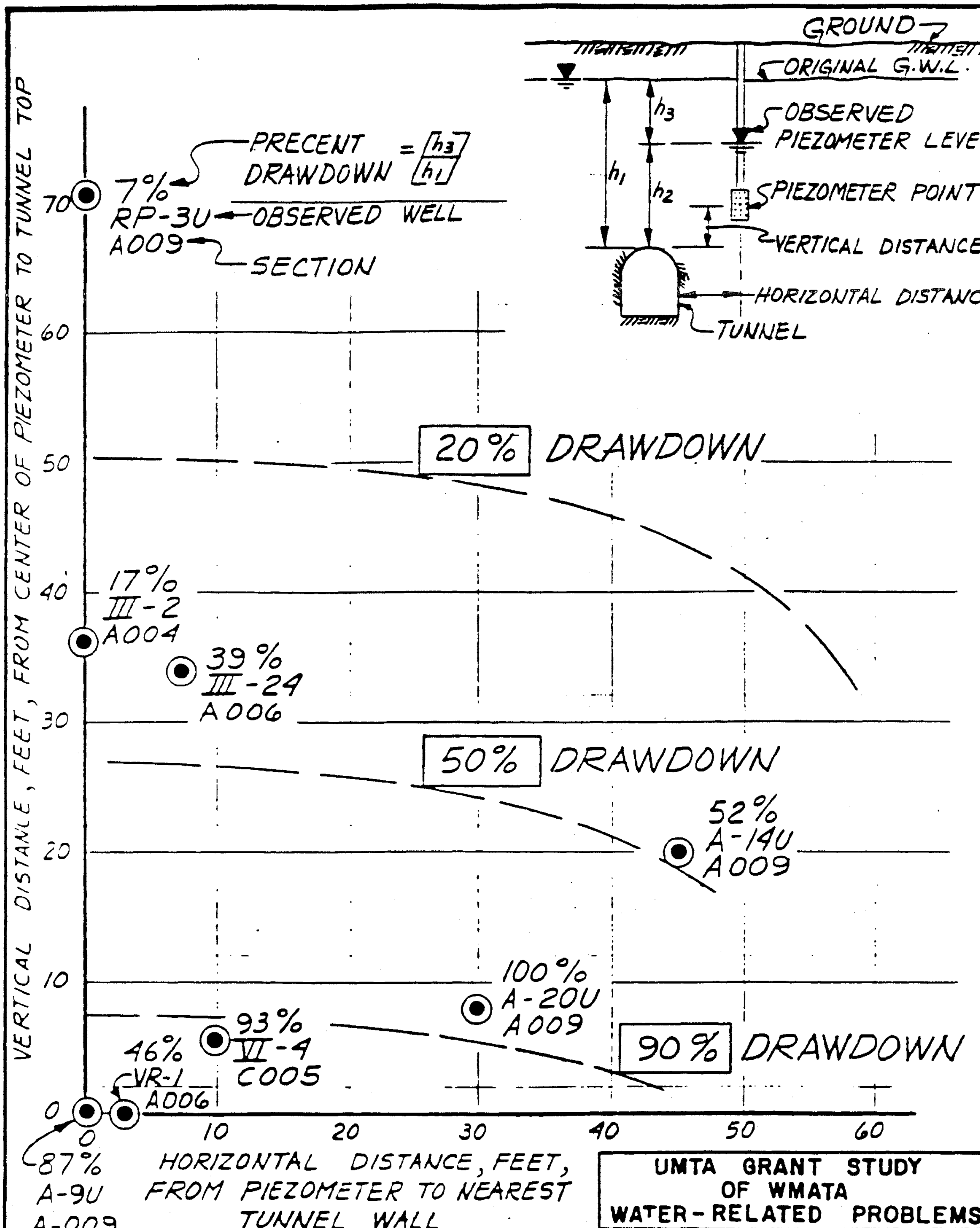
3.7 NATM Drainage and Water Pressure Resistance

Drawing No. 2-4 contrasts the standard horseshoe tunnel specified in Section B010 of Glenmont Route with the competing section constructed under the value engineering change proposal for the "New Austrian Tunneling Method" (NATM). The conventional cast-in-place horseshoe section was installed in adjacent Section B009. The contrast between leakage inflow where these two running tunnels abut is striking. Specific information on the extent of exterior drawdown in the rock surrounding B009 has not been available. Numerous pumping wells were carried to the jointed rock in Section B009 and the overall effect of the construction dewatering was to create a substantial drawdown. It is expected that much of the drawdown has been sustained by the continuing leakage to running tunnels and shafts in B009.

In Section B010 piezometers have been placed from within the running tunnel, carried through the initial shotcrete at a height about five feet above the invert and then brought through the fleece, waterproof liner and final concrete lining to emerge on the interior tunnel wall. Before tunneling, a group of four deep observation wells had been installed from the ground surface to bottom positions midway between the two running tunnels, with intake points about 10 feet above tunnel crown. Since their installation, the interior piezometers have recorded 4 to 6 feet of water head with no significant change as tunneling progressed to completion and the final concrete lining was cast.

The observation wells from the ground surface have shown a continual gradual drawdown during mining to a depth of 35 to 40 feet below the original water table. Then the residual head above the tunnel crown is 15 to 20 feet of water at a distance of 10 feet above the crown. The gradient to the crown is about 2½ to 1 taken on an angle from the position of the piezometer. This gradient is similar to the average gradients directed toward the cast-in-place lined tunnels and stations of Rockville Route on Drawing No. 3-1. According to the interior piezometers, a residual head of five feet of water is present in the drainage fleece, and there is a differential head of roughly 30 feet in the 20 or 25 foot distance between the tips of the exterior observation wells and the interior piezometers. This is equivalent to a gradient of about 1½ to 1. All piezometers are reacting to an active flow field directed into the drainage fleece of the tunnel where there is a reduction of head of 50 to 60 feet below the original water table. There is not yet (in Autumn 1988) an indication that this extensive drawdown is being restored as tunneling work is completed.

The drainage fleece and the waterproofing membrane in the NATM design is extended up the shaft walls and surrounds the top and sides of the Wheaton Station, providing an extensive drainage medium and a complete waterproofing enclosure for all the mined underground structures of Section B010. The key question that will only be answered by the passage of time is whether the drainage fleece could become less pervious because of continuing compressive stresses, vibrations, chemical changes, the intrusion of sediment or the accumulation of precipitates within the drainage fleece. Since carbon dioxide gas released from calcite-charged inflowing ground water will tend to be trapped within the fleece, its presence in the fleece may inhibit continuing calcareous precipitation. Therefore it is likely that the fleece is much less vulnerable that conventional drains to clogging by precipitates. Experience in Europe does not indicate any significant loss of drainage capacity of the NATM fleece with passage of time.



UMTA GRANT STUDY OF WMATA WATER-RELATED PROBLEMS

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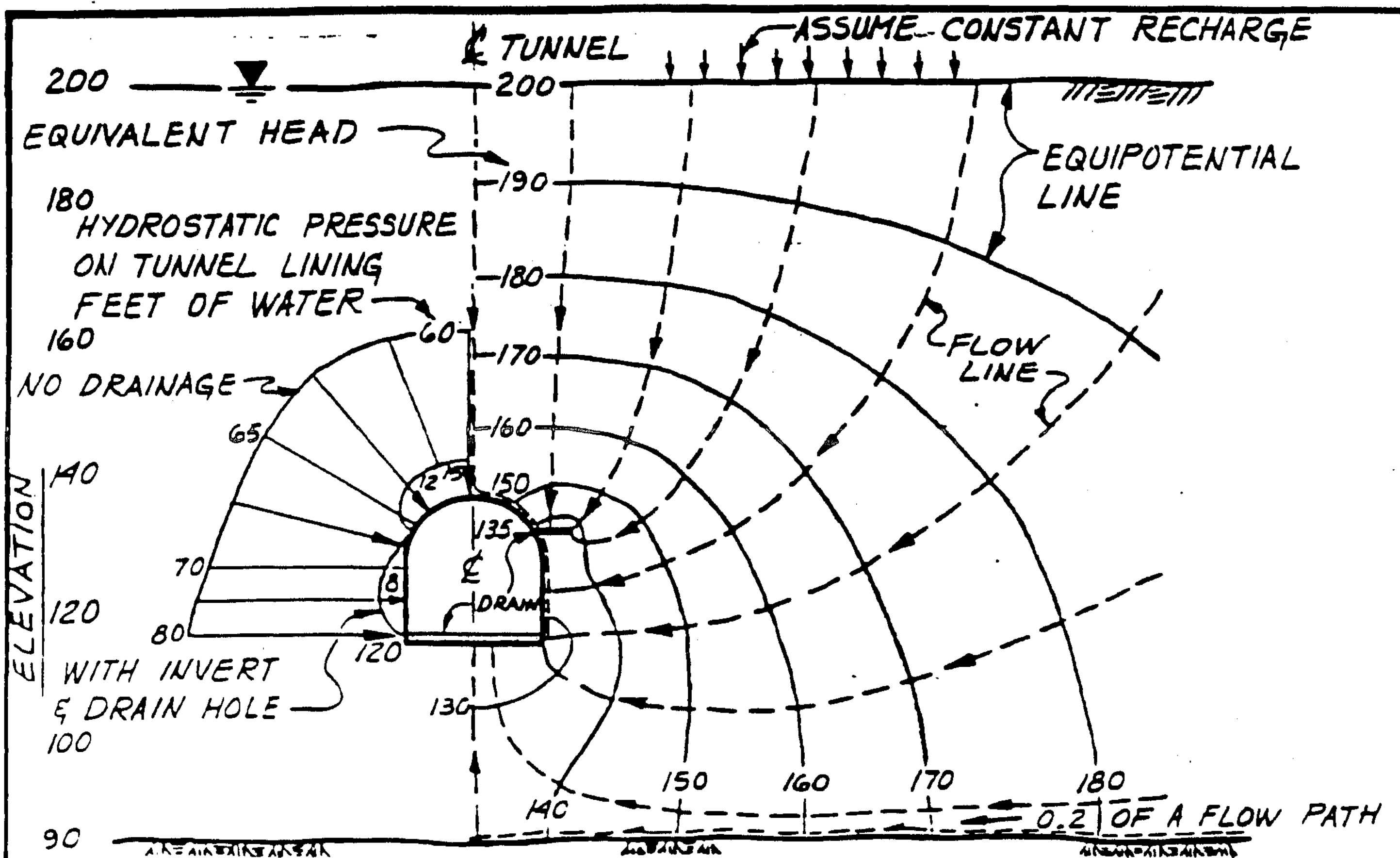
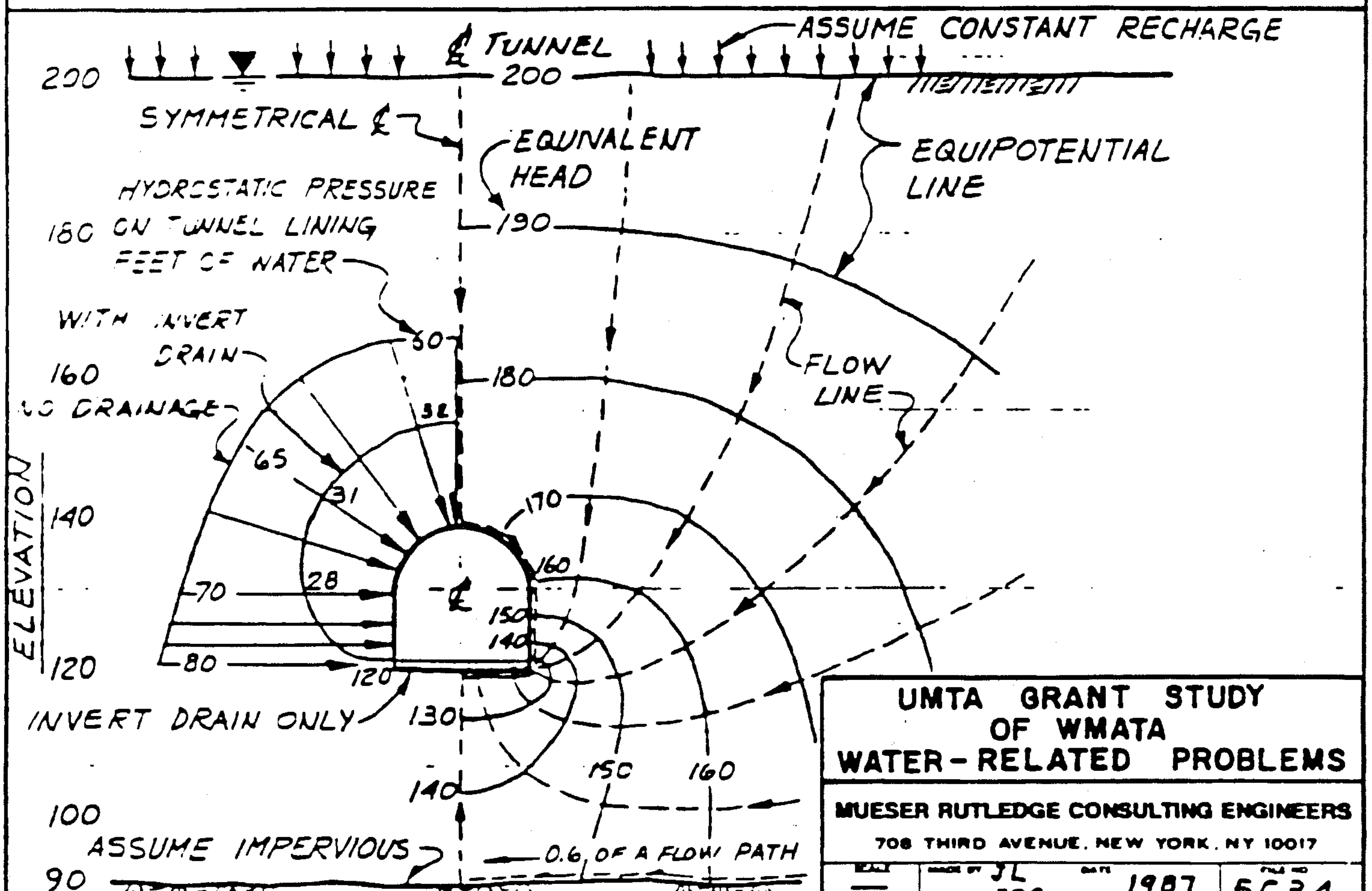
OBSERVED DRAWDOWN AROUND ROCK TUNNELS — DRAWING NO 3-1



EFFECT OF INVERT PLUS WALL DRAIN ON TUNNEL HYDROSTATIC PRESSURE



EFFECT OF INVERT DRAIN ONLY ON TUNNEL HYDROSTATIC PRESSURE

3-18

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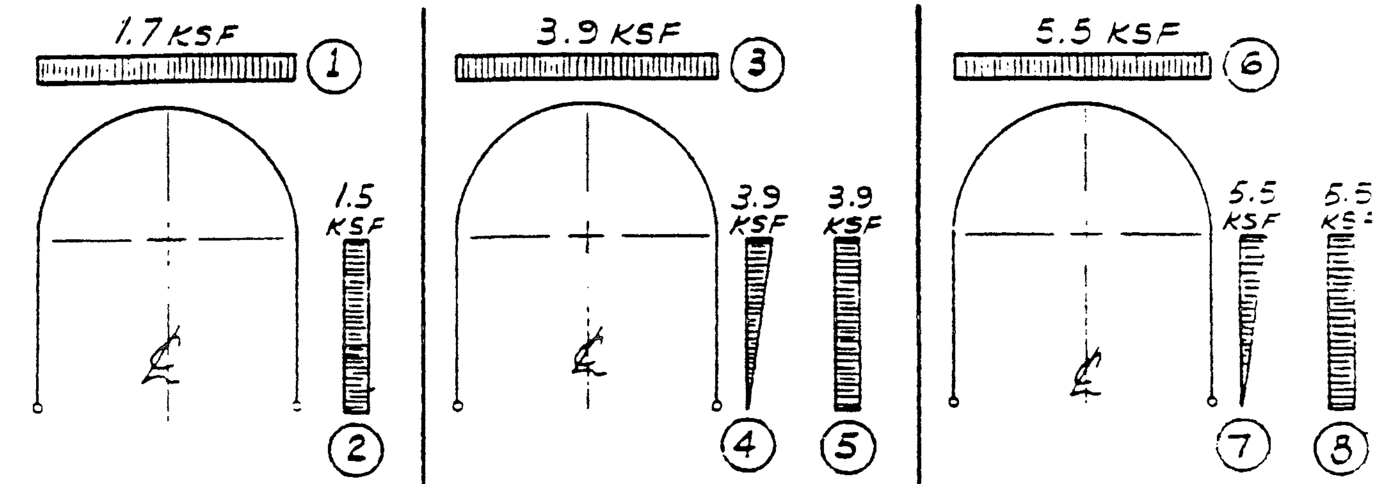
SCALE —	MADE BY JL · CHKD BY JPG	DATE 1987 · FILE NO 5634
EFFECT OF DRAINAGE ON HYDROSTATIC PRESSURE		DRAWING NO 3-2

INDIVIDUAL AND COMBINED LOADINGS



ROCK PRESSURE

HYDROSTATIC PRESSURE 50% OF ORIGINAL GWL

HYDROSTATIC PRESSURE 70% OF ORIGINAL GWL

LOADING CASES	MOMENT @ SPRING LINE, KF	MOMENT @ CROWN, KF	SAFETY FACTOR $M_{ULT.}$ = 35 KF
(1) VRP	-19	14	
(2) LRP	17	-19	
(3) VHP	-43	32	
(4) LHP	31	-31	
(5) LHP	46	-49	
(6) VHP	-60	45	
(7) LHP	44	-44	
(8) LHP	64	-69	
(9) 1+2	-2	-4	
(10) 1+2+3+4	-13	-3	2.7
(11) 1+2+3+5	1	-21	1.7
(12) 1+2+6+7	-18	-5	1.9
(13) 1+2+6+8	3	-28	1.3

NOTE:

1. VRP & LRP STANDS FOR VERT. & LATERAL ROCK PRESSURE RESPECTIVELY.
2. VHP & LHP STAND FOR VERT. & LATERAL HYDROSTATIC PRESSURE RESPECTIVELY.
3. +M PRODUCES TENSION @ INSIDE FACE OF LINING. LOADING IS SYMMETRICAL IN ALL CASSES

3-19

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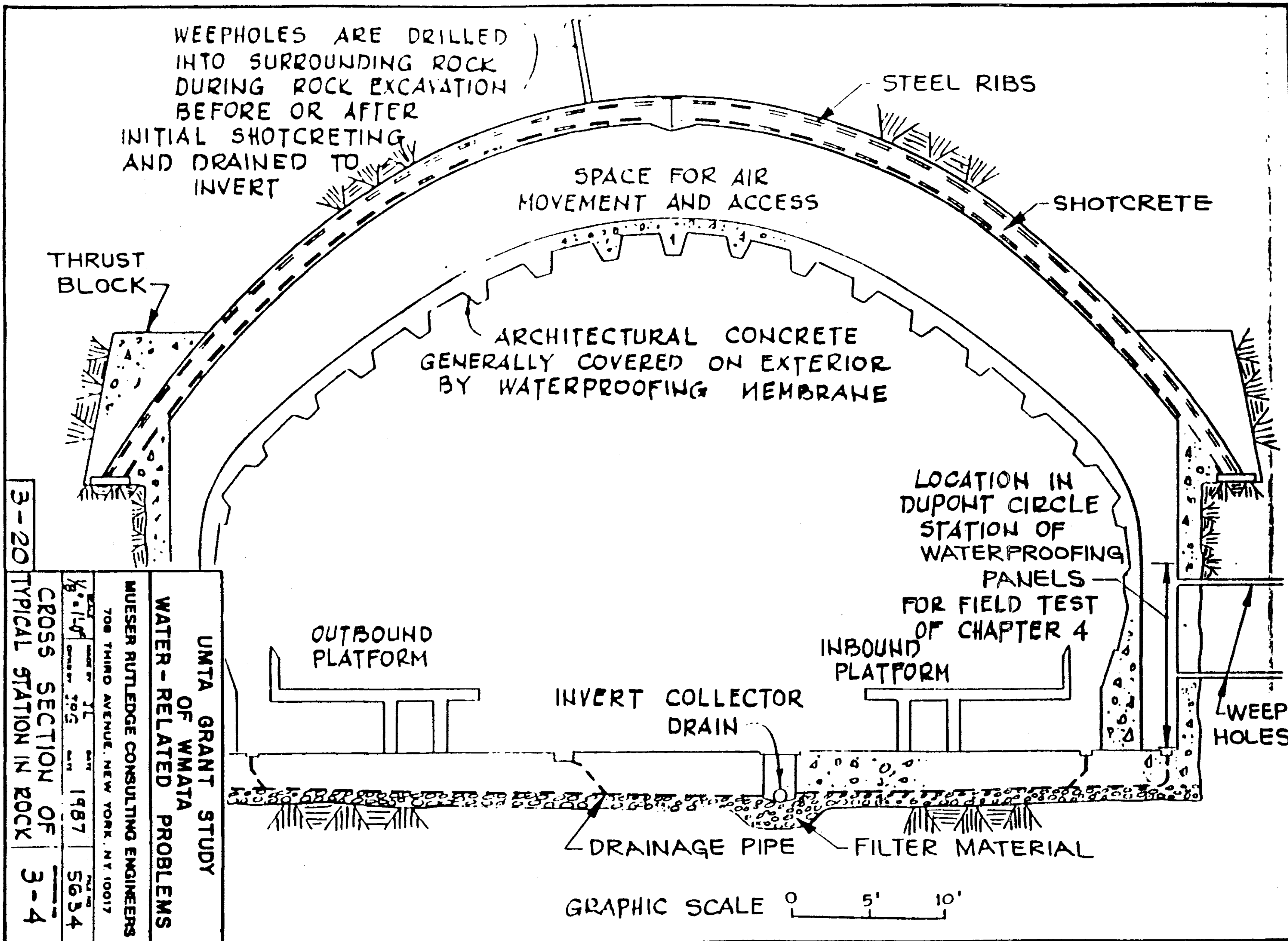
—	JL	1987	5634
	CHKD BY JPG	DATE	

EFFECT OF PRESSURES ON HORSESHOE TUNNEL

DRAWING NO 3-3



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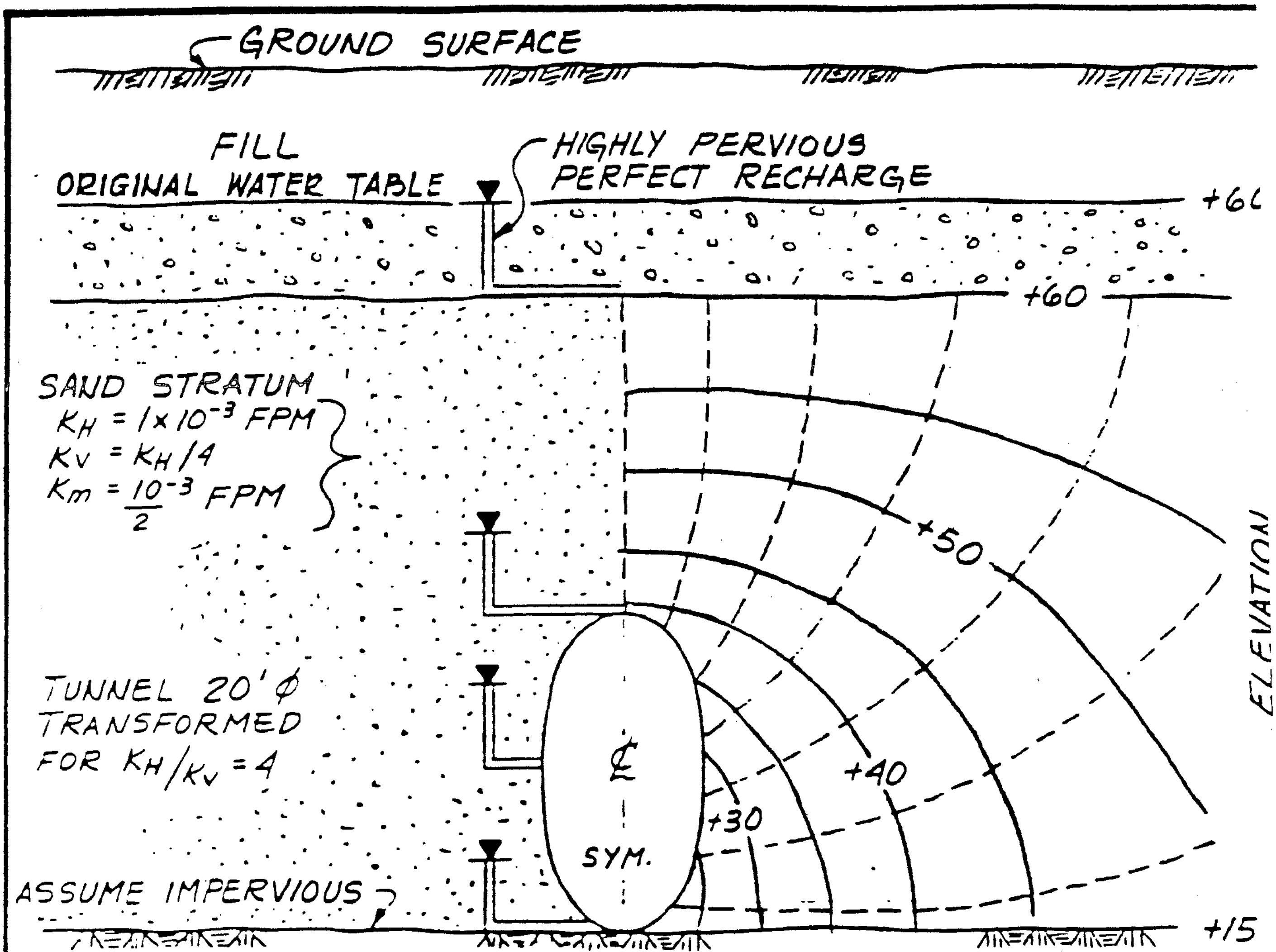
1/8"=1'-0"	JL	TPG 1987	5634

CROSS SECTION OF TYPICAL STATION IN ROCK

3-4



ΔH = HEAD LOSS IN SAND

n_f = NUMBER OF FLOW PATH

Δh = HEAD LOSS IN LINER

n_d = NUMBER OF HEAD DROPS

SHAPE FACTOR $f = n_f/n_d = 6.3/8 = .8$ FOR ½ FIELD

SHAPE FACTOR FOR FULL FIELD = 1.6

FLOW IN SAND STRATUM = $K_m \cdot f \cdot \Delta H$

$\Delta H = 45' -$ LOSS IN LINER

FLOW THRU TUNNEL LINER = $\dfrac{\Delta h \cdot \pi \cdot 20 (K_L)}{t}$

COMPATIBILITY OF FLOW REQUIRES :

$$K_m \cdot f \cdot (45 - \Delta h) = \frac{\Delta h \cdot \pi \cdot 20 \cdot K_L}{t}$$

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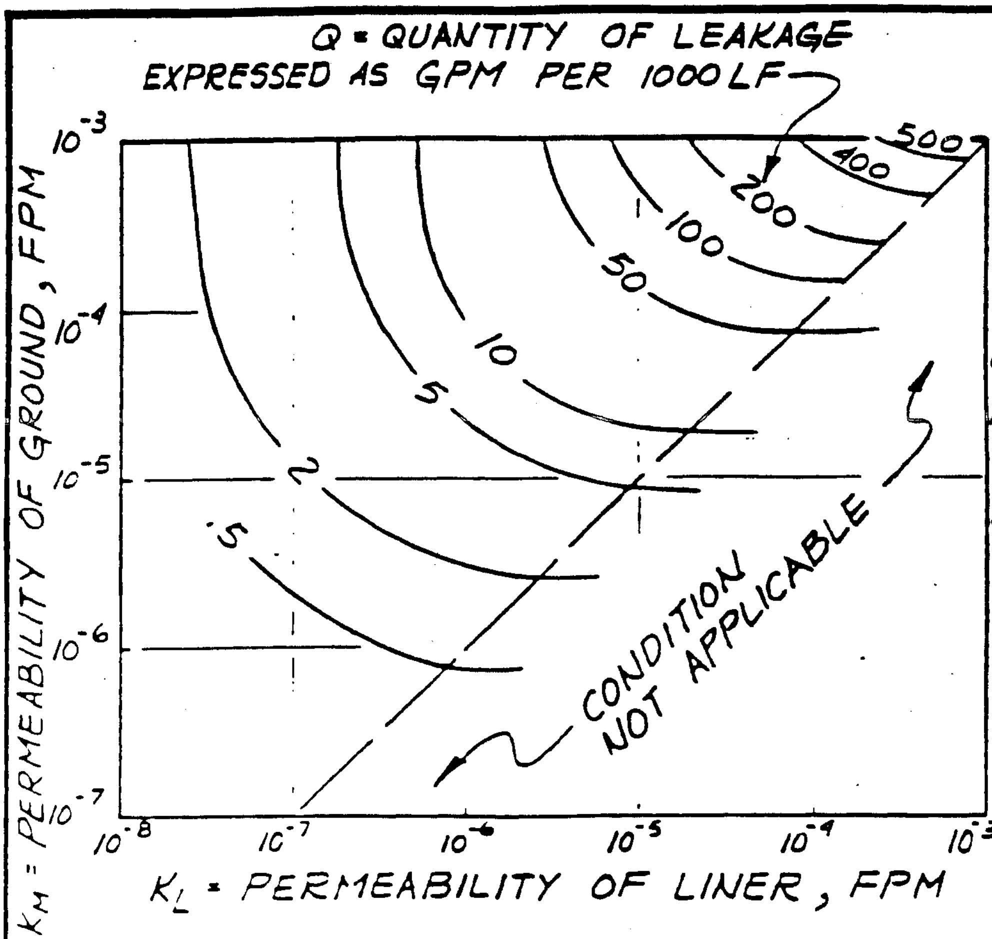
SCALE — MADE BY JL CHKD BY JPG DATE 1987	FILE NO. 5634
FLOW TO A LEAKY TUNNEL LINER	DRAWING NO. 3-5



Assume:

Flow net of Dwg No. 3-5

f = Shape factor = 1.6

t = Thickness liner = 1'

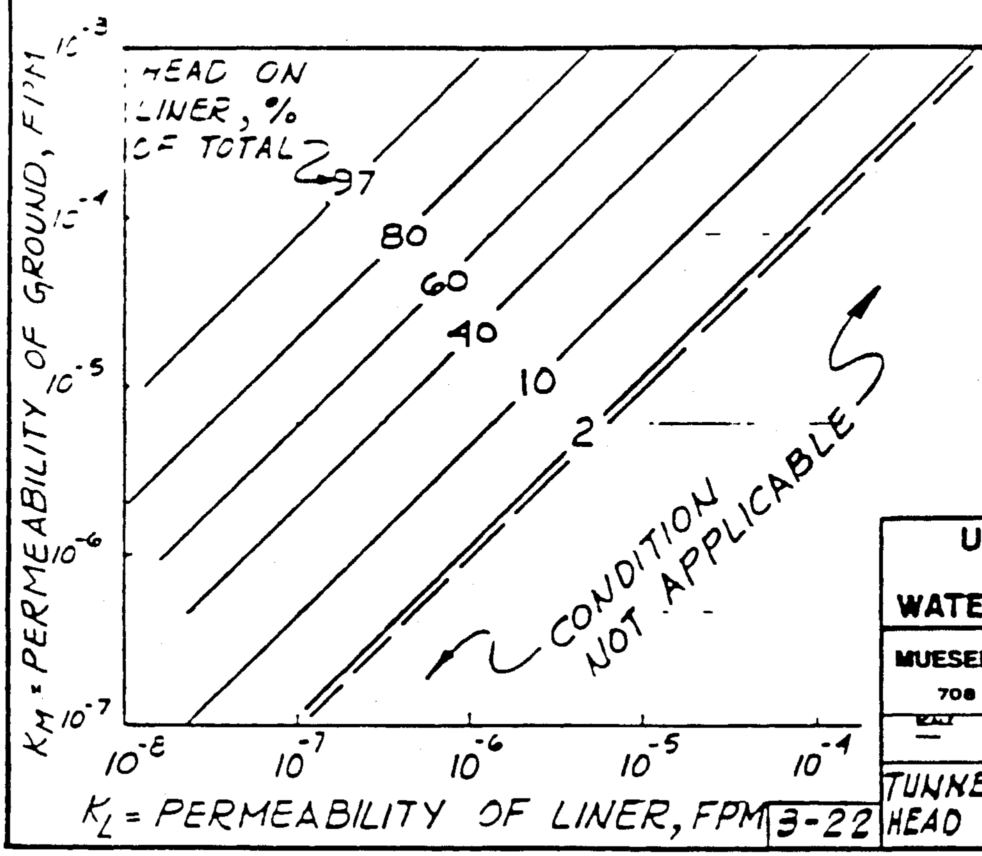
d = Diameter liner = 20'

K_M = Median permeability of surrounding ground

Δh = Head on outside of liner

45' = Total head of ground water on tunnel

$Q = K_M \cdot f \cdot (45 - \Delta h)$ per lf of tunnel



From Dwg. No. 3-5

$$K_M \cdot f \cdot (45 - \Delta h) = \Delta h \frac{\pi\, 20\, K_L}{t}$$

Substitute from above:

$$\Delta h = \frac{72\, K_M}{1.6\, K_M + 63\, K_L}$$

$$\frac{1}{\Delta h} = .022 + .875 \frac{K_L}{K_M}$$

3-22

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SCALE	MADE BY JL	DATE 1987	FILE NO. 5638
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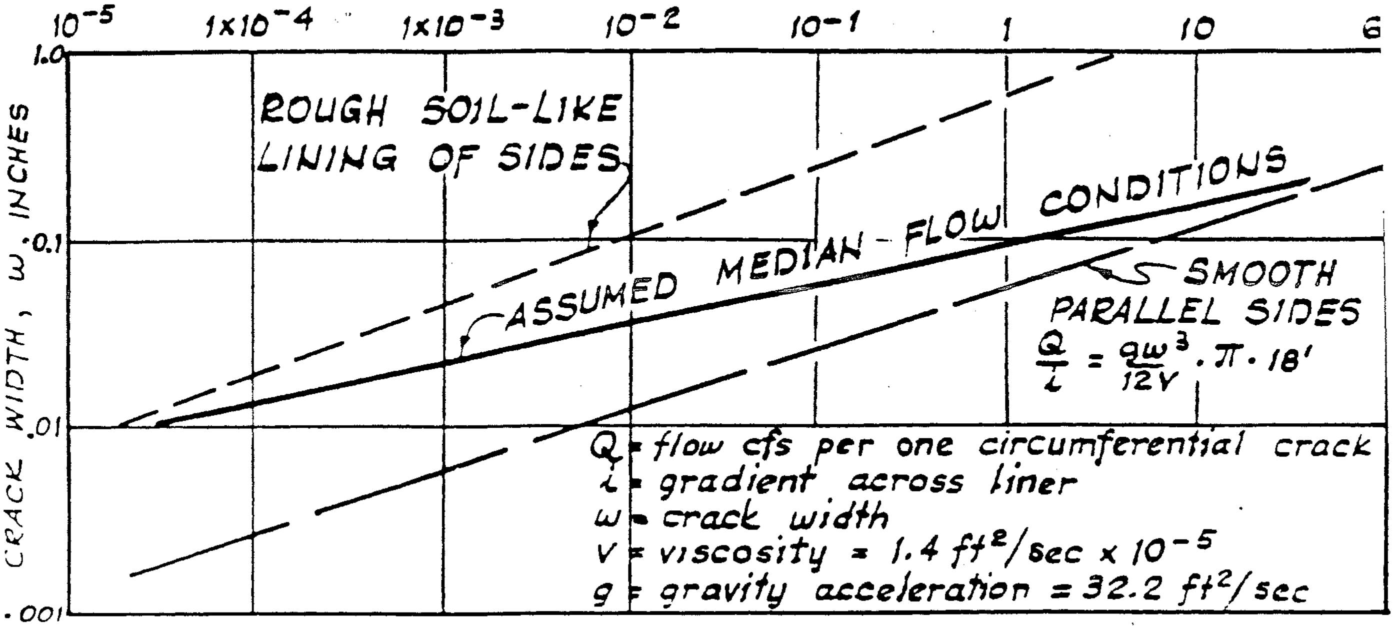
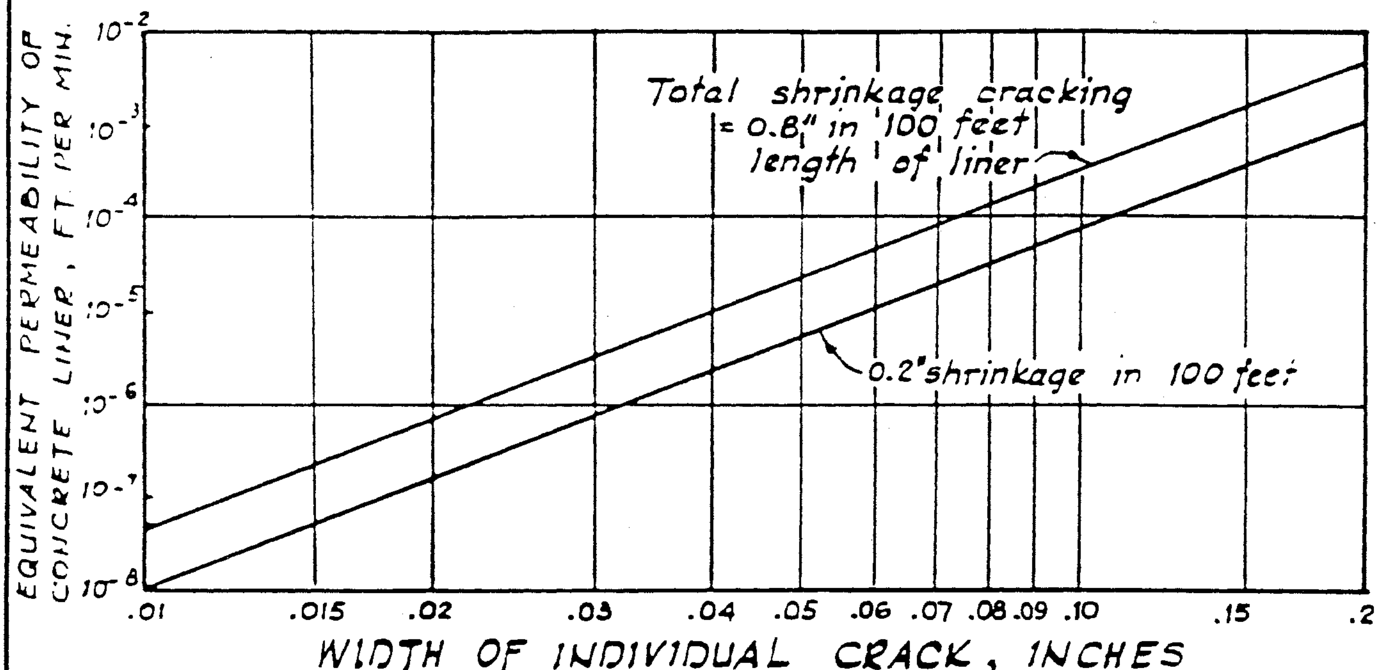
TUNNEL LEAKAGE AND HEAD VS RATIO K_M/K_L — DRAWING NO. 3-6





Notes: Liner is assumed to be cast-in-place concrete 18' in median diameter. Cracking is assumed to be spread evenly as cracks throughout the cross section.

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SCALE — MADE BY JPG CHKD BY DATE 1987 DATE	FILE NO 5634
CRACK WIDTH VS LINER PERMEABILITY	DRAWING NO 3-7

CHAPTER 4: CALCIFICATION, CAUSE AND EFFECT

4.1 Background of the Calcification Problem

Nine wide arch stations were constructed for WMATA in 1970 to 1980, eight on the Rockville Route and one, Rosslyn Station, on the Huntington Route. Characteristics of these stations, their drainage arrangements and the problems of leakage into the stations were summarized in Section 2.6 of Chapter 2. These stations are all positioned in metamorphosed sedimentaries of the Wissahickon formation. Bedrock strikes west of north, roughly paralleling the axis of the Rockville stations, with a steep dip westward. The stations' permanent support consists of shotcrete layers over heavy wide-flange steel ribs. The top of rail is in the range of 60 to 100 feet below ground surface. The stations are excavated largely in unweathered rock with typically 30 to 60 feet of rock cover above the crown of the opening. Within this space is the distinctive architectural lining which has become a hallmark of the Washington Metro System.

The station structural design loading consisted of a symmetrical rock load of "tent" shape, verified by analyzing load transfer from discrete rock blocks sliding in a direction controlled by the attitude of the rock joints. Hydrostatic pressures were assumed to be removed entirely be drainage into weepholes placed through the shotcrete and connected by collecting headers to the invert slab underdrainage system. The weepholes drilled into rock are typically two-inch diameter, eight feet long at 10 foot centers. These lead into collectors which open directly into the drainage layer beneath the track invert slab or into an access corridor on either side of the architectural concrete, carried from there by collector pipe to the track drain. The invert slab is underlain by a pervious layer which feeds the central drain pipe directed to the pumping sumps at intervals along the tunnel.

From the early stage of construction of these rock stations, problems developed with precipitates of calcium carbonate in the form of a white or grey sludge which hardened on exposure to air. Calcite is widely distributed in joints of the bedrock, in greatest proportion where the rock is most weathered, and has been carried into solution by moving ground water, precipitating where the inflowing water reaches atmospheric pressure in the station interior or in its drainage system. The small diameter cleanouts provided on the drainage header have thwarted efforts at maintaining unimpeded flow. The precipitate has clogged small diameter drains and decreased the effectiveness of the track underdrainage. It has covered drainage grates and seriously reduced the cross section of large diameter main drains. It interferes with pumping from sumps by forming a build up on pump impellers. All of this necessitates periodic cleaning and removal by labor-intensive methods, substantially increases maintenance activities and costs. Of potentially great importance is the possibility that clogging of the drainage system will permit a gradual buildup of water pressures outside the station's walls, imposing a load not considered in the original structural analysis. That possibility was investigated by DeLeuw, Cather and Co., as subconsultant to MRCE and was reported by them in Reference 3-1. The problem has long concerned the General Engineering Consultant and the Authority, and with each successive station design efforts were made in the layout of the drainage system to minimize problems with precipitates.

4.2 Experiences of Other Systems

4.2.1 MBTA Porter Square Station. Porter Square Station for the new Red Line extension of the Massachusetts Bay Transit Authority, completed in 1985, exhibits similarities to the WMATA rock stations (Reference 4-1). It is excavated in the local Cambridge argillite as a cavern 550 feet long, 70 feet wide and 45 feet high with a total depth to crown of about 70 feet. The argillite cover reaches 33 feet and the original water table is 58 feet above the crown. Drainage provisions consisted of an array of two inch diameter weep holes, typically eight feet long, at 10 foot centers, placed after the first shotcrete application, with slotted PVC pipes inserted. These led to 1½ inch diameter PVC collectors, each provided with a clean out opening. Structural support was similar to WMATA rock stations, consisting of several layers of shotcrete over 8WF40 steel ribs placed at five foot centers. The design loading followed the WMATA pattern with a symmetrical tent load assumed, verified by discrete rock blocks posing an asymmetric loading.

An array of piezometers was used to measure water head built up outside the shotcrete. In a manner similar to the WMATA experience there was unplanned pressure relief through cracks in the shotcrete lining of the chamber at rib locations. It was thought that fluctuating tensile stresses in the ribs were high enough to aggravate cracking of the adhering shotcrete. Water pressure measured in the piezometers was several feet of head outside of the shotcrete lining several years after construction. This value increased to a maximum of four feet, probably as a result of general return of the surrounding water table to its original level. Total inflow from the drainage system was less that one gallon per minute. As in other metasediments, a calcareous precipitate was carried by the flow through the lining. This appears to have sealed many cracks, contributing to the slight increase in hydrostatic pressure. However, there now appears to be an equilibrium, with some relief pipes clogging while new small cracks in the liner open, so that a balance is reached in the exterior water pressures. Measured compressive stresses in the steel ribs have reached maximum values in the range about 5 to 8 ksi, due to thrust from the rock overbreak loads. Exterior water pressures make an insignificant contribution to thrust in the ribs.

4.2.2 Baltimore Subway Procedures. WMATA experience with difficulties of drainage in rock prompted an evaluation of problems that might be encountered in Baltimore subway rock sections by specialists involved in both Washington and Baltimore systems. These studies lead to the following conclusions:

1. Invert drainage layers are rapidly clogged by introduction of water discharging from the tunnel weep holes directly into the granular drainage material.

2. Two inch diameter PVC pipes inserted within weep holes and drain lines were shown to be subject to clogging and damage by attempts to clean the pipe of precipitates.

3. One improvement considered was to substitute three inch diameter weep holes drilled at 15 foot centers through the cast-in-place liner after its completion, with additional holes where seeps appeared during tunneling. These would discharge in a vertical chase in the face of the tunnel liner to control the staining and confine formation of deposits.

4. Future plans were to consider the practicability of redesign to eliminate the need for hydrostatic pressure relief in running tunnels in rock.

4.3 The Calcification Process

4.3.1 Ambric Investigation. When the calcification problem was first encountered in the mid-1970's, Ambric Testing and Engineering Associates was retained by the General Engineering Consultant to test the precipitate and analyze its source. They reported in February 1976 (Reference 4-2) with the following conclusions from their work performed at Rosslyn and DuPont Circle Station:

1. The shotcrete lining did not appear to be damaged or deteriorated by the process which formed the calcareous precipitate. Neither the shotcrete nor the aggregate itself reacted when tested with the groundwater, indicating that the precipitate does not originate from the structural materials of the station lining.

2. The calcareous precipitate tends to seal cracks in the shotcrete and also to clog the invert drainage layer. Complete clogging of that layer seems to be inevitable in several decades. These developments point up the need for direct connection of any drainage lines with the main invert collector pipe and that well-placed clean out arrangements are essential.

4.3.2 Evaluation by U.S Geological Survey. Early in the MRCE study in 1983 a contact was made with the Groundwater Branch at the U.S Geological Survey Headquarters in Reston, VA. It was hoped to draw on their understanding of the basic mechanism of calcareous precipitate production. They repeated a common opinion that although concrete is often disfigured by unslightly efflorescence of lime, it is highly unusual for good quality concrete to be damaged or made unserviceable by leaching of lime from void spaces to create a surface precipitate. The chemical reaction that forms the precipitate is recorded in Drawing No. 4-1. As a solution (groundwater flow) contacts a vapor containing carbon dioxide (the atmosphere), the solution will lose carbon dioxide until equilibrium is established. The partial pressure of carbon dioxide is generally higher in groundwater than in rainwater. Solutions passing through soil also generally increase in calcium ion concentration. The precipitate of calcium carbonate in efflorescent crusts is related to the carbonate system's reactions. The occurrence of calcium bicarbonate in water in the Piedmont is not surprising since this is commonly associated with alumina-silicate-rich aquifers. The weathered metasediments contain high concentration of HCO_3 and CA^{++} which are conducive to the saturation of the groundwater with calcium carbonate.

4.3.3 <u>Studies for MRCE.</u> A report by Dr. R.S. DeSanto, scientist of DeLeuw Cather and Company, dated February 23, 1984, (Reference 4-3) was based on a field trip to Rockville Route stations on December 21, 1983. He identified the familiar mechanism of calcareous precipitation. Inhibitating precipitation would require shrouding the discharge of drains to maintain a back pressure in the gas above the discharge. Warmer temperatures within the transit structures encourage release of CO_2 from the draining water and concurrent precipitation. Adding acid to the discharge would restore the balance of hydrogen ions, limiting or delaying the supersaturation of the discharge with calcium carbonate.

A report of Prof. W.B. White of February 17, 1985 was based on inspection and tests of March 5, 1984 (Reference 4-4). His tests were performed on samples of leaking water and the precipitates and involved measurements of pH values and chemical constituents. The presence of relatively high sulfates in the water tested suggests that DuPont Circle and Van Ness stations leakage had a contribution from combined storm drains with sanitary sewers which included organic materials. The majority of samples taken indicated supersaturation of the inflowing water with calcium carbonate. He also noted that typically there is a substantial content of calcium carbonate available in the profile of weathering in metasediments. Experience with the intensity of precipitation indicated that the concentration is greatest where weathering extends closest to the station opening and is the least where igneous intrusions have most altered the metasediments of the country rock.

4.4 Field Test of Waterproofing Compounds

In a month from November to December 1983, a field test was conducted in an exterior corridor at DuPont Circle station and in one at Rosslyn station to assess the performance of waterproofing compounds on the shotcrete liner and to determine the accompanying increase of exterior pressures. Attention was focused on the two oldest stations mined rock, where it was feared that calcification would eventually clog drains and allow build up of excessive pressures on the shotcrete liner between steel ribs. Application of the materials was carried out by Technical Grouting, Inc. under contract to MRCE and funded out of the MRCE portion of the study grant. Table No. 3 summarizes the chronology of contract work and studies at the two stations. The Contractor's field work occupied one full month between November 16 and December 16, 1983.

The program consisted of the following operations:

1. Three proprietary waterproofing compounds were applied on individuals panels in DuPont Circle station and three other compounds on panels at Rosslyn station. Each compound was utilized in accordance with manufacturers' instructions and in most cases manufacturers' representatives were present at the time of application to provide guidance.

2. Water pressure gauges adapted and supplied by Goldberg-Zoino and Associates (GZA) were installed in weep holes

which had been previously drilled through the shotcrete lining at DuPont Circle and into the exterior rock (Reference 4-5). At Rosslyn station gauges were attached to the drainage collector lines which lead from the weep holes above the rock arch through the shotcrete lining and discharge water into the floor drain at the outside of the architectural concrete. The purpose was to measure the change of water pressure outside the shotcrete lining as the lining was sealed by application of the waterproofing compounds.

3. MRCE field personnel made periodic visits to the test sections, photographing the results, observing the performance of the waterproofing, reading the water pressure and strain gauges and reporting general conditions in the test corridors.

Location of the test panels in the cross section of Dupont Circle station is illustrated on Drawing No. 3-4 and the position in plan with the detailed results at the waterproof panels are shown in Drawing No. 4-3. For Rosslyn Circle station a similar cross section with the location of the work is shown on Drawing No. 4-1 and the specific results are noted in longitudinal section on Drawing No. 4-2. Samples of the water leaking from a number of the stations in rock were obtained by Engineering Sciences, Inc. in September of 1983 and tested by them. Their test report is included in the appendix volume. Water samples of the precipitate were obtained by Professor William White of Pennsylvania State University in 1984 working under contract to MRCE and the report of his test results also appears in the appendix.

Assessment of the waterproofing tests is depicted on the longitudinal sections showing the face of the waterproofing panels in Drawings No. 4-2 and 4-3 and discussed in the following text sections. It should be noted that the conditions of testing these waterproofing compounds were far from ideal. In the corridor of Dupont Circle station there was a continual drip on the water-proofed panels from leaks above in the station arch which interfered with curing of certain compounds. Both test locations contain shrinkage cracks of various widths and in Dupont Circle station the face of the panels was perforated at frequent intervals by weepholes. The performance of any of these compounds in this special situation does not necessarily reflect their effectiveness in better controlled interior waterproofing situations.

4.4.1 <u>Dupont Circle Station Test.</u> Three waterproofing products were utilized in the inbound corridor outside the architectural lining: Five-Star, IPA Drycon, and Hey-Di Rapid. The shotcrete to be waterproofed had been sprayed on a vertical rock excavation face 20 feet high, applied in three coats of two inches. It presented a relatively smooth, undulating surface lacking the reflection cracks which accompanied the ribs in the station arch roof. The shotcrete varied from four to eight inches thick and was generally hard and sound. Leaking water charged with precipitates dripped from above on the shotcrete surface. The shotcrete was punctured by two rows of weepholes at about 10 foot intervals vertically and horizontally. Each material was applied in panels about 65 feet long, extending from the invert to a height of 12 feet. Dripping from above complicated the determination of leaks that were occurring directly through the treated shotcrete surface. These three products were coatings which bonded to the surface without supposed crystallizing within pore spaces of the shotcrete.

The shotcrete surface was cleaned with a water blaster using a pressure of 1,000 psi. After cleaning, all of the penetrating weepholes were plugged with "Thorite" sealer except for those holes which were to receive pressure gauges. The gauges consisted of a porous probe, packer and Bourdon gauge attached. Three gauges, PG-1, PG-2 and PG-3 were installed in the three test panels. Gauge PG-4 was placed on the inbound corridor beyond the panels. PG-5 was installed in the outbound corridor on the opposite side of the station arch as a control.

On Panel WP-4 the Five-Star product was spread by hand using rubber gloves. Ten, 100 pound bags were spread over 700 square feet of the panel to make a single layer 1/8 inch thick; 25 pounds of the material being mixed with two quarts of water. The results expressed in terms of the condition of the plugged weepholes and the presence of continuing leaks through the panel are tabulated on Drawing No. 4-3 with a description of the pressure gauge fluctuation in the panel.

On Panel WP-5 for the IPA Drycon, the cleaned shotcrete surface was sprayed with a bonding agent then the material was brushed on in three coats, except the end 15 feet of the panel which received two coats. These successive coats were applied with a coloring agent of white and gray. In the humid environment and in the presence of dripping moisture curing of a coat took more than a day. The application was damaged by drips from above while still soft. Eleven, 50 pound bags were used to cover 700 square feet of panel in the first coat.

The Hey-Di Rapid was brushed onto the surface of the prepared Panel WP-6 in a single coat which required a bonding agent on the prepared surface. Because of the lack of supply, type 1 Portland cement was added in completing the end of the panel. The set-up time was rapid and the material easily applied by brushing.

4.4.2 <u>Rosslyn Station Test</u>. Three waterproofing panels were set up in the inbound corridor utilizing Vandex, Xypex and Hansit between station 140+50 to 142+50. The shotcrete here had been applied on steel ribs over wire mesh with a average total thickness between four and six inches, but there were substantial area of broken shotcrete and exposed rock. While there were few interferences with the application, the surface of the shotcrete was much less regular and smooth and generally was more difficult for the application of waterproofing materials than in the Dupont Circle station corridor.

The existing hydrostatic pressure relief system consisted of numerous weepholes across the station arch at the standard spacing, which were connected to small diameter plastic drainage collectors which followed a line down the arch and dripped onto the base of the corridor to flow into the collecting drains. The station cross section is shown on Drawing No. 4-1.

The pressure gauges were inserted in the discharge line of the hydrostatic pressure relief system and those line that did not receive pressure gauges were plugged. The purpose was to simulate to the extent practical a sealing not only of the surface of the shotcrete by also of the HPR system.

Vandex was placed in Panel WP-7 with two coats brushed on the shotcrete. This is a "crystallizing" compound which is mixed with water in a two to one proportion by volume. The second coat could be brushed on within 20 minutes after the first application. The contractor suggested that the consistency of the mixture would have readily permitted it to be sprayed on the surfaces. Gauge PG-5 was installed in an HPR pipe in this panel.

Xypex is a similar crystallizing compound mixed with three parts of the powder to one water, producing a thin paste-like consistency. After brushing on the first coat, a curing compound was sprayed over the surface and a second coat applied in Panel WP-8. Gauge PG-7 was placed in this location.

Hansit was applied in two brushed coats to Panel WP-9 with a sealing agent spread on the final coat. The material was applied as a cement-water mix with each 55 pound bag blended with 1-3/4 gallons of water to form a thick past consistency. Six bags were used for the complete first coat and two for the partial second which constituted all the material available. Gauge PG-8 was installed at the Hansit-treated section and PG-9 was placed on a HPR discharge at an untreated section adjacent on the south.

Observations of the results of these applications and the build up in the pressure gauges installed are noted on Drawing No. 4-2.

4.5 Conclusions on the Calcification Problem.

A review of experiences in other metasediments in Baltimore, Boston and New York indicated that the precipitation of calcium carbonate from inflowing groundwater is a common condition. The sedimentary origin and the near approach of bedrock weathering to transit tunnels in these rocks offer ample calcite to saturate the groundwater converging on the tunnels. Calcium carbonate precipitates when carbon dioxide is released as confining fluid pressures are reduced to atmospheric.

The superficially simple control methods of hooding the drain outlet to maintain a back pressure or adding acid to the discharge are not considered practical solutions in the conventional drainage arrangement; but drain lines or weepholes should be kept submerged until the discharge reaches a point where the precipitate can be broken and removed. The drain line opening should be as large as practical. Inflowing water, if allowed to diffuse through a pervious granular underdrainage layer, can cause a progressive decrease in the ability of the layer to function. The NATM filter and waterproofing membrane appear to offer a near-ideal solution to the problem. The complete confinement of the fleece may allow sufficient back pressure of contained gas to build up to prevent precipitation within the fleece.

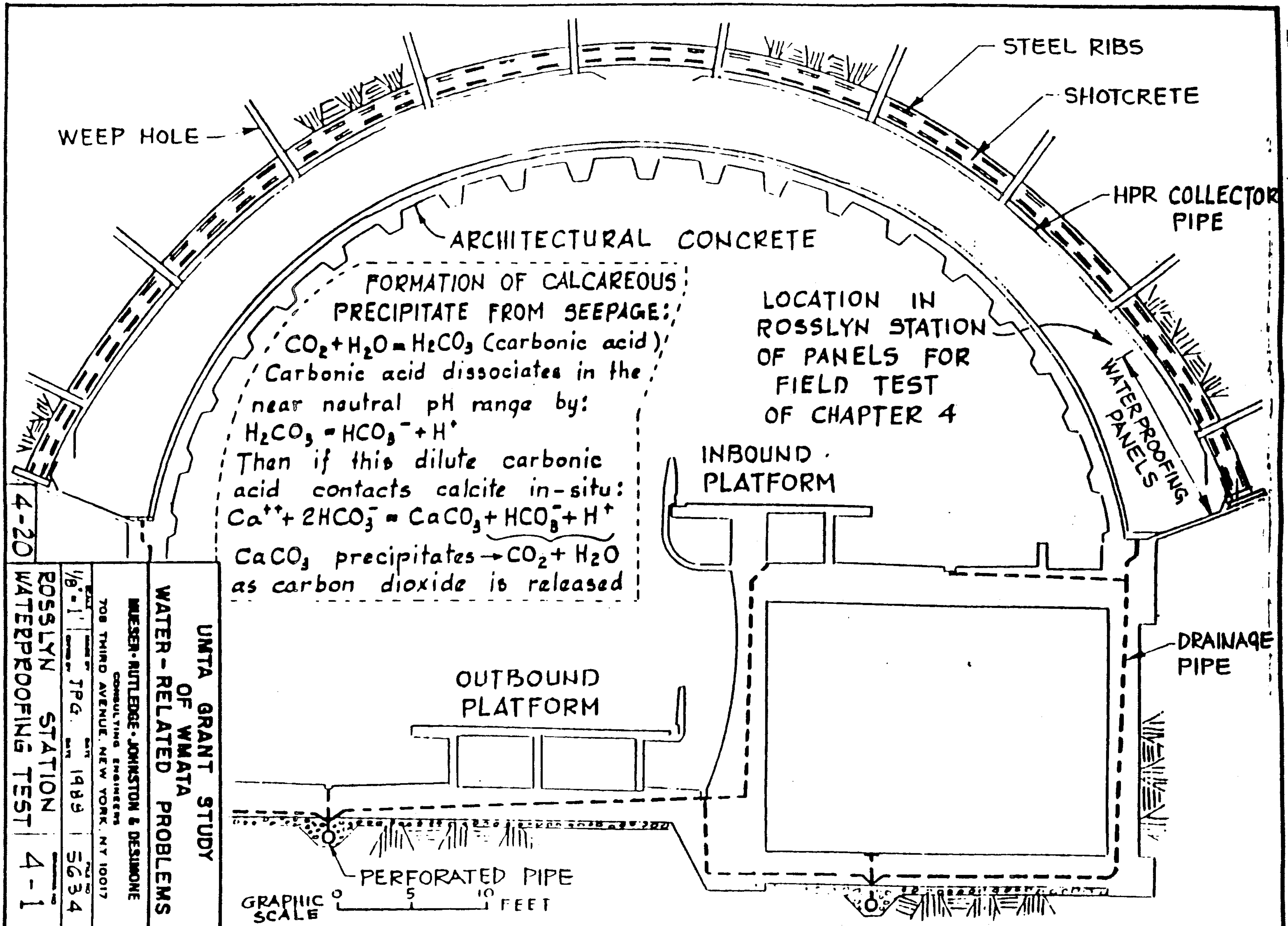
Waterproofing compounds were tested in two rock stations in an effort to force a build up of exterior water pressures to simulate the effect of drainage throttled by precipitates. The maximum water pressures which could be build up over an interval of six months amounted to four to six feet of head behind panels which had used the thick brush-on membrane waterproof compounds. After several years these maximum pressures stabilized or slightly decreased. This experience is directly comparable to the observed performance at the MBTA Porter Square station where plugging of small weepholes by calcite was offset by the continuing development of reflection cracks in shotcrete adhering to the heavy steel ribs. The strains indicated by the gauges placed on the shotcrete skin were so small as to be within the range of the instrument error. Considering the propensity for cracking of the shotcrete to continue in these broad arch rock station, there appears to be no practical threat to the structural lining due to future increase in exterior water pressures.

The secondary purpose of the test in the two rock stations was to evaluate the efficacy of a group of six commercial waterproofing compounds. Four of these were of the membrane type, the remaining two were "crystallizing capillary" materials. The test conditions were difficult, involving random uncontrolled leaks and active weepholes in shotcrete of varying thickness, and, in some cases, continuing drip of leaking water on the treated surface. Judging by the effectiveness of the seal and the magnitude of water pressure build up, two of the membrane materials gave the most favorable results. A third could not properly set up in the humid environment. The crystallizing compounds were the least efficient. In their ordinary intended use on formed concrete surfaces their performance could be more effective.

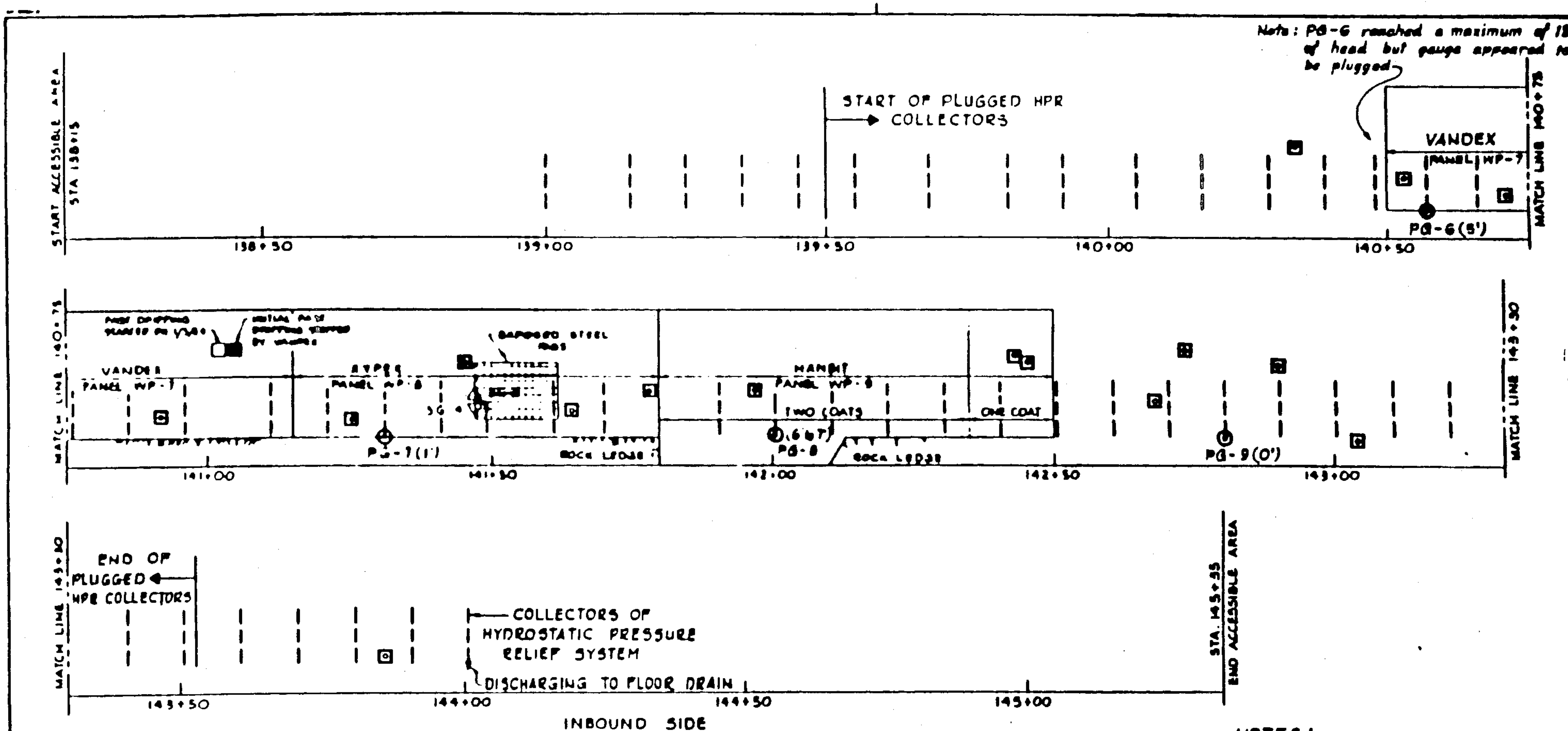
It was generally acknowledged by the manufacturers of these compounds that cracks wider than about 0.02 to 0.03 inches cannot be properly sealed by merely brushing the compound on the negative side or interior surface. Transit tunnels with their seasonal temperature changes and repeated train vibrations present a distinctly unfavorable environment for the success of such applications.

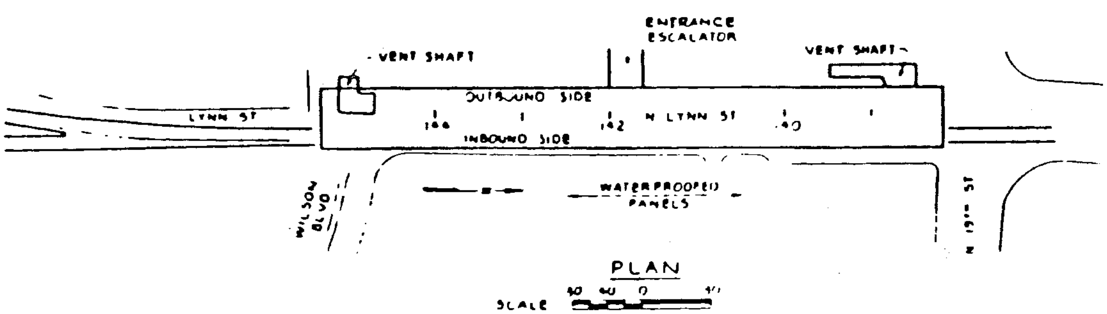
TABLE NO. 3, CHRONOLOGY OF WORK
FOR FIELD TESTS IN DUPONT CIRCLE AND ROSSLYN STATIONS

Date	Event
Sept. 30, 1983	Invitation to bid on waterproofing application sent to three specialist contractors.
Oct. 21, 1983	Bids received: Low = $19,991., High = $32,536. Engineer's Estimate = $30,500.
Oct. 28, 1983	Notice to proceed to low bidder, Technical Grouting Services, Inc. of Hyattsville, MD.
Nov. 16, 1983	Work starts on waterproofing panels in west (inbound) corridor of DuPont Circle Station.
Nov. 29, 1983	Completed panels at DuPont Circle Station.
Nov. 30, 1983	Start on waterproofing panels in east (inbound) corridor of Rosslyn Station.
Dec. 2, 1983	5 Water pressure piezometers with Bourden gauges and 2 strain gauges installed in DuPont Circle by Goldberg Zoino representative.
Dec. 16, 1983	Completed panels at Rosslyn Station.
Dec. 21, 1983	4 Water pressure piezometers with Bourden gauges and 2 strain gauges installed in Rosslyn Station by Goldberg Zoino representative.
Dec. 30, 1983 to May 8, 1984	Readings on piezometers and strain gauges at approximate 2 week intervals by MRCE staff.
Jan. 16, 1984	Post-application report on waterproofing work submitted by Technical Grouting Services, Inc.
Jan. 24, 1985	Inspection of waterproofing panels and reading of piezometers and strain gauges by MRCE engineer.
Jan. 2, 1986	Inspection of waterproofing panels and reading of piezometers and strain gauges by MRCE engineer.



STEEL RIBS
SHOTCRETE
WEEP HOLE
HPR COLLECTOR PIPE
ARCHITECTURAL CONCRETE
FORMATION OF CALCAREOUS PRECIPITATE FROM SEEPAGE:
$CO_2 + H_2O = H_2CO_3$ (carbonic acid)
Carbonic acid dissociates in the near neutral pH range by:
$H_2CO_3 = HCO_3^- + H^+$
Then if this dilute carbonic acid contacts calcite in-situ:
$Ca^{++} + 2HCO_3^- = CaCO_3 + \underbrace{HCO_3^- + H^+}$
$CaCO_3$ precipitates $\rightarrow CO_2 + H_2O$
as carbon dioxide is released
LOCATION IN ROSSLYN STATION OF PANELS FOR FIELD TEST OF CHAPTER 4
WATERPROOFING PANELS
INBOUND PLATFORM
OUTBOUND PLATFORM
DRAINAGE PIPE
PERFORATED PIPE
GRAPHIC SCALE 0 5 10 FEET
4-20
UMTA GRANT STUDY OF WMATA
WATER-RELATED PROBLEMS
MUESER·RUTLEDGE·JOHNSTON & DESIMONE
CONSULTING ENGINEERS
708 THIRD AVENUE, NEW YORK, NY 10017
1/8"=1'
JPG
1989
5634
ROSSLYN STATION
WATERPROOFING TEST
4-1





NOTES:

1. For explanation of symbols see Dwg No. 4-3

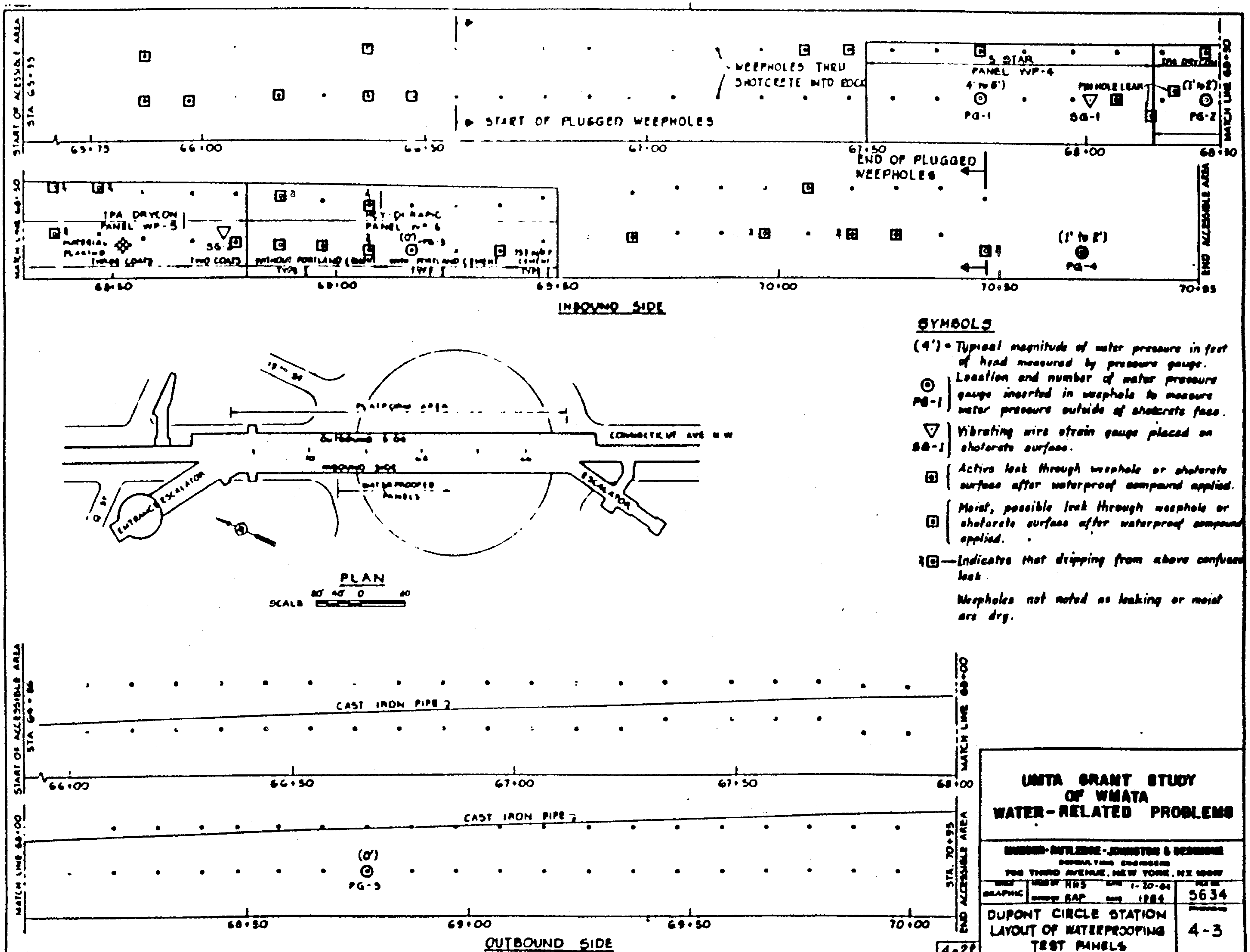
2. Pressure gauges were placed with probe points inside plugged HPR collector pipes. Readings of feet of head measured at these gauges are typical values from 6 months to 2 years after installation.

PROFILE SCALES
GRAPHIC
HORIZONTAL 10' 0 10' 20'

UMTA GRANT STUDY OF WMATA WATER-RELATED PROBLEMS

MUESER · RUTLEDGE · JOHNSTON & DESIMONE
CONSULTING ENGINEERS
708 THIRD AVENUE, NEW YORK, N.Y. 10017

GRAPHIC	HHS	1-30-84	5634
	RAF	1984	


START OF ACCESSIBLE AREA STA 65+75
WEEPHOLES THRU SHOTCRETE INTO ROCK
START OF PLUGGED WEEPHOLES
5 STAR PANEL WP-4
(4' to 8')
PG-1
PINHOLE LEAK
SG-1
IPA DRYCON
(1' to 2')
PG-2
MATCH LINE 68+50
65+75
66+00
66+50
67+00
67+50
68+00
68+50
END OF PLUGGED WEEPHOLES
MATCH LINE 68+50
IPA DRYCON PANEL WP-5
MATERIAL FLAKING
THREE COATS
TWO COATS
SG-2
PANEL WP-6
WITHOUT PORTLAND CEMENT TYPE I
WITH PORTLAND CEMENT TYPE I
(0')
PG-3
(1' to 2')
PG-4
END ACCESSIBLE AREA
68+50
69+00
69+50
70+00
70+50
70+85
INBOUND SIDE
PLATFORM AREA
OUTBOUND SIDE
INBOUND SIDE
WATERPROOFED PANELS
CONNECTICUT AVE N.W.
ESCALATOR
ENTRANCE
ESCALATOR
PLAN
SCALE
SYMBOLS
(4') = Typical magnitude of water pressure in feet of head measured by pressure gauge.
PG-1 Location and number of water pressure gauge inserted in weephole to measure water pressure outside of shotcrete face.
SG-1 Vibrating wire strain gauge placed on shotcrete surface.
Active leak through weephole or shotcrete surface after waterproof compound applied.
Moist, possible leak through weephole or shotcrete surface after waterproof compound applied.
Indicates that dripping from above confuses leak.
Weepholes not noted as leaking or moist are dry.
START OF ACCESSIBLE AREA STA 65+86
CAST IRON PIPE
MATCH LINE 68+00
66+00
66+50
67+00
67+50
68+00
MATCH LINE 68+00
CAST IRON PIPE
(0')
PG-5
STA. 70+95 END ACCESSIBLE AREA
68+50
69+00
69+50
70+00
OUTBOUND SIDE
4-22
UMTA GRANT STUDY
OF WMATA
WATER-RELATED PROBLEMS
MUESER RUTLEDGE JOHNSTON & DESIMONE
CONSULTING ENGINEERS
708 THIRD AVENUE, NEW YORK, N.Y. 10017
GRAPHIC
HHS
RAP
1-20-84
1984
5634
DUPONT CIRCLE STATION
LAYOUT OF WATERPROOFING TEST PANELS
4-3

CHAPTER 5: ACID WATER INTRUSION, CAUSE AND EFFECT

5.1 Background of the Problem

Section G002 of Addison Route is located southwest of the "Fall Line" and south of the Anacostia River, entirely within the Coastal Plain geologic province, between Stations 347+40 and 474+15. The subway consists of two circular, cast-in-place concrete-lined, single-track tunnels. Construction commenced in December 1976 with basic structural work completed in June 1978. The shield-driven, soft-ground tunnels were positioned entirely in Cretaceous sediments of the Potomac group consisting of inter-layered clay of Stratum P1 and clayey or silty sands of Stratum P2 which contained scattered lenses and concentrations of carbonized organic material in the form of lignite. Specifications required extensive drawdown of piezometric levels for the tunneling. The contractor installed a number of deep wells which lowered piezometric levels to below the tunnel springline. Some thick undrained sand zones where water was trapped above clay lenses caused local runs leading to loss of ground at the face. As a consequence of these difficulties with face stability, a section of both tunnels roughly 600 feet long remained open for a relatively long period while injecting chemical grout in the surrounding soils between Stations 371 and 377. The construction history is described in Reference 5-1.

During 1978 before final concreting of the tunnel lining, seepage flowing through the rib and lagging initial supports proved to be highly acidic with pH values as low as 1.7 and a median pH of 2.8 during that time. Intense corrosion of the steel sets of the temporary supports and of sheet metal forms for casting portions of the invert was experienced. Corrosive conditions were most active between Stations 371 and 384.

After the permanent concrete lining was poured and contact grouting complete, the acid attack continued because of vigorous leaks through construction joints and shrinkage cracks in this section. Inflowing seepage continued to be highly acidic and iron staining was intense near the leaks. Lowest pH values were found where groundwater was at the lowest level in the ground surrounding the tunnel; presumably where inward directed gradients were a maximum. Extensive maintenance difficulties were foreseen and the possibility of a major long-term threat to the structural integrity of the concrete final liner was envisioned.

The location of Section G002 in the overall central subway system is shown at the lower right in the plan of Drawing No. 1-1. Basic information on the problem of acid intrusion is illustrated on the following drawings included in this chapter:

No. 5-1, "Mechanics of Acid Production";
No. 5-2, "Cross Section at G002 Running Tunnels";
No. 5-3, "Profile of Conditions, G002 Acidic Inflow";
No. 5-4, "Chronology of G002 Acidic Inflow".

5.2 Chronology of Investigations

Because of concern for possible damage from acid water attack on the cast-in-place concrete lining, the invert and track supports, investigations were initiated by WMATA as construction was being completed in 1978. Studies continued by a number of organizations from that date until completion of MRCE field studies in January 1986. A chronology of events in this period is presented in Table No. 4 following the text of this chapter.

Investigations commenced with sampling of leaking water and pH determinations by DCCo assisted by the General Construction Consultant, Bechtel Associates. WMATA retained the firm of Geraghty & Miller, Inc. in March 1979 to investigate the acid groundwater condition. At their direction, MRCE contracted for four monitoring wells to be drilled in the vicinity of the acidic inflow to observe water levels and to collect groundwater quality data. The position of one of these wells, GM-1, is shown at the left of the cross section in Drawing No. 5-2 which depicts the tunnels within the Cretaceous strata. These wells were used as a means of sampling in addition to samples taken from existing observation wells of the design exploration program. Periodic rounds of water samples were taken from all the wells and from seeps through the tunnel liner during this sampling period.

In that study, the pH of seeps in the tunnels and of the well water between Stations 369 and 392 ranged from 1.7 to 6.5. Sulfate concentrations in sampled water in the tunnels and from the wells ranged from several hundred to as high as 13,000 parts per million. No significant changes in water quality were noted during the 6-month period of the Geraghty and Miller investigation from March to September 1979.

Six, 3" diameter concrete cores were recovered by Bechtel Associates field forces drilling through the permanent concrete tunnel lining in 1979. Tests performed by Erlin, Hime Associates included microscopic examination of the concrete cores and chemical tests of the constituent materials. The cause of the acid production in Section G002 was first suggested by engineering geologists for Bechtel Associates and the General Engineering Consultant, Messrs, C.G. Bock and C.W. Daugherty, respectively. Specialists at the University of Maryland and at the University of South Carolina identified the specific mechanism of acid production. Chemical reactions are summarized in Drawing No. 5-1. Both groups were retained by WMATA to test soil samples from borings then being made in design investigations of new tunnel sections. The General Engineering Consultant monitored flow from leaks in the G002 liner and sampled leakage from other sections of the system. Their work continued from September 1979 to March 1982. The conclusions by these investigators are summarized in Section 5.3.

Because of the extensive maintenance problems which the acid inflow could cause to trackage, utilities and lining, the acid water intrusion became a principal topic of the UMTA-sponsored investigation. In January 1983, the MRCE study commenced by sampling the monitoring wells previously installed. This was followed by a second round of coring of the liner in six locations in June 1983. Water sampling continued periodically to January 1986. Using observations of construction conditions by Bechtel Associates, sampling by DCCo and MRCE, MRCE studied factors contributing to the acidic inflow, as reported in Section 5.4. The generally accepted conclusion was that the Cretaceous sediments containing lignite and sulfur in the form of pyrite and marcasite produced sulphuric acid in the groundwater when exposed to oxygen. The process was reinforced by continuing seepage toward the leaking tunnel which maintained acid production.

5.3 Mechanism of Acidic Water Production

5.3.1 Acid Mine Waste: Similar problems on a larger scale are encountered with mine drainage water flowing through coal measures or sulfur-charged mine debris (Reference 5-2). Oxidation of sulfur-rich minerals produces ferrous iron and sulfuric acid in the discharge water. Bacteria act as a catalyst in the oxidation process. The result is elevated levels of iron, sulfate and a lowered pH in the discharge. Most stream pollution comes from abandoned mines rather than modern active coal mines, many of which have acid abatement procedures. For abandoned workings, the condition can be moderated by mine sealing techniques; but these often are only marginally successful unless the passage of air through the old workings is retarded. Other methods include controlled roof collapse, water diversion, bacteria inhibition and improved drainage. Lime neutralization with aeration is a standard method of treating draining water.

5.3.2 Carrucio-Geidel Studies Their work was initiated by DCCo as subcontractors to MRCE in 1979 and was summarized in two reports, on October 6, 1979 and on April 30, 1980 (References 5-3 and 5-4). In their view, acid content of leachate in sulfur-rich ground depends on: relative weight of contained sulfur, type of pyrite crystal form, overall acidity or alkalinity and background factors such as the presence of iron-producing bacteria and access to oxygen. Their first WMATA studies comprised tests of soil samples from Section G002 borings. These exhibited relatively low total sulfur content but included fine grained pyrite crystals in all samples at the location of acidic seepage. They concluded that acid-producing sulfides were commonly contained in clay and clay-like constituents. The acid problem was most acute in horizons where a clay-sand interface exists, in particular where a water-bearing sand layer is juxtaposed with an acid-producing clay. They note that USGS publications emphasize the presence of lignitized wood in the upper Potomac Patapsco formation compared to the lower Potomac Patuxent group. Section G002 is in upper Potomac strata with bedrock at Elev. -900, the top of Cretaceous at about Elev. +150 and the tunnels at Elev. +40.

The April 1980 report summarized tests on 20 samples from Sections F003 and F004 of Branch Route which were then being explored for final design. Carrucio-Geidel determined total weight of sulfur, the crystalline character of the pyrites and tested to leach soluble constituents. Samples included recent alluvium, Pleistocene terrace soils and Cretaceous materials. They concluded that the darker the color of the soil, the greater its organic content and the higher percentage of included pyrites. The coarser grained samples exhibited lower sulfur content than the fine grained Cretaceous samples. Recent river organic silt clearly exhibited the greatest acid-producing potential of the samples.

<u>5.3.3 Foss-Wagner Studies</u> Foss-Wagner studied the occurrence of acid soils in the Maryland Coastal Plain (Reference 5-5) at the University of Maryland. In November 1980, they met with WMATA and MRCE representatives to commence testing for acid producing soils within the subway system. Samples were provided to them from borings in Section F003. Tests of these samples were reported in March 1982. Sulfides, notably pyrites, are ubiquitous in sediments formed in brackish or shallow tidal water which includes many phases of the Coastal Plain series, both Cretaceous and Tertiary. Weathering of sulfides to form acidic sulfate soils called "cat clays" is a problem throughout the Maryland Coastal Plain. Their experience has been that strata which are dominated by clay-sized minerals can be reactive, while coarser grained strata dominated by quartz are relatively inactive. The presence of pyrites is indicated by organic frag-

ments, either fresh or materials carbonized to lignites. Their dark colors result from the presence of organic compounds associated with reduced sulfidic strata as well as the darkness of metallic sulfides themselves.

In many instances, sulfide-bearing strata may be thin and laterally discontinuous, particularly in the Potomac series. Lower Cretaceous typically contain large pyrite crystals that are discernable to the eye and are associated with lignite fragments. In younger deposits pyrite crystals were not discernable without magnification. Microscopic clusters, known as "framboids," because of their smaller size and proportionally greater surface area are more reactive than the large pyrites. In their tests on Section F003 samples, the lower Pleistocene terrace materials containing unoxidized fresh organic materials, designated in the WMATA classification system as Stratum TO, showed a moderate potential for acid production. The companion sandier lower terrace Stratum T4 showed slight potential.

5.4 MRCE Studies of Acid Intrusion

There were four principal purposes in the on-going studies undertaken by MRCE for the WMATA investigation in January 1983:

1. Determine the hazard posed by acidic groundwater to the exterior of the cast-in-place concrete lining;

2. Determine the changes with time in the acidity of the surrounding groundwater and the inflowing seepage;

3. Determine the background factors affecting acid production;

4. Evaluate measures to moderate or eliminate the acid water intrusion.

A number of inspections of G002 conditions were carried out through 1983 by MRCE engineers K. Westermann and J. Vigilanti. A first step in the MRCE field program was to purge the four monitoring wells installed in 1979 to sample the contained groundwater. This work was carried out by the construction dewatering and groundwater development firm, Division 2. Sampling information obtained by DCCo was complied and consolidated. A second round of coring of the concrete tunnel lining was carried out by WMATA maintenance forces under MRCE direction in June 1983. The liner cores were examined by Erlin, Hime Associates, who reported on November 3, 1983 to MRCE. The upper panel of Drawing No. 5-6 illustrates a scheme proposed by DCCo for maintaining a concrete test core in contact with the exterior groundwater, allowing periodic removal for examination and test.

A packer devised by F. Gregory of Warren George, Inc., which was controlled by a valve and allowed sampling of the groundwater at the core hole locations, was installed in each of the six cored holes. A detail of that packer is shown in the lower panel of Drawing No. 5-6. Periodic sampling of leakage continued through January 1986.

A synoptic view of the G002 tunnels in profile, the lowest measured pH values, speed of tunneling, and location of grouting is shown on Drawing No. 5-3. Drawing No. 5-4 shows the progression of change of pH values and groundwater levels with time. On Drawing No. 5-5 are plotted more details of the subsoil profile from the MRCE pre-construction exploration, contours of pH values at the end of active tunneling in 1978, the location of core holes and information on rate of tunnel advance.

5.4.1 Experience in Mining Section G002 The following information is obtained chiefly from a detailed report by Bechtel Associates, dated October 1979, "As Built Geological Report on Tunneling Conditions, Addison Route, Contracts G1-G2-G3" (Reference 5-1). Section G002 was longer and encountered more difficult mining than either G001 or G003. Mining the two, 6650 foot long, tunnels took more than 20 months, with the two mined simultaneously each with its own crew. The outbound tunnel lost more than 14 weeks due to major repairs when the hood of its shield buckled. Inbound tunnel mining was halted almost three weeks when flooded because of a power failure. All other significant slowing of progress was related to excavation difficulty.

Records show that 45% of the outbound and 50% inbound shifts actually made tunneling advance. Average advance for the outbound was only 73% as fast as for the inbound. Differences in design of the outbound Memco shield and the inbound Zokor shield accounted for a portion of that difference. The Memco shield had been used for more previous projects than any other in Addison Route and had been substantially modified. Its breasting capability and excavator rip-out force was less than that of the Zokor and the Memco encountered more difficulty excavating hard soils and cemented sandstones. In both tunnels the work started at the juncture with Capital Heights Station near Station 416 and proceeded northwest, down-station and downslope, to Station 347 where tunneling was completed in June 1978 on the outbound and in February 1978 in the inbound.

The Cretaceous strata encountered ranged from nearly massive hard clay greater than 20 ft. thick, to interlensed sands and clays several inches to several feet thick and to sand beds greater than 20 feet thick. Sandstone, a few inches to four feet thick was encountered intermittently during the last 1000 feet of driving, Station 357 to 347. The tunnel crown ranged between 15 and 40 ft. below the original water table. Some thick saturated sand beds were encountered and sand and water flows up to 50 GPM occurred. Grouting was performed both as a contract requirement to protect an existing culvert at Station 415 and at the contractor's option to stabilize the tunnel heading and running ground. Progress slowed significantly to an average of 30 feet per week between Stations 380 and 368 because of wet running sands.

5.4.2. Causes of Acid Water Intrusion. Measurement of pH values of the inflowing water in Section G002 usually has been made with a portable, electrical metering device. The individual pH determinations on a specific sample appear to be reproducible to about ±0.5. However, there is a wide variation in the results from different seeps, depending on the chance conditions of oxidation, recharge and the stage of acid production in the soil. To assess the factors producing low pH values, a simple statistical study was made of values measured in the period of particularly low pH through the end of 1978. It is this array of low values which has been contoured by pH number on the strip map in Drawing No. 5-5.

Through the period of this investigation the pH measurements have not all been made at consistent locations nor by a single observer and there are many erratic values which tend to disturb trends. Using judgment to eliminate the most erratic pH values, medians were computed from the preconstruction boring program of 1974 to the final reading of January 1986, which are plotted on a time scale in Drawing No. 5-4. These were divided into two general bands, between Stations 375 to 389 in sandy soils, and between Stations 367 to 375, where sand overlies clay in the lower half of the tunnels. The latter section shows the lower pH values, between 4 and 5 in both soil and water samples taken before construction, which have only gradually returned to their original range by 1986. Ground water in the sandy soils was initially at a neutral pH, dropped to low values at the end of tunneling and by 1986 have returned to their original neutral condition. It appears that without oxygen, an equilibrium is reached where abnormally low pH values are gradually removed by the flushing of ground water flow.

To assess the importance of contributing influences, a series of eight computer plots were made which related pH value to various factors, which are summarized on attached drawings, designated as follows.

1. pH values plotted versus tunnel stationing and the following factors:

   a. Inbound distinguished from outbound tunnel, Drawing No. 5-7;

   b. Versus soil type, Drawing No. 5-8;

   c. Versus voids and seeps, Drawing No. 5-9;

   d. Versus grout types Drawing No. 5-10.

2. pH values versus speed and the following factors;

   a. Inbound distinguished from outbound tunnels, Drawing No. 5-11;

   b. Versus soil types, Drawing No. 5-12;

   c. Versus voids and seeps, Drawing No. 5-13;

   d. Versus grout type, Drawing No. 5-14.

The correlation of factors can be summarized in the sequence of the drawings, as follows;

1a. No strong distinction can be made between inbound and outbound tunnels. The outbound tunnel, which is the slower of the two, shows lower median values between Stations 370 and 384, but the inbound tunnel exhibits certain lowest individual values.

1b. There is a marked difference in the character of the ground near Station 380. Down-station from this the soils combine sand and clay, whereas up-station is in sandy soil. It appears that layered mixed soils are more susceptible to acid production.

1c. The condition of seeps and voids are examined on Drawing No. 5-9 which shows a similar distinction between uniform sandy soil south of Station 380 and the lenticular sand and clay in which voids can be more easily maintained.

1d. It was suspected that oxidizing agents used in the grouting might have increased the intensity of acid formation. Drawing No. 5-10 indicates that grouting affects are secondary, and simply reflect the problems encountered with seeps and flowing materials in the lenticular soils north of Station 377.

2a. In Drawing No. 5-11, the tunneling speed, expressed as feet per day, is plotted vs. the individual pH values and the mean value of pH grouped in successive bands of tunneling speed. While there is a wide scatter, because of the variability of the pH of individual seeps, there is a trend from a pH of 3 for tunneling speeds where progress is stalled to high value of 5 to 5½ where tunneling speeds reach 50 to 60 feet per day. Speed influences both the ease of access to oxygen and the opportunity for sustained flow in and around the tunnel heading.

2b. Basic soil types are plotted with tunneling speed to normalize the values in Drawing No. 5-12. The category "Sand and Clay" is associated with a band of low pH values at lower than average tunneling speed. This reflects a particularly unfavorable condition where clays containing sulfides are layered with water bearing sand layers.

2c. In Drawing No. 5-13 the condition of "Voids at Crown" appears to offer a distinctively low pH values at less than average tunneling speed. This is simply a reflection of the factors noted in 2b of lenticular strata where clays with cohesive strength bridge over voids caused by the caving of the water bearing sand lenses.

2d. In Drawing No. 5-14 various grouts are normalized with tunneling speed. It is difficult to conclude that the oxidizing agents utilized in the grouting have had a significant effect in increasing acid production.

To summarize, the wide variation in pH values from seep to seep tends to mask generalizations as to cause and effect. Speed of tunneling, reflecting access to oxygen, has a definite influence. Fine grained pyrite appears to be scattered throughout the soils, both clays and sands, within this section and it is not clear that a specific soil type is more influential. Lenticular strata of sand and clay appear more associated with acid production, presumably because this is an arrangement whereby trickling flow is directed inward to the tunnel, rather than being permitted to flow downward. Combining an interruption in the tunneling progress with fine grained pyrites and infiltration directed into the tunnel, created conditions for acid production which have not yet been duplicated in another WMATA tunnel section.

5.4.3. - Structural Effects. The first study by Erlin, Himes Associates (Reference 5-6) was concerned with concrete liner cores taken in 1979, five transmitted in May and four in August. Small samples of these core were pulverized and analyzed for pH and content of sulfates. Thin section petrographic analyses were performed on specimens taken across the outer exposed surface of the concrete. Conclusions regarding acid attack on the concrete were reported as follows;

> "Deterioration of the concrete portions in contact with groundwater was evident in each core. The deterioration, as measured from existing surfaces, was to maximum depths of 1/8 inch, and manifested as softening of the paste and reactions of the paste with ferrugenous components of the groundwater. In the softened paste areas on the core end surfaces, lime had been leached, leaving behind silica gel. -- The contact distance between the softened paste and firm, original paste was very abrupt; hence, there was essentially no transition zone. -- The chemical analyses revealed the outer one-half inch of the concrete had been affected by contact with the acid water in two ways: (1) "slight" neutralization of the alkaline cement paste; and (2) uptake

of sulfate. --- However, little or no alteration of concrete deeper than ½ inch has occurred, except possibly along fracture surfaces. --- The literature and our experience indicates that sulfate attack on concrete is minimized in strong sulfuric acid solutions due to the formation of a protective gypsum layer that is relatively insoluble in strong acid. Likewise, acid attack is minimized by the presence of iron salts due to formation of nearly water-impermeable gelatinous iron hydroxide by reaction with the alkaline cement paste. ---- Thus, although the water in contact with the concrete is ostensibly very harmful to concrete due to the presence of two extremely aggressive agents - acid and sulfate, the presence of the ferrous salt mitigates both affects and the acid lessens this sulfate attack."

The progressive change in groundwater acid conditions with time after completion of construction late in 1978 is shown on Drawing No. 5-4. As the groundwater gradually rises towards its original elevation, a flushing of the low pH values in the ground surrounding the tunnel appears to occur. Actually the affected tunnels are positioned beneath a groundwater high with fairly active downward migration of infiltrating surface water. It is probably inevitable that the water movement has gradually raised the low pH value so that in the 10 years since construction, the pH appear to be returning toward its original values. In the clayey soils, this normal is between 4 and 5. In the sandy materials with higher permeability and more active ground water movement, the pH is near neutral

However, there have been some significant lasting effects from the acid water intrusion. The area between Station 284 and 286 has exhibited significant leaks in both tunnels on the safety-walk side, which adjoins the centrally placed vent shaft. In the final MRCE inspection of 1986, holes through the tunnel walls were leaking small amounts of sand at some locations. On April 22, 1983 a substantial blow-in of sand occurred at the upper quadrant of the outbound tunnel at Station 382. The leakage condition has been aggravated by the etching or softening of surfaces on construction joints where a protective gypsum coating could be removed by continual seeps. The flowing sand condition doubtless was also associated with the presence of single size, clean SP sands in the Cretaceous surrounding the tunnels.

As a follow up to initial liner coring, a group of six cores were taken in April 1983 at locations plotted on Drawing No. 5-5. These were also transmitted to Erlin, Himes Associates for their petrographic evaluation. Petrographic studies were carried out on specimens taken from the ends of each of the six cores to assess the progress of acid attack and to compare conditions with the cores taken four years earlier. Their conclusions were summarized as follows, Reference 5-7:

> "With the exception of Cores C-1, C-3 and C-6, the outside surfaces of the specimen evinced little evidence of deterioration either from acid or sulfate attack. In Core C-1, the paste had been weakened up to a depth of ¼ inch; chemical testing does not reveal any evidence of sulfate uptake. In Core C-3 and C-6 there was alteration of the paste at the surface end and chemical studies revealed a significant uptake of sulfate in the near-surface regions -- Sulfate attack may be associated with organic acids from decaying wood and appears not to have become more severe than it was in the initial study".

It is interesting to note that each one of the cores had been in direct contact with wood lagging on its exterior surface and, as pointed out in the petrographic analysis, this may have had more influence on the surface alteration than the quality of the exterior groundwater.

Probably the most important remedial measure was the repair and sealing of leaks so as to reduce groundwater gradients and reduce active flow toward the tunnel. Where leaks remained problems continued of weakening of the surface of cracks or joints. This emphasizes again the importance of minimizing shrinkage cracks in the cast concrete lining.

5.5 Conclusions on Acid Water Intrusion.

Important experience was gained with acid water conditions in Section G002. The principal lesson is that under unfavorable circumstances acid water inflow can develop when tunneling in Coastal Plain sediments with annoying and costly consequences during construction and serious maintenance problems in subway operations. Conclusions on the cause and effect of acid production are:

1. A cast-in-place tunnel concrete lining is vulnerable to acid water because of its potential for shrinkage cracking. Damage to the exterior surface of the tunnel liner appears to be one of the lesser problems because a protective coating of gypsum compounds develops when inflow to the tunnel is throttled and contact with oxygen is interrupted. A greater threat is

concentrated seepage at joints and cracks that continues acid attack on the crack surfaces and within the tunnel. It may be that the weakening effect of acidic seepage on joints and cracks in Section G002 contributed to the 1983 blow-in of running sand into the tunnel. This experience emphasizes again the value of a tunnel lining which strictly limits cracking.

2. Use of the NATM scheme where tunnel sides are quickly covered or of a precast concrete lining erected immediately following shield advance, will inhibit both the oxygen supply and inflow of groundwater. Nevertheless, there remains the threat of aggravated leakage around shafts which can direct seepage from the overburden to the running tunnels. Shaft locations are often a source of seepage and should receive special treatment, such as careful waterproofing details, waterstops at structure connections, rapid closure of the shaft excavated face against oxygen and a perimeter cutoff around the shaft to inhibit downward seepage.

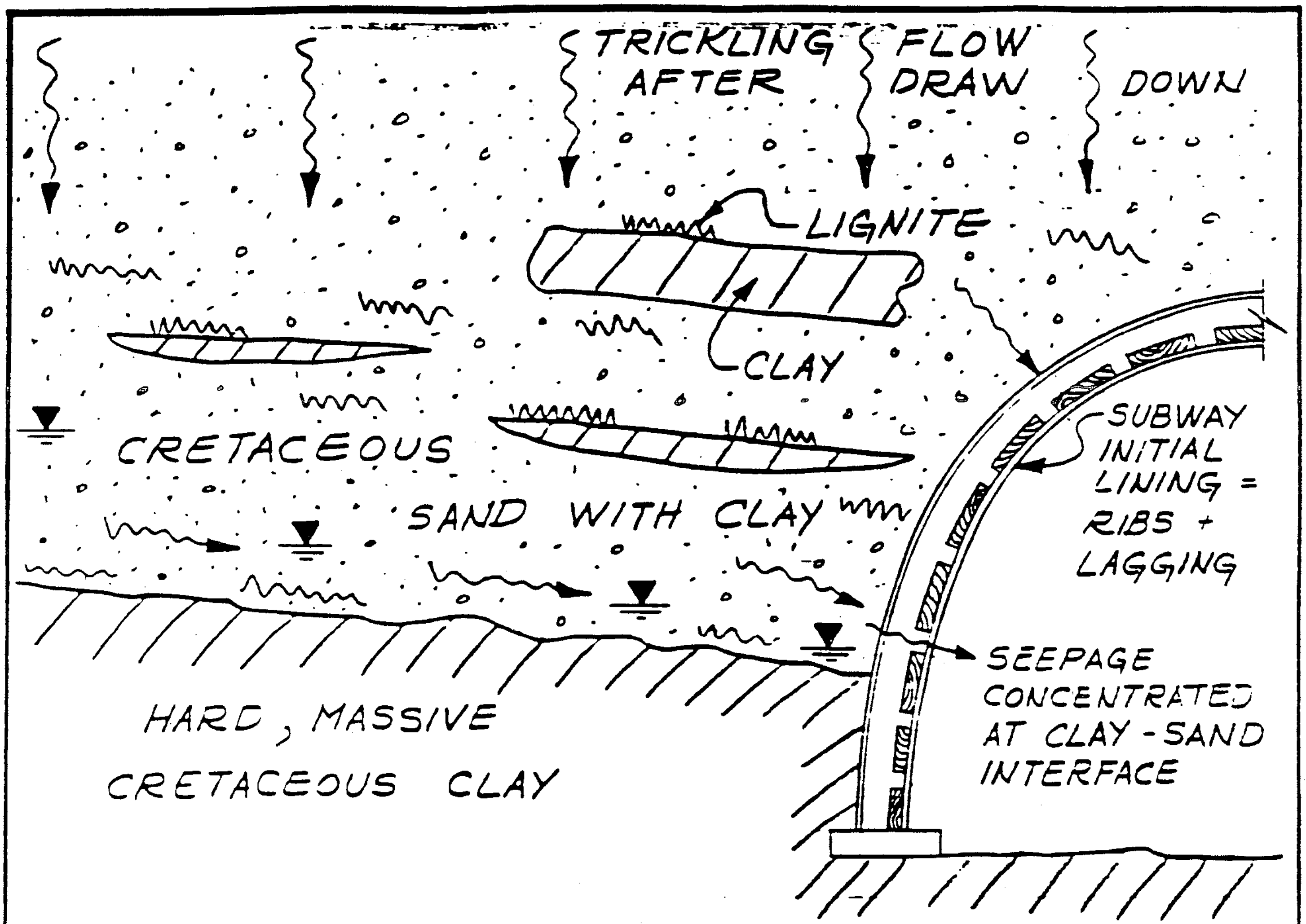
3. A special combination of conditions is responsible for the intense acid water intrusion at Section G002. These conditions include a delay in tunneling which exposed the surrounding ground to vigorous air exchange, the presence of sulfur in fine grained pyrite, and an interface between water-bearing sand above and impervious clay within the tunnel opening. No other section of subway in soft ground has yet experienced this special combination. There is a potential for acid

production in lignite-rich sand of the lower Cretaceous in Sections E005 and E006 of Greenbelt Route. Some Tertiary formations which will be tunnelled on Branch Route could also be sources of acidic groundwater.

4. For the WMATA system and also for other underground construction in sediments which contain organic remnants, basic chemical testing should be undertaken during boring exploration to assess the potential for acid production. In the test borings, soil sampling should be concentrated in the vertical interval directly adjacent to the planned underground opening. For example, in the WMATA borings, continuous soil samples are now obtained throughout the interval which will be occupied by the tunnel cross section. Dark colored soils and those with organic material should be given attention in testing for acid potential. In addition to pH, total sulfur content as a percent of dry weight should be determined. A total sulfur content greater than 0.1% by dry weight of total sample suggests a potential for acid production in inflowing groundwater.

TABLE NO. 4, CHRONOLOGY RELATING TO SECTION G002 ACID WATER PROBLEM

Date	Event
Dec. 1976	Construction starts in G002.
June 1978	Tunneling essentially complete in G002.
During 1978	Inflowing seepage appeared highly acidic.
April 1979	DCCO undertook tests of inflowing seepage in G and K Routes.
March to August 1979	Geraghty & Miller, Inc. studied acidic inflow in G002 and corrective measures, report in September 21, 1979.
August 1979	Erlin, Hime Assoc. report of August to GM on tests of liner cores taken by Bechtel.
Sept. 1979	Drs. Caruccio & Geidel confer with WMATA and MRCE on acid production, report in October 6, 1979.
Nov. 1979	Caruccio & Geidel investigate acid-producing potential in F003-F004, report in April 30, 1980.
Nov. 1980	WMATA and MRCE meet with Drs. Foss and Wagner on continuing testing for acid producing soils in system. Report of March 24, 1982 on tests on samples from F003.
1981-1982	Periodic measurements of pH values in leakage in G002 tunnels by DCCO.
Jan. 1983	MRCE study of water intrusion commences.
March 1983	Division Two purges existing wells in G002 and MRCE samples groundwater.
April 1983	Sudden sand inflow at Station 382 of G002, MRCE inspection on April 22.
June 1983	Cored liner at six locations by WMATA Maintenance forces under MRCE direction.
June to Dec. 1983	Periodic sampling from wells and packed core holes in G002 by MRCE for pH testing.
Nov. 1983	Erlin, Hime Assoc. report Nov. 3 to MRCE on petrographic tests on concrete from 6 core holes in liner.
1984-1986	Periodic water sampling and testing by MRCE in G002.
Jan. 1986	Final MRCE inspection and sampling in G002, noting leakage at Stas. 384+95, 385+50 (IB); 375 to 377 and 384 to 386+50 (OB).



Oxidation of pyrite yields sulfuric acid and ferrous sulfate:

$$2\,FeS_2 + 7\,O_2 + H_2O \longrightarrow \underbrace{2\,Fe^{2+} + 4\,SO_4^{2-}}_{\text{Ferrous Sulfate}} + \underbrace{4\,H^+}_{\text{Sulfuric Acid}}$$

Pyrite + Oxygen + Water

Oxidation of the ferrous iron produces ferric ions:

$$2\,Fe^{2+} + \tfrac{1}{2}\,O_2 + 2\,H^+ \longrightarrow 2\,Fe^{3+} + H_2O$$

Ferric ion hydrolyzes to produce insoluble ferric hydroxide and more acid: $Fe^{3+} + 3\,H_2O \longrightarrow Fe(OH)_3 + 3\,H^+$

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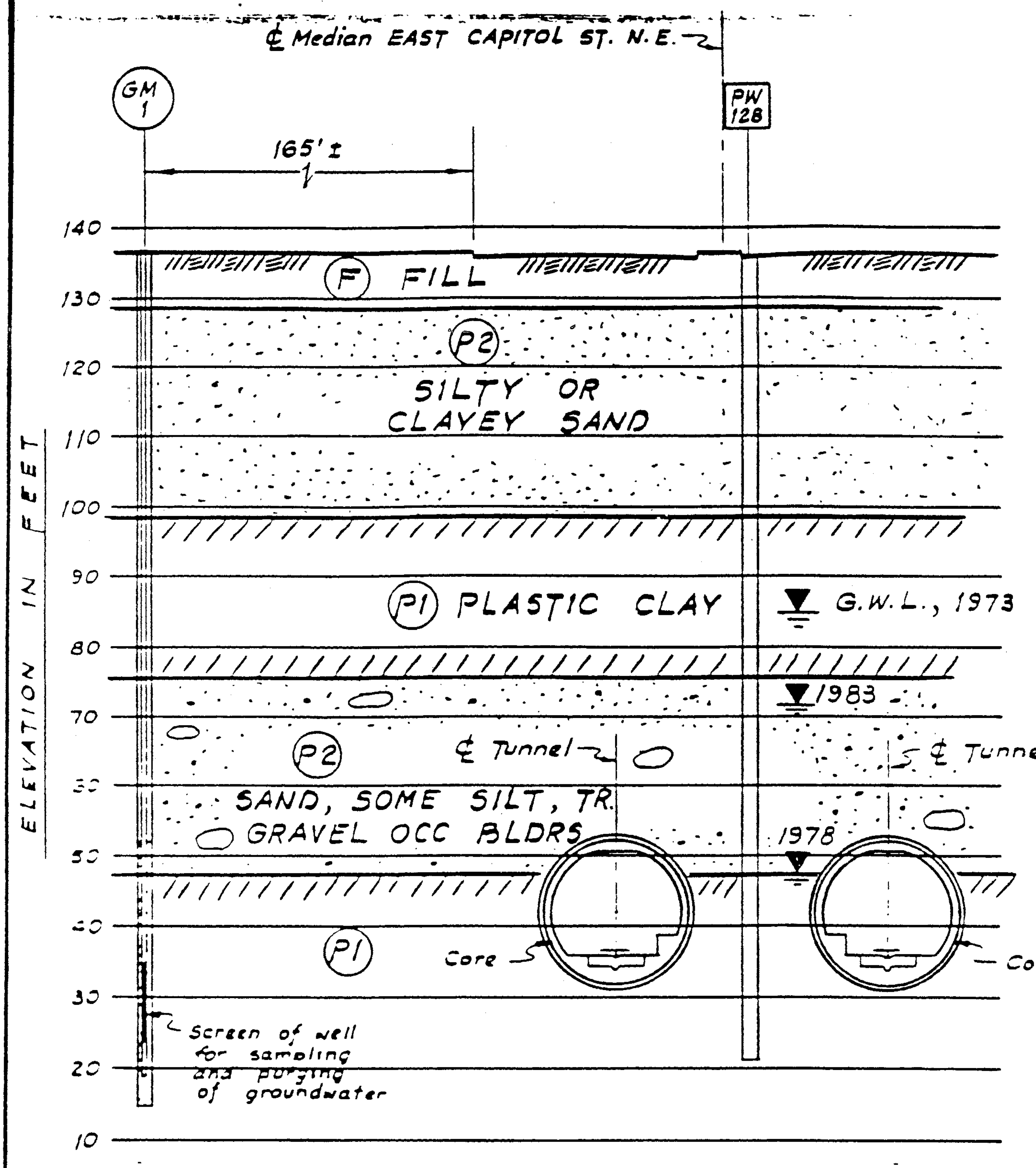
SCALE —	MADE BY JPG / CHKD BY	DATE 4-88	FILE NO 5634
MECHANICS OF ACID PRODUCTION			DRAWING NO 5-1



SECTION G002 TYPICAL GEOLOGICAL CROSS SECTION

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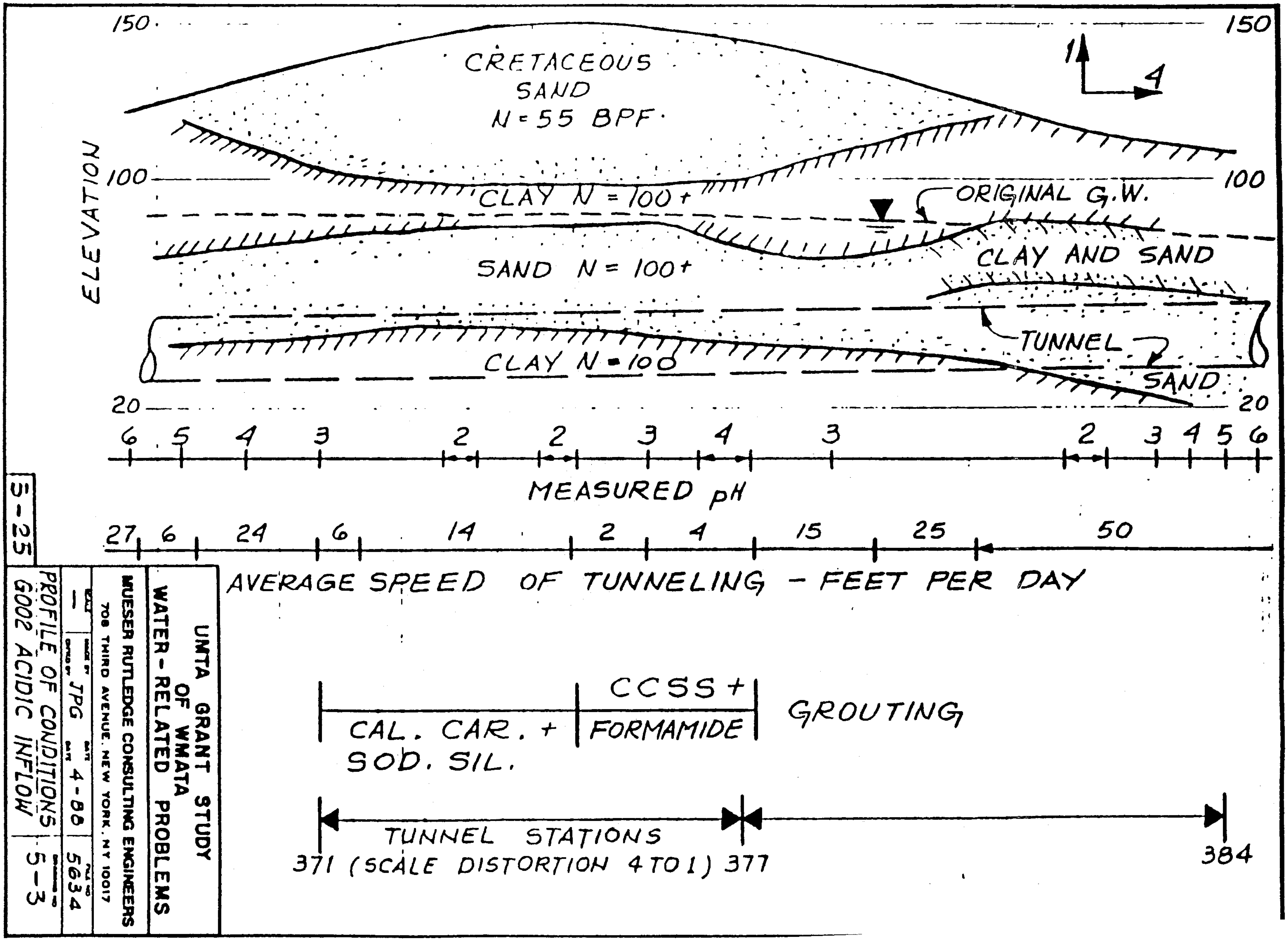
1" = 20'	JPG	4-88	5634

CROSS SECTION G002 RUNNING TUNNELS — DRAWING NO. 5-2



150
150
CRETACEOUS SAND N=55 BPF
1
4
100
100
CLAY N = 100+
ORIGINAL G.W.
SAND N = 100+
CLAY AND SAND
TUNNEL
CLAY N = 100
SAND
20
20
ELEVATION
6 5 4 3 2 2 3 4 3 2 3 4 5 6
MEASURED pH
27 6 24 6 14 2 4 15 25 50
AVERAGE SPEED OF TUNNELING - FEET PER DAY
CAL. CAR. + SOD. SIL.
CCSS + FORMAMIDE
GROUTING
TUNNEL STATIONS
371 (SCALE DISTORTION 4 TO 1) 377
384
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JPG
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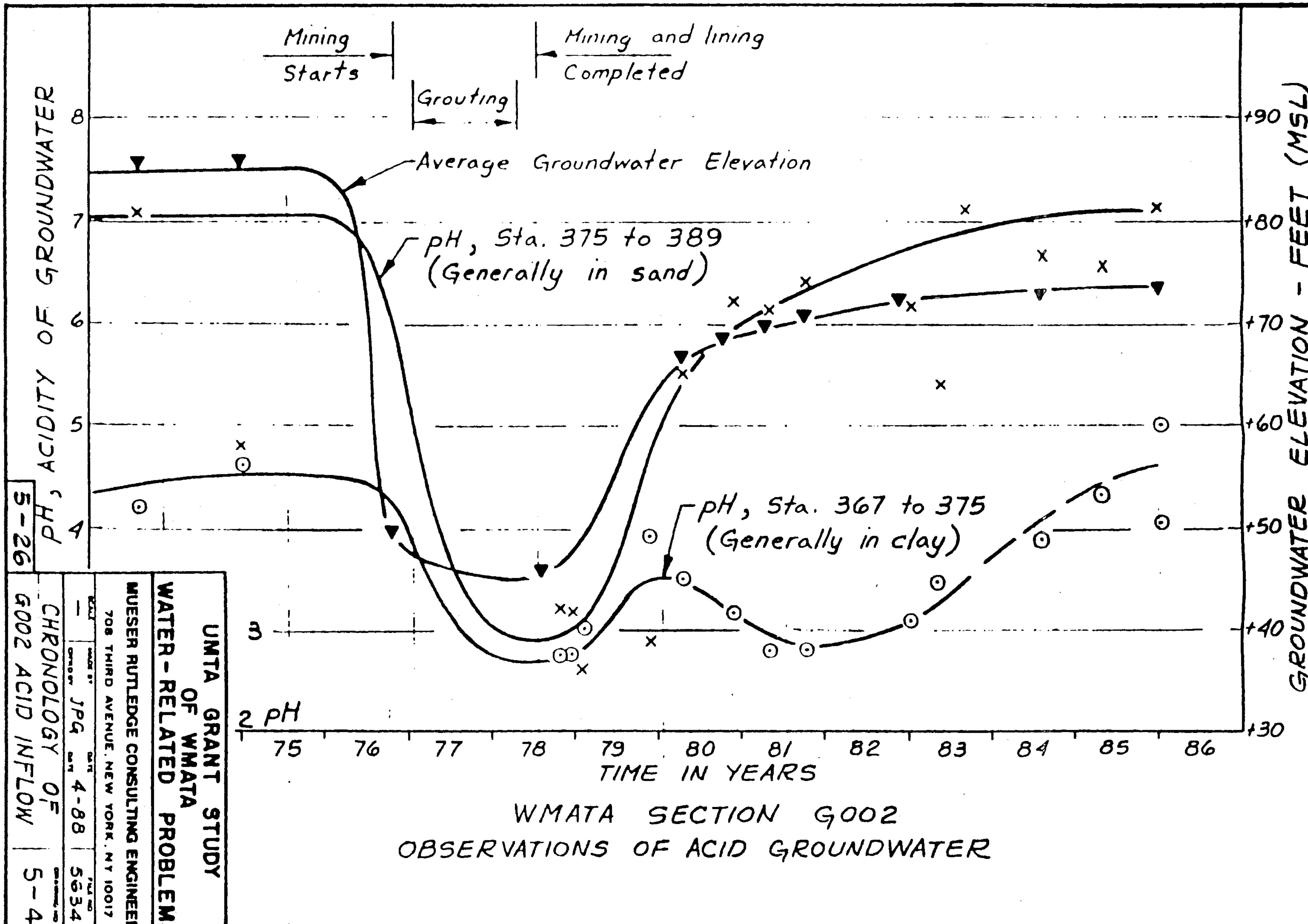
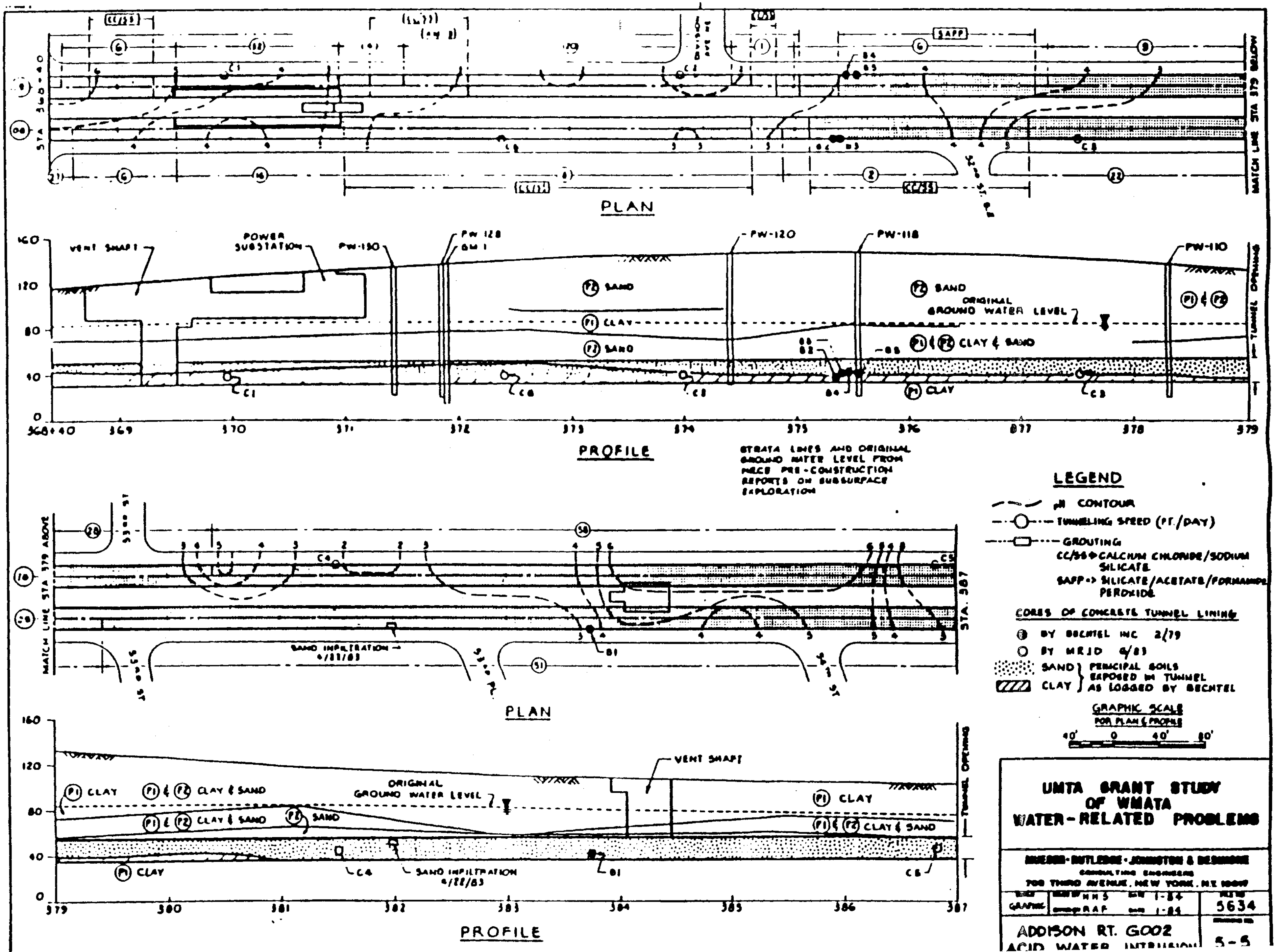
5634
PROFILE OF CONDITIONS
G002 ACIDIC INFLOW
5-3
5-25



WMATA SECTION G002
OBSERVATIONS OF ACID GROUNDWATER


PLAN
PROFILE
VENT SHAFT
POWER SUBSTATION
PW-130
PW 128
OM 1
PW-120
PW-118
PW-110
TUNNEL OPENING
MATCH LINE STA 379 BELOW
MATCH LINE STA 379 ABOVE
STA. 387
P2 SAND
P1 CLAY
P2 SAND
ORIGINAL GROUND WATER LEVEL
P1 & P2 CLAY & SAND
P1 CLAY
P1 & P2
STRATA LINES AND ORIGINAL GROUND WATER LEVEL FROM NECE PRE-CONSTRUCTION REPORTS ON SUBSURFACE EXPLORATION
SAND INFILTRATION 4/22/83
SAND INFILTRATION 4/22/83
P2 SAND
P1 CLAY
LEGEND
pH CONTOUR
TUNNELING SPEED (FT./DAY)
GROUTING
CC/SS→CALCIUM CHLORIDE/SODIUM SILICATE
SAPP→SILICATE/ACETATE/FORMAMIDE PEROXIDE
CORES OF CONCRETE TUNNEL LINING
BY BECHTEL INC 2/79
BY MRJD 6/83
SAND } PRINCIPAL SOILS
CLAY } EXPOSED IN TUNNEL AS LOGGED BY BECHTEL
GRAPHIC SCALE FOR PLAN & PROFILE
40' 0 40' 80'
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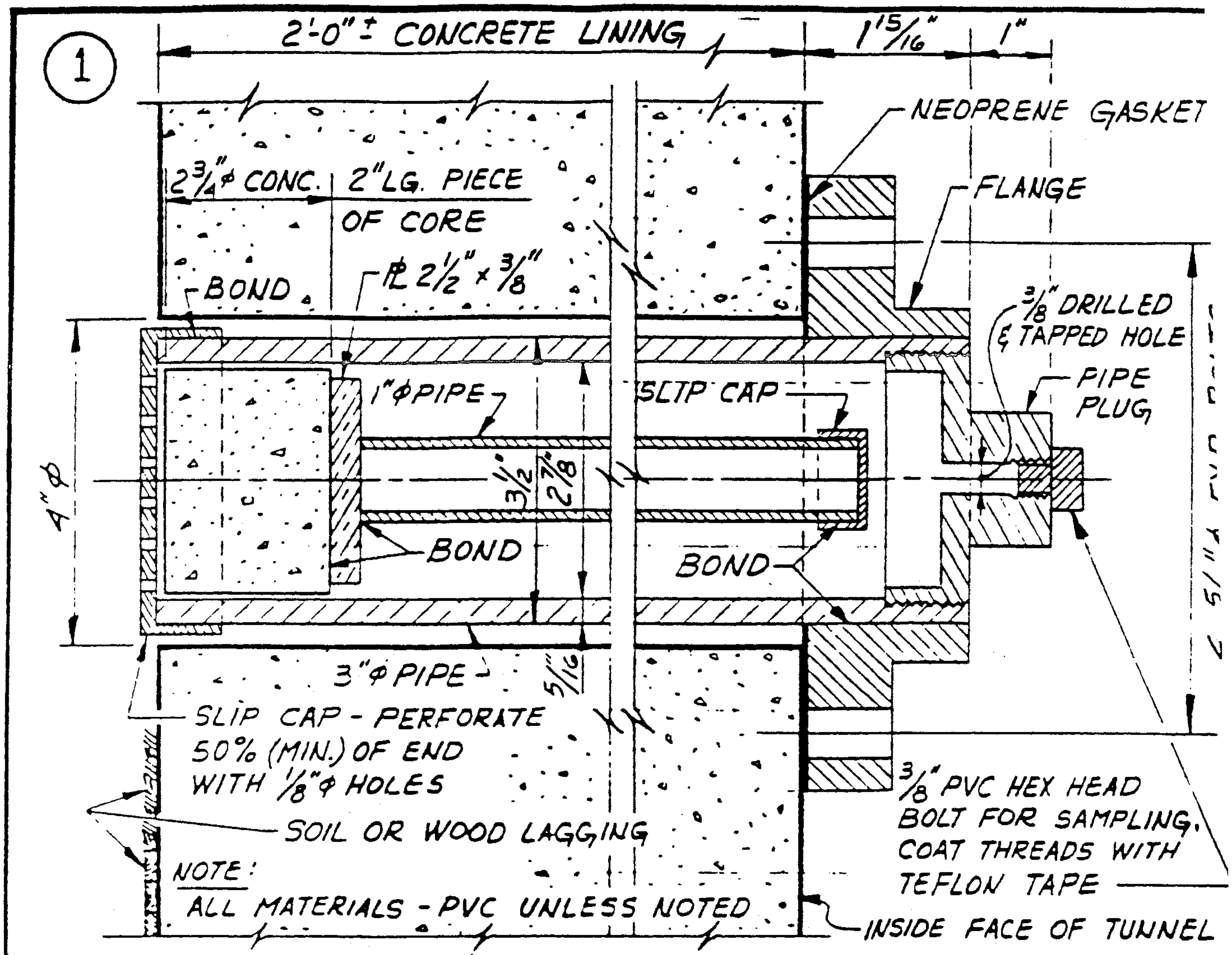
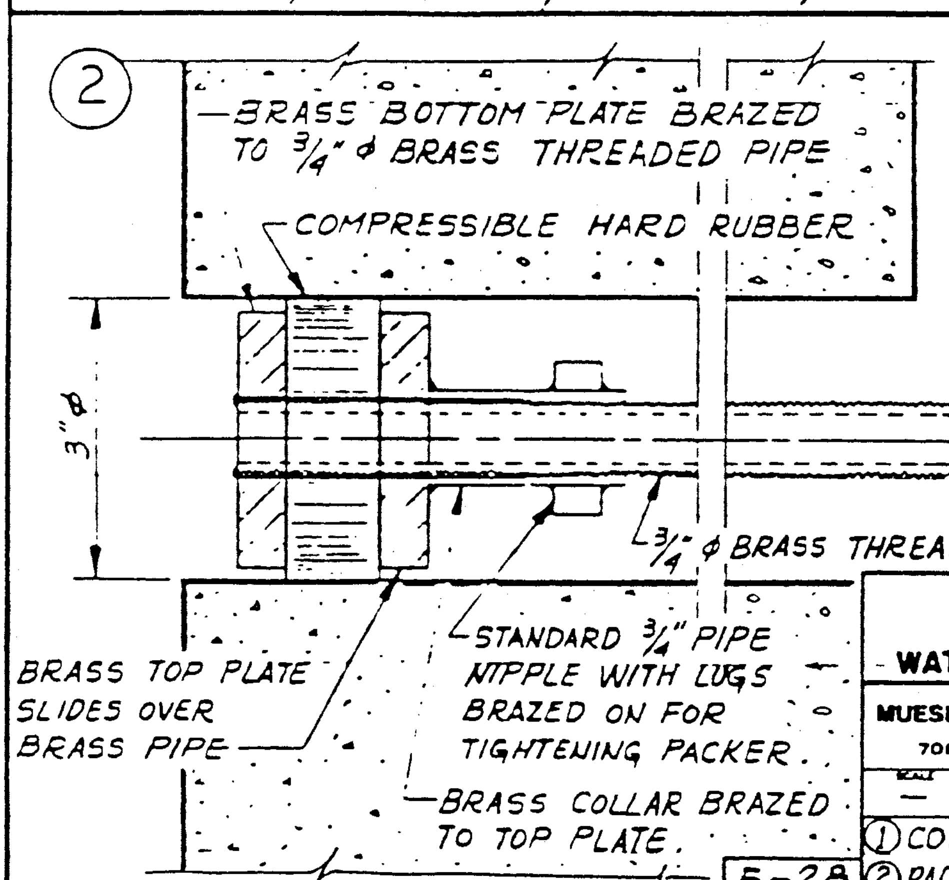
ADDISON RT. G002
ACID WATER INTRUSION
5-5





NOTES:

1. FOR INSTALLATION IN G-00? THIS PACKER WAS DESIGNED WITH 2 3/4"±φ TOP & BOT. PLATES & 3"φ COMPRESSIBLE RUBBER TO PLUG 3"φ CORE HOLES THROUGH CONCRETE TUNNEL LINER
2. PACKER TO ACCOMODATE VARIOUS SIZE CORE HOLES CAN BE FABRICATED BY CUSTOM MACHINING TOP & BOT. PLATES & RUBBER.

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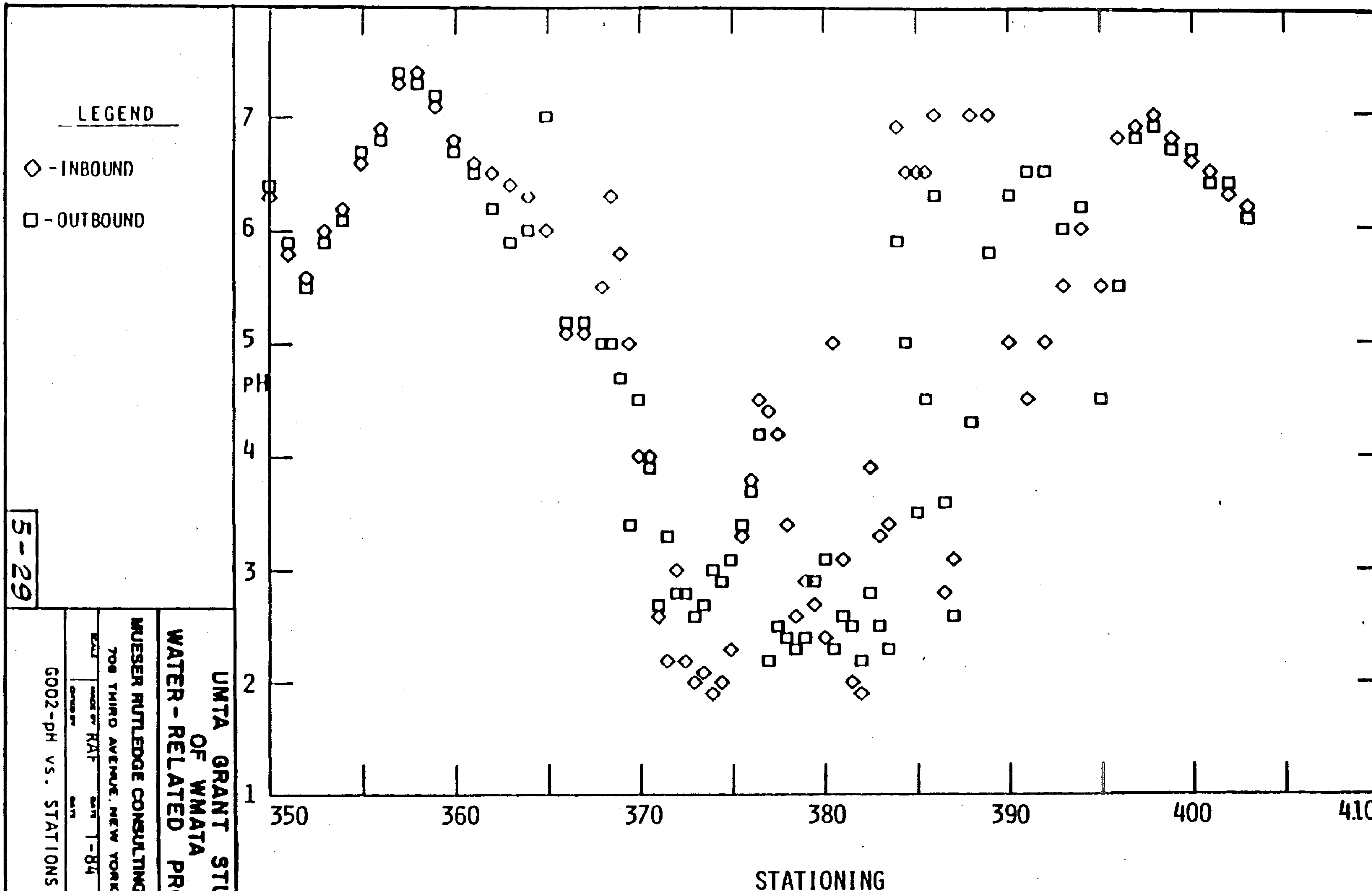
SCALE —	MADE BY JPG / CHKD BY	DATE 4-88	FILE NO 5634
① CONCRETE TEST CORE ② PACKER FOR WATER SAMPLE			DRAWING NO 5-6



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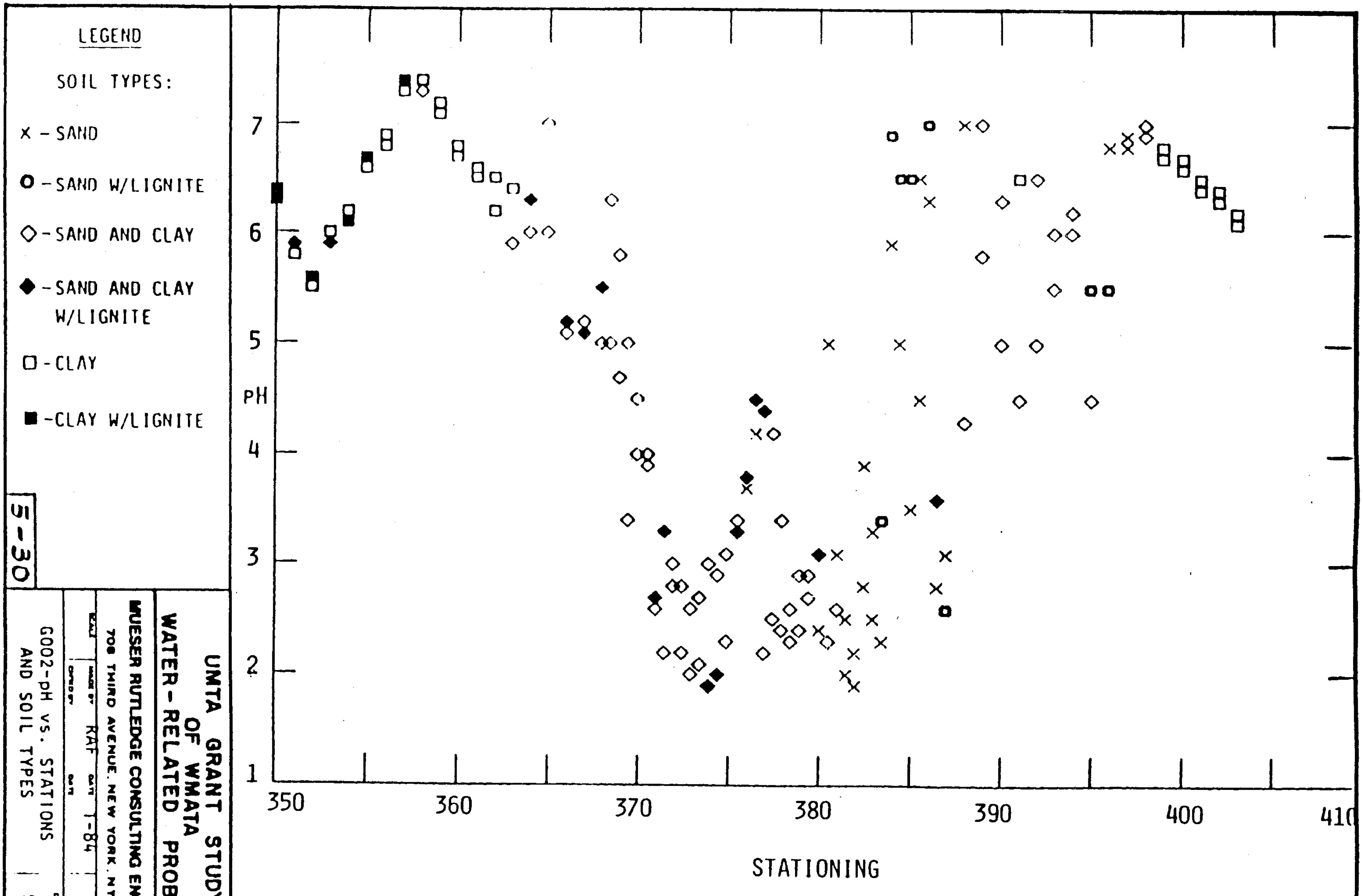
	Checked by	Date	

G002-pH vs. STATIONS

Drawing No. 5-7



5-30

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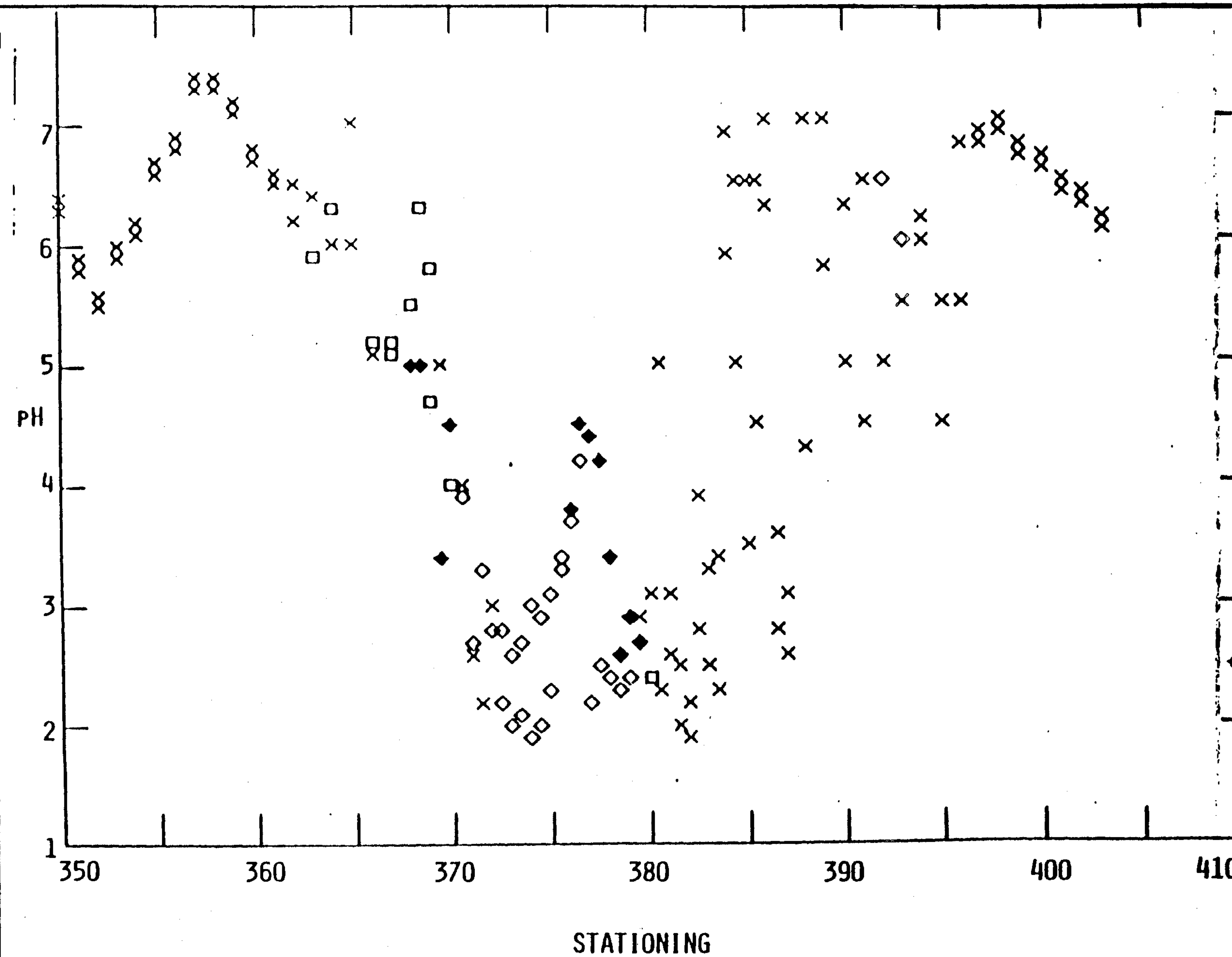
G002-pH vs. STATIONS AND SOIL TYPES

DRAWING NO 5-9



LEGEND

VOIDS & SEEPS:

◇ - VOIDS AT CROWN

◆ - VOIDS AT CROWN AND SEEPS

□ - SEEPS

× - NONE

5-31

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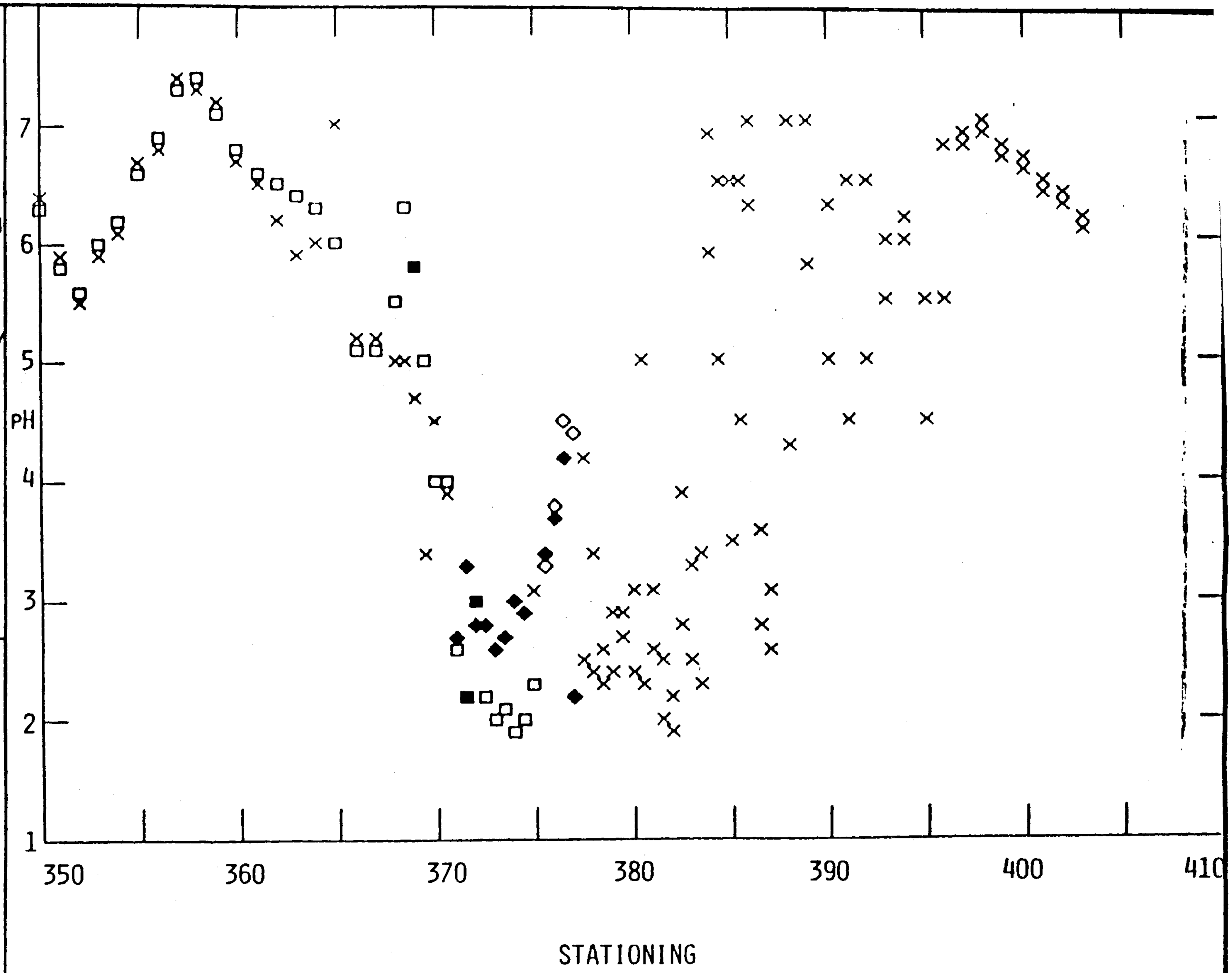
SCALE / MADE BY RAF / DATE 1-84 / CHECKED BY / DATE	FILE NO. 5634
G002-pH vs. STATIONS AND VOIDS AND SEEPS	DRAWING NO. 5-9



LEGEND

GROUT TYPES:

□ - AM-9

■ - AM-9 AND CALCIUM CHLORIDE/SODIUM SILICATE

◆ - CALCIUM CHLORIDE/ SODIUM SILICATE

◇ - SILICATE/ACETATE FORMAMIDE/ PEROXIDE

X - NONE

5-32

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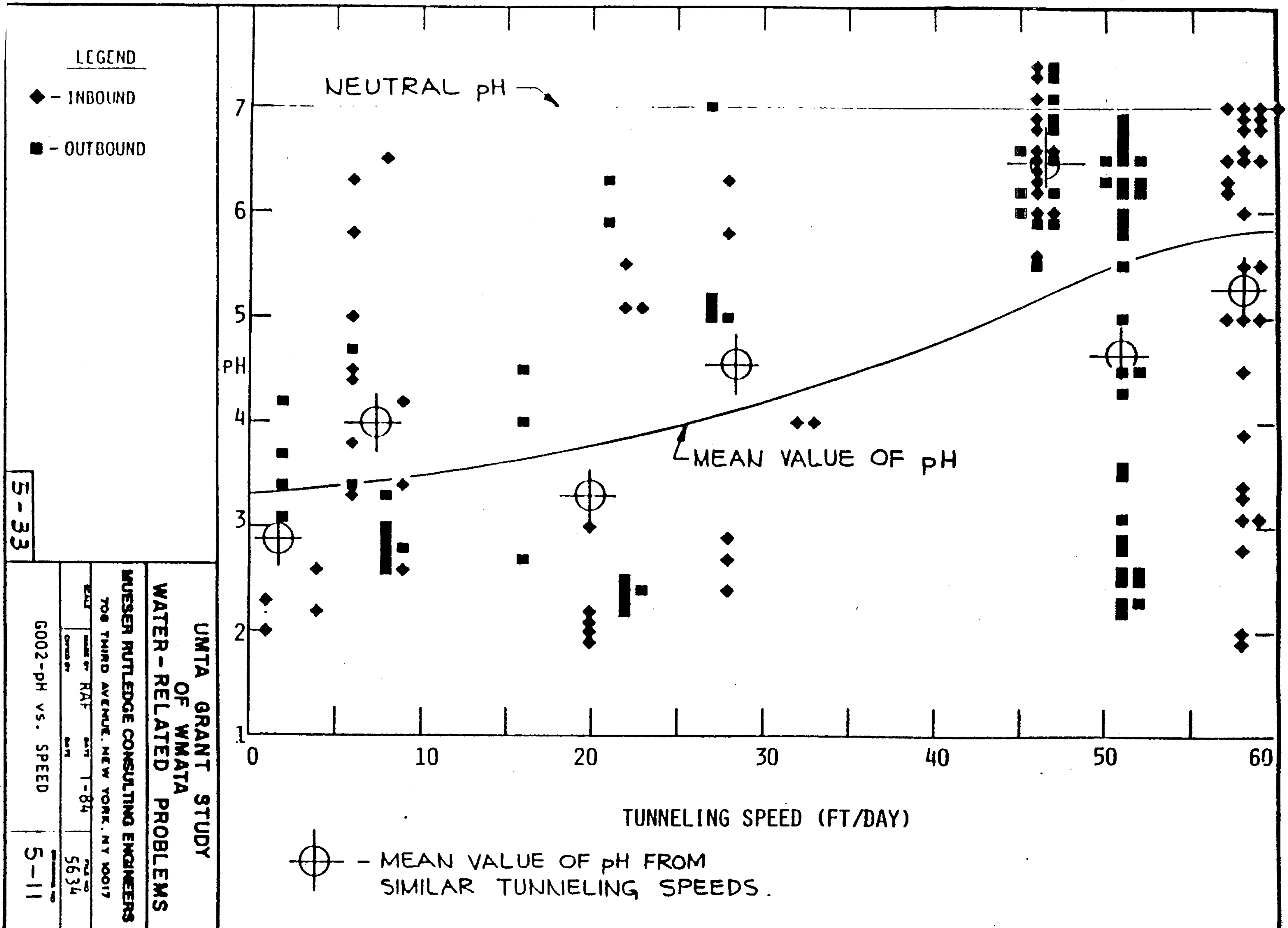
G002-pH vs. STATIONS AND GROUT TYPES

DRAWING NO 5-10



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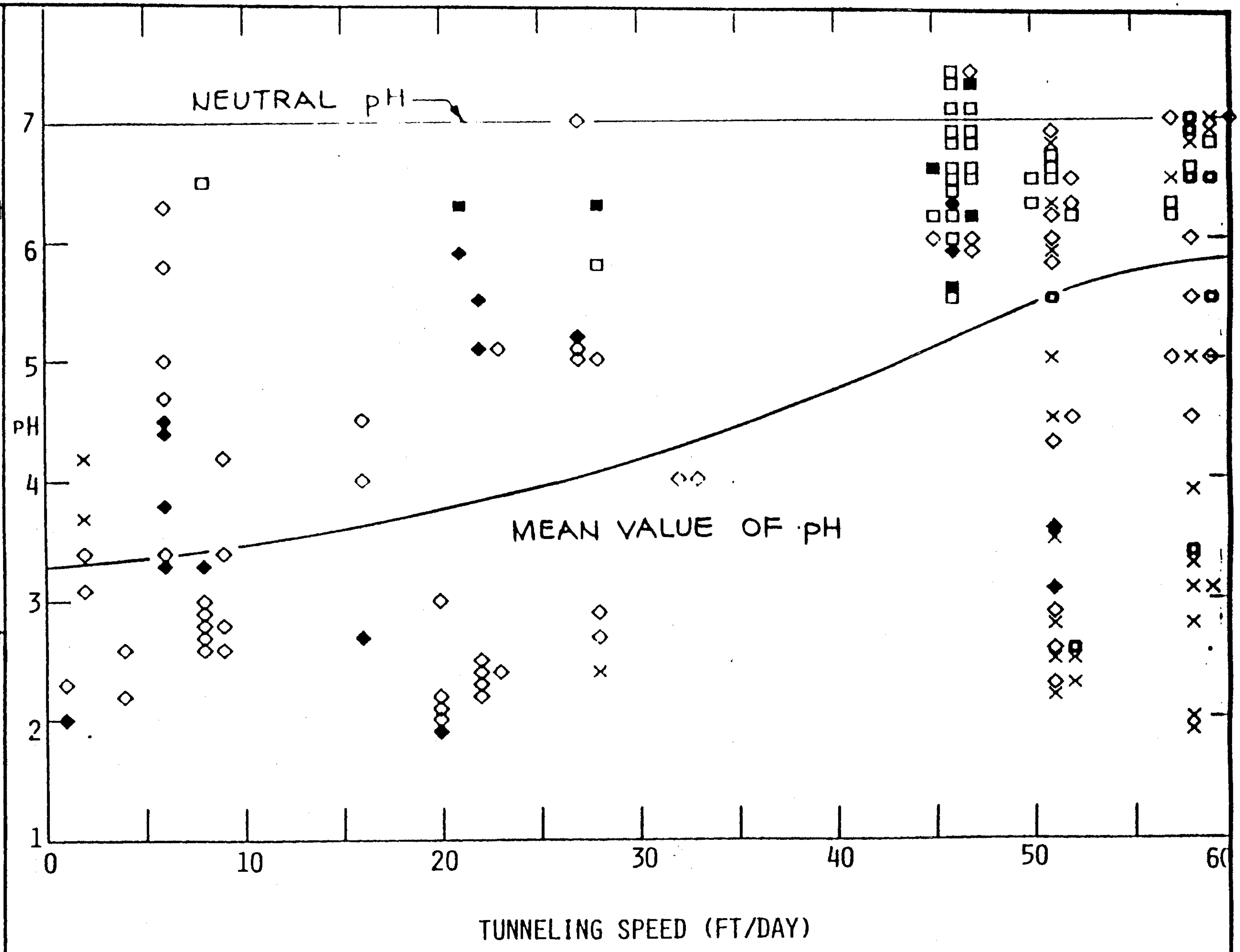
G002-pH vs. SPEED

DRAWING NO. 5-11



LEGEND

SOIL TYPES:

× - SAND

O - SAND W/LIGNITE

◇ - SAND AND CLAY

◆ - SAND AND CLAY W/LIGNITE

□ - CLAY

■ - CLAY W/LIGNITE

UMTA GRANT STUDY OF WMATA WATER-RELATED PROBLEMS

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SCALE	MADE BY RAF	DATE 1-84	FILE NO. 5634
	CHK'D BY	DATE	

G002-pH vs. SPEED AND SOIL TYPES

DRAWING NO. 5-12

LEGEND

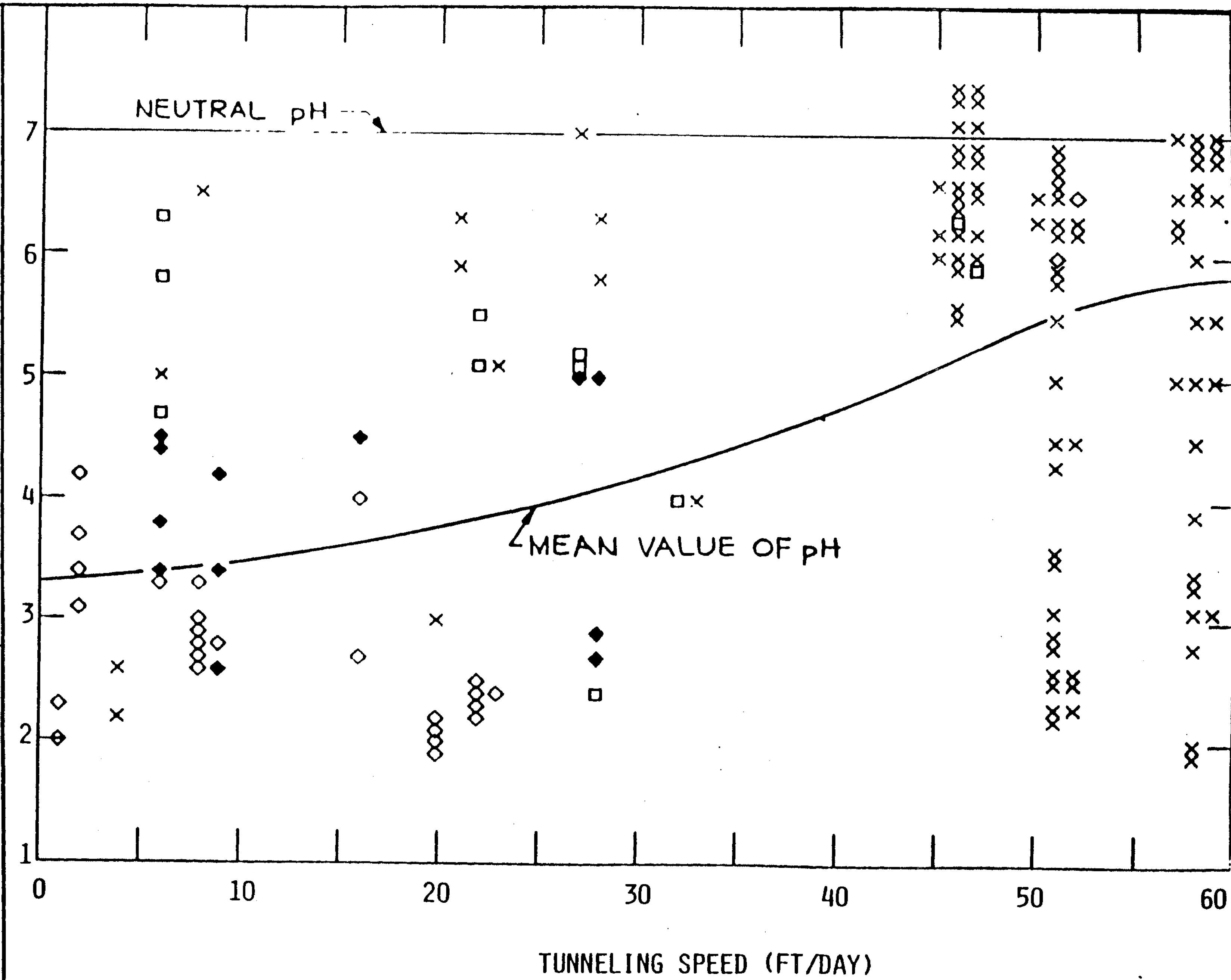
VOIDS & SEEPS:

◇ - VOIDS AT CROWN

◆ - VOIDS AT CROWN AND SEEPS

□ - SEEPS

X - NONE



5-35

UMTA GRANT STUDY OF WMATA WATER-RELATED PROBLEMS

MUESER RUTLEDGE CONSULTING ENGINEERS

708 THIRD AVENUE, NEW YORK, N.Y. 10017

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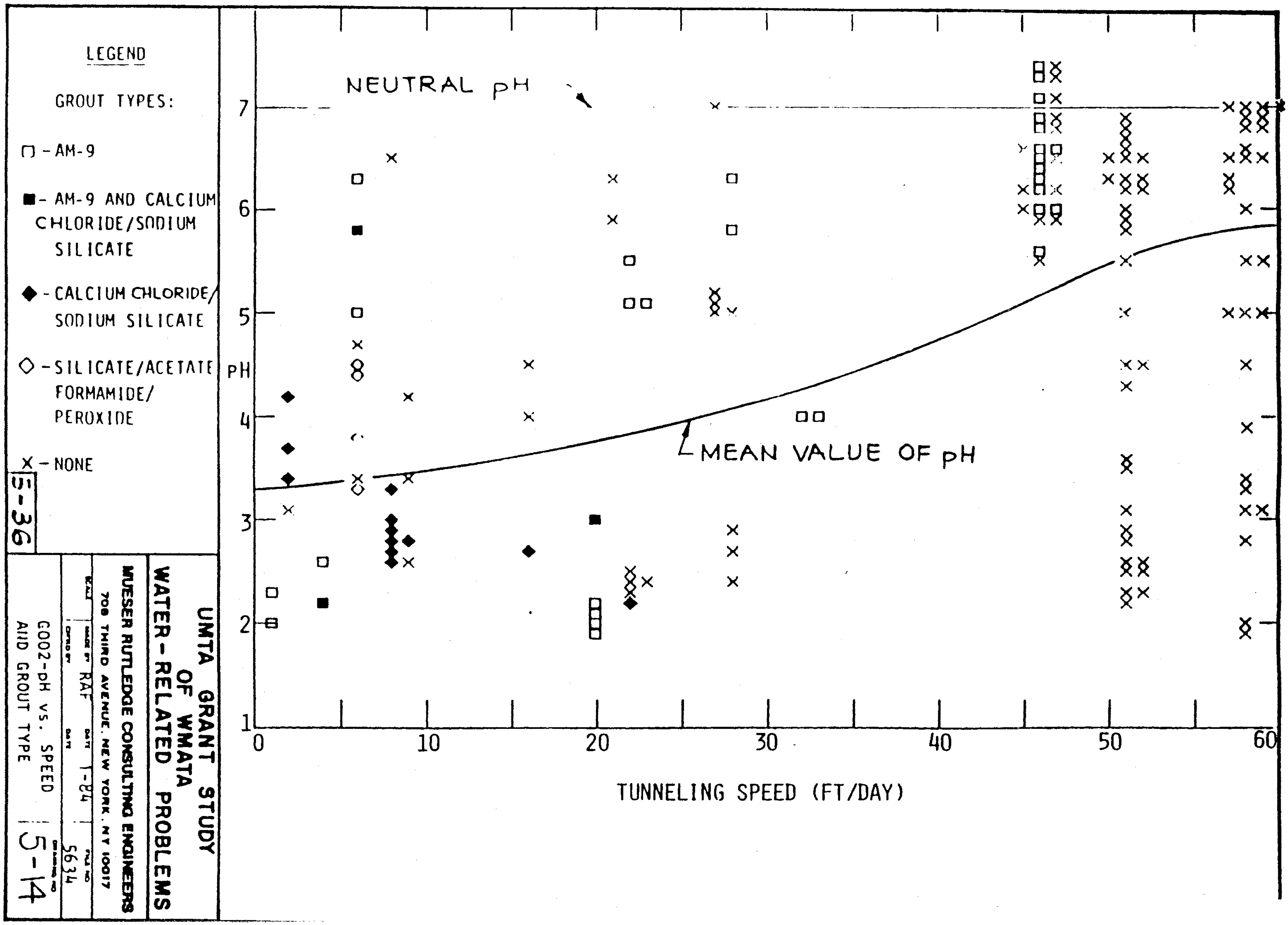
G002-pH vs. SPEED AND VOIDS AND SEEPS

DRAWING NO 5-13


LEGEND
GROUT TYPES:
□ - AM-9
■ - AM-9 AND CALCIUM CHLORIDE/SODIUM SILICATE
◆ - CALCIUM CHLORIDE/SODIUM SILICATE
◇ - SILICATE/ACETATE FORMAMIDE/PEROXIDE
× - NONE
5-36
NEUTRAL pH
MEAN VALUE OF pH
pH
TUNNELING SPEED (FT/DAY)
UMTA GRANT STUDY OF WMATA
WATER-RELATED PROBLEMS
MUESER RUTLEDGE CONSULTING ENGINEERS
708 THIRD AVENUE, NEW YORK, NY 10017
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G002-pH vs. SPEED AND GROUT TYPE
5-14

CHAPTER 6: CONTACTS WITH OTHER RAPID TRANSIT SYSTEMS

6.1 Purpose and Background

One portion of the project scope covered, "site visits to transit systems and other areas where underground construction has had to deal with and solve the problem of water intrusion." Contacts were made with several other systems, including those of Atlanta, Baltimore, Boston, and Buffalo without carrying out interviews or on-site inspections. Information obtained has been used to supplement the data and analyses in the preceding chapters. Additional details on experiences of these systems with infiltration problems are given in Reference 2-3.

Somewhat more detailed exchanges were carried out with New York City Transit Authority (NYCTA) and London Transport, involving office visits and field inspections extending over a period of several years. The pertinent experience of these two systems with underground water problems is summarized in this chapter.

6.2 New York City Transit Authority

6.2.1 Investigations. The initial meeting with NYC Transit Authority staff to arrange for exchange of information was on January 24, 1983, followed by field inspections of January 25 by L.H. Heflin and W.H. Anderson and of January 26 by L.H. Heflin and K.S. Westermann. Field inspections included the following stations: Roosevelt Island, Bergen Street, Essex Street, DeKalb Avenue, and the Lenox Avenue line from 116th to 125th Streets. Observations are recorded in MRCE office memorandums of January 24 and 27 and February 15, 1983.

6.2.2 General Conditions. Leakage has been aggravated by rising groundwater level in certain areas of deep sandy soils, particularly downtown Brooklyn and the upper east side of Manhattan between 110th and 130th Streets. Most of the overburden soils in New York City are of glacial origin, chiefly water-sorted outwash. The single-sized gradation of the outwash materials, including delta sands and the typical New York "Bull's Liver", accentuate leakage problems because of the "runny" nature of these soils. Water problems of the New York subways are classic examples of an older system constructed at shallow depths in subsoils that are difficult to drain and in which there is ample recharge due to leaking utilities plus shallow and rising groundwater levels. Remedial measures include the range of traditional treatments including, channeling of leakage to drop pans; treatment to exclude water by various forms of grouting, brush-on compounds, joint sealers; and finally, in drastic cases, reconstruction of the subway invert and underdrainage system.

6.2.3 Lenox Avenue Subway Reconstruction. The most troublesome recent problem on an operating line probably is represented by the Lenox Avenue line (Reference 6-2). The two-track subway lies beneath the southbound lanes of Lenox Avenue from 110th to 138th Street in Manhattan. Lenox Avenue is 150 feet wide between building lines with a mall separating the two 37 foot wide roadways. Neighboring buildings are typically five story residential structures. The ground surface rises from approximately Elev. +20 at 115th Street to Elev. +28 at 125th Street. Two sewers, each about four feet in diameter parallel the subway at about mid-height of its wall. The subway was opened to service in 1906. It is a two-track concrete box nominally 19 feet high by 31 feet wide constructed by cut-and-cover methods and supported in glacial sand and silt. The roof of the box is only three to four feet beneath the surface. The subway box was originally waterproofed with alternating layers of brick and mastic beneath an unreinforced concrete invert slab.

The generalized geologic section, Drawing No. 6-1, shows the upper 10 feet of soil is granular fill. Elev. +10 to -10 is an outwash deposit of compact coarse to fine sand. From Elev. -10 to -40 is a stratum of compact reddish brown silty fine sand overlying compact varved silt. Glacial Lake Flushing deposits comprise the latter two strata. Bedrock is the Manhattan schist which lies at Elev. -40 at the south end of the section, rises to Elev. -8 at 117th Street and drops to Elev. -120 at 125th Street. Groundwater was typically at Elev. +11.5 when the subway was constructed and has risen to about Elev. +14.5. Historical maps indicate that an old stream crossed Lenox Avenue between 118th and 119th Streets.

The original concrete invert slab contained no reinforcing or structural steel. NYCTA has concluded that over a period of years the impact of train travel caused cracking in both the slab and waterproofing. Since the slab was unreinforced, the cracks were not restrained from movement. As openings enlarged, fine sand and silt particles were carried into the invert by seepage, causing loss of subgrade support and, consequently, settlement of the subway and progressive increase in the rate of water and soil inflow.

The quantity of groundwater pumped from sumps at 116th Street increased from 20 gpm in 1910 to more than 100 gpm in 1968, to about 125 gpm in 1970 and was as high as 450 gpm in 1977. This amounted to a peak inflow of about 13 gpm per 100 route feet. NYCTA estimated that 60 cubic feet of soil was carried in with the water in 1975, increasing to about 300 cubic feet in 1977. In 1977, two sumps were installed in the southbound trackway at 117th Street and 123rd Street which reduced inflow to the 116th Street sump to 50 gpm. However, undermining of the invert and the consequent settlement problems continued. Invert concrete settled as much as six inches, increasing slab cracking and separation of some of the columns from the slab at the base of the side wall. As a result of the invert deterioration, it was necessary to drastically reduce operating train speeds.

Rehabilitation of this segment began in 1980 with installation of a single line of wellpoints paralleling the subway to depress the groundwater table to three feet below invert. Dewatering was more difficult at the south near the buried stream channel. At the ground surface, trenches were excavated to permit access to the subway roof. Holes were cut through the roof to obtain access to the columns. The columns were then held at the ground surface and the invert slab was removed in five foot segments across the full subway width and down to subgrade. The replacement invert included successive layers of brick and mastic base for waterproofing. A new structural slab was installed over the waterproofed base and included direct rail fixation. All work was performed on nights and weekends to minimize traffic disruption.

6.2.4 Conclusions on NYCTA Problems. The considerable age of the subway sections in soil, the City's geologic setting with its dominant glacial outwash soils, the rising water table and ample recharge combine to create frequent shallow leaks in the subway structures. The piping of soil with leakage is aggravated by the single-size and largely cohesionless nature of the glacial outwash and varved glacial lake soils of New York City. These particular difficulties do not include the unusual elements of the WMATA problems. Recently, public notice was taken of the leakage problem in the subaqueous crossing of the East River and beneath Roosevelt Island Reference 6.1. This leakage condition was caused by the proximity of river recharge, the temporary absence of pumping in the lower tubes of the subway following construction and the delay of efforts to eliminate leakage seeping through shrinkage cracks in the concrete walls of the subway. These problems are not comparable to the difficulties characteristic of the WMATA system.

6.3 London Transport Subway System

6.3.1 Investigations. As part of the requirement for investigating leakage problems and treatment in other rapid transit properties, WMATA authorized a limited contact with London Transport International to learn from the staff of London Transport of their experiences with underground portions of their system. A preliminary discussion was held on May 9, 1983 and was followed by later meetings on September 12, 13, 14, and 21, 1983. The meetings of September included a night inspection of several underground sections to view typical conditions in-situ. Memorandums summarizing these meetings were submitted to WMATA on the date of May 12 and September 26, 1983.

6.3.2 General Features of the London Subway. London Underground is the oldest and probably the most extensive system in the world. Earliest sections for rapid transit were built in the 1860s and consisted of shallow, double-track, cut-and-cover, brick-lined boxes. Of their underground trackage, approximately 25% is in cut-and-cover and 75% in single-track circular tube made by tunneling methods. These tubes are generally within London Clay which provides highly favorable mining conditions and low impermeability. The overlying coarse stream terrace deposit, the "Thames Gravel," is avoided by mined tunnels to the extent practical. The Thames Gravel is similar in age origin and grain-size characteristics to the coarser grained Pleistocene terrace deposits of the Washington Metro system. The London clay is roughly comparable to the Cretaceous clays of Washington.

The older cut-and-cover boxes ordinarily are at the shallowest practical depth with groundwater relatively low on the wall, influenced by drawdown caused by the presence of the subway. In older construction, a brick invert contains a center collecting drain between the two tracks, discharging to pump sumps at intermediate locations, generally within the stations. These invert drains in some instances are in contact with exterior groundwater and carry groundwater infiltration to the sumps. Some of the older track sections are placed on ballast distributed over the natural gravel subgrade without a brick invert. In the cut-and-cover sections track is generally on ballast; whereas in mined tunnel sections track is fixed to wooden ties on the concrete invert.

6.3.3 Modern Cut-and-Cover Construction. There are two aspects of interest in London's modern cut-and-cover construction. One is the frequent need to reroof the old brick box sections because of changing surface or street conditions. A procedure has been devised to reroof by an arrangement of precast concrete T-beams inverted with their flat bases abutting to serve as forms for poured in-fill concrete. These replace the "jack arches" which consisted chiefly of the familiar short brick arches with axes perpendicular to the side wall, supported on steel T-beams with wide flange on the bottom serving as the arch support. The reroofing process and repair of the waterproofing of the old brick boxes has utilized rather elaborate multi-layer membrane waterproofing which includes an asphaltic tack coat followed by a layer of flat tile, covered by a two inch concrete screed layer. This membrane was reported in 1983 to cost £12 per square meter, roughly $1.50 per square foot. This durable and sturdy coating is expected to accommodate all wear and tear from street use directly above. Replacement utility construction is carefully coordinated to avoid breaking the waterproofing membrane surface.

6.3.4 Subway Extension to Heathrow. A recently constructed facility is the cut-and-cover extension to Heathrow Airport built between 1975 and 1977. This utilized secant piles for vertical walls which serve both as a cofferdam and as the permanent subway walls. The secant piles were installed in a "Benoto-style" procedure which provided a uniform caisson of high quality. The Benoto rig advances a casing with cutting teeth on the bottom by an oscillating torque which works its way downward in compact ground. The casing is cleaned, concrete poured to form the caisson while the casing is withdrawn by the same oscillating motion. The roof was then constructed by placing precast T-beams on seats in the pile wall with the standard membrane waterproofing on the structural roof. It is noteworthy that no particular effort was made to provide significant moment transfer at the wall-roof contact. No center wall was provided on this or other cut-and-cover box running tunnels. No unbalanced horizontal force or sidesway condition is taken into account in the design and no exterior waterproofing was utilized on the secant wall. In fact, the wall intersected the contact between Thames gravels and weathered London clay and leakage through joints in the secant wall was handled by grouting after construction plus later remedial grouting as leaks manifested. It was recently reported that a significant leak developed in the secant wall where channel gravels indented the top of the London clay. Leakage and track drainage is simply accommodated by a central invert drain carried to pumping sumps at intervals.

6.3.5 Heathrow Airport Loop Track. A single track loop was constructed (1983-1986) to extend the subway to all Heathrow terminals, principally by tunnel boring machine mining in London clay but with a short shallow section of cut-and-cover construction. London Transport supplied the contractor with cast iron tunnel segments at a favorable price of £50 per metric ton. In the shallow cut-and-cover section, the contractor chose to use the cast iron liner in a circular cross section in lieu of the original design of slurry walls and precast roof. The contractor's scheme, which was accepted for a £250,000 saving, consisted of making a sloped open cut, using wellpoints in the overlying Thames gravel with steep sides in the London clay, placing a concrete cradle for the cast iron liner, erecting the liner with six or seven rings in a day. Liner joints were sealed with an exterior joint sealing tape and sealant. The upper surface of the liner was covered by a shotcrete layer for protection. Backfill around the tunnel and for a distance above the crown consisted of excavated London clay. Above this was placed the sand and gravel saved from the excavation to permit groundwater movement over the tunnel without forming an underground dam. Following completion of the backfill many of the liner rings which had been surrounded by clay backfill settled, some as much as 2½" in the 12-foot diameter. The distortion was arrested and in part reversed by grouting from the surface within the clay backfill (Reference 6-3).

6.3.6 Mined Tube Sections. These constitute by far the greater proportion of London running tunnels. They are relatively small-sized, typically 14 to 16 feet inside diameter, and consequently distinctly economical. They contain no safety walk and are designed to accommodate the smaller London Transport cars. The mined circular sections first used bolted cast iron lining for running tunnels in about 1870. The earliest use of segmented precast concrete liner was in 1968 on the Victoria Line. Leakage in the tube sections seems to be a function of chance occurrence, such as holes drilled for support of hanging utilities or incidental appurtenants inside the tunnel, or the change of tunnel cross sections from large to small across a head wall which serves as a groundwater barrier. Leakage is monitored as a routine matter and treated as an ordinary maintenance activity. One typical source of leaks is where direct infiltration from retained cut sections is allowed to flow through a cut-and-cover portal into a mined tunnel.

Overall average leakage typically appears to be 0.05 to 1 gpm per 1000 tunnel feet; that is, values at worst slightly greater than WMATA allowable. Expectably, the least seepage appears to be in tunnels surrounded by London clay. If leakage measurements were confined to the worst 100 to 200 feet of tunnel, the local rate of leakage might be three to five times the average.

6.3.7 <u>Conclusions on London Transport Experience</u>. London has an old transit system with a number of shallow cut-and-cover sections in brick walls with ballasted invert. Groundwater is rising in Central London as in New York City because of cessation of deep well pumping for industrial uses. This increases infiltration at the invert of shallow cut-and-cover tunnels. However, the great age and the long-continued additions to the ballast tend to choke off piping of subgrade soils, as compared to the New York Lenox Avenue case.

London's geological setting is favorable to highly favorable. Mined tunnels lie chiefly within the London clay which is equivalent in age, strength and quality to the hard Cretaceous clays in Washington, D.C., except that the London clay is fractured and fissured compared to the extensively slickensided Cretaceous clay. The shallow cut-and-cover construction is in the Thames terrace gravels which are much more stable than the late glacial deposits of New York City and are comparable in quality to the coarse grained Pleistocene terrace soils in Washington, D.C.

Conclusions from the brief contact with London Transport are as follows:

1. In the shallow cut-and-cover sections, minor leakage problems are constantly encountered and create maintenance difficulties which are handled routinely and which lack the unusual aspects of leakage in Washington Metro. Much of the shallow cut-and-cover tunnel is brick lined with no center wall, and in many locations, rehabitated roof structures include heavy membrane waterproofing described in Section 6.3.3. Seepage responds to water table fluctuations, rainfall, utility leaks, and the like. An instructive aspect of their maintenance procedures is the efficient liaison maintained by London Transport with the Thames Water Authority. When leaks are encountered of more than ordinary significance, the inflowing water is sampled and if it appears to be of potable quality, the Water

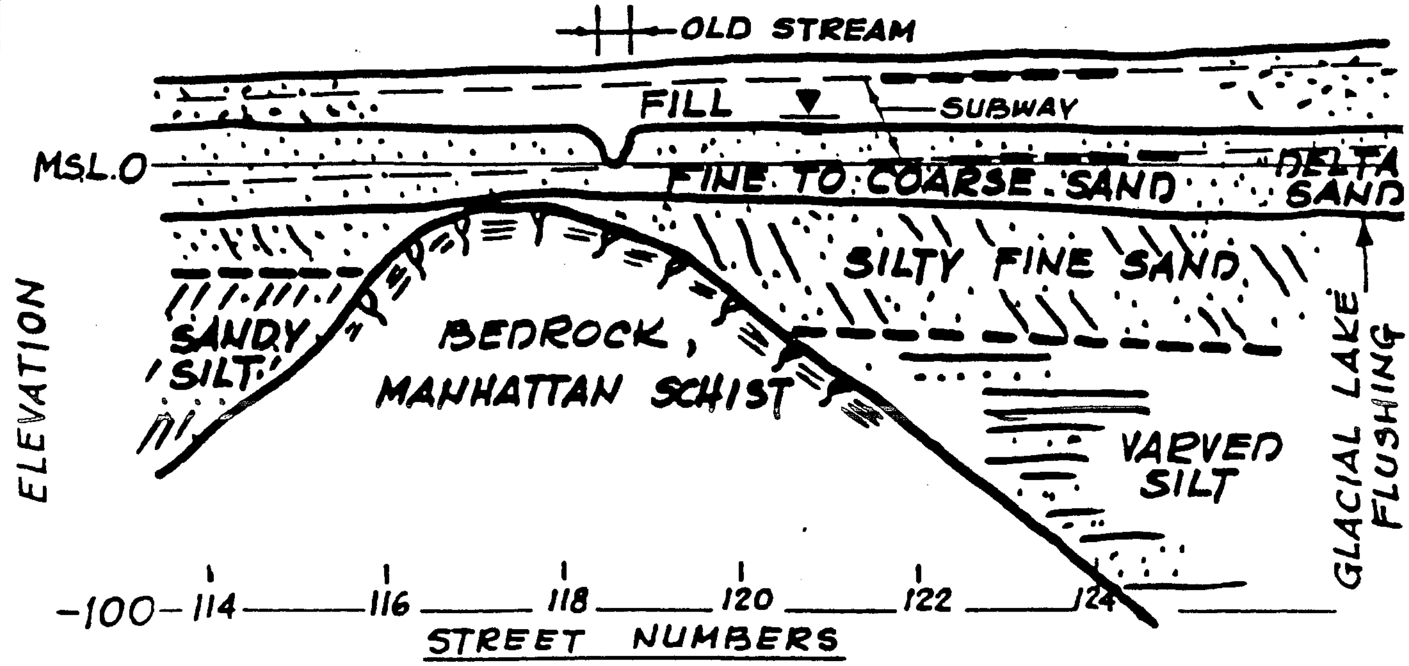
Authority is notified. They typically respond with an effort to find and eliminate the source.

2. The current rise of groundwater in Central London as a result of shutdown of well pumping is significant. This has increased infiltration to invert drains in shallow cut-and-cover sections and has intruded deep basements. On-going studies are being undertaken but probably there is no lesson to be learned here applicable to WMATA.

3. Water intrusion in mined tunnel sections is not especially troublesome, despite the fact that the system include a number of subaqueous tubes beneath the Thames. Leakage to mined sections is concentrated at head walls, where there is a change in section from larger to smaller diameter near stations, where utility conduits or entranceways penetrate from the surface into the tunnel and generally in tunnel sections beneath the river. Cast iron segmented liner is considered more watertight than precast concrete and therefore has been used in tunnels beneath the river in modern work.

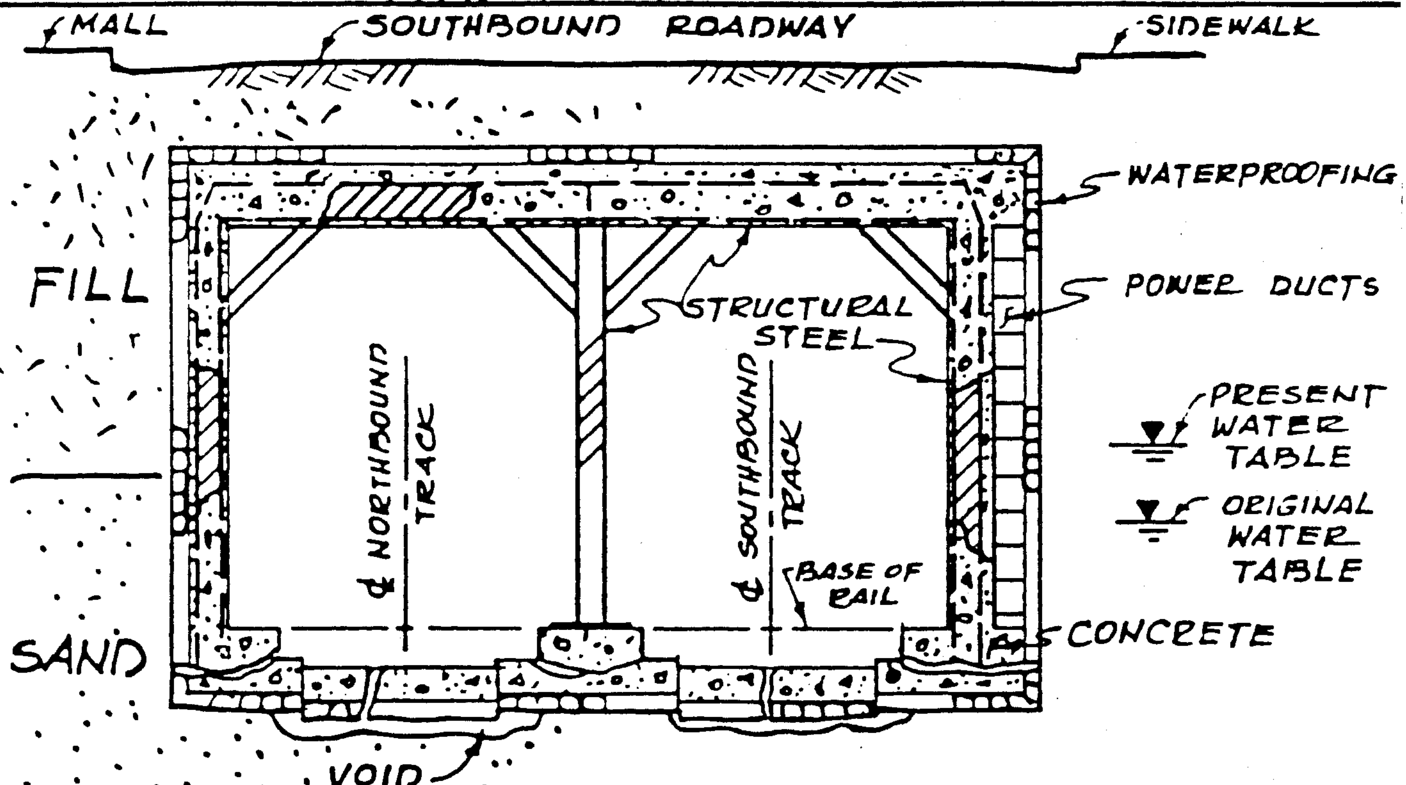
4. London Transit operates with two electrified rails insulated from ground. Thus the stray current corrosion problem is minimal. Groundwater generally appears to have a pH value near neutral and consequently corrosion and attack on concrete is not significant.

5. The London system is a more economical construction which pays less attention than does WMATA to conservative structural criteria and modern amenities. Deeper sections and stations are generally in London clay and do not have significant leakage. Where leakage occurs in new and unexpected circumstances, diligent efforts are made to determine the source and to eliminate it and this involves a long standing cooperation with other public agencies of greater London.



LONGITUDINAL GEOLOGICAL SECTION ALONG LENOX AVE.

0 500 1000 1500 FT.
APPROX. HORIZ. SCALE



CROSS-SECTION SHOWING DETERIORATED INVERT

SCALE: 0 5 10 15 20 FT.

UMTA GRANT STUDY OF WMATA WATER-RELATED PROBLEMS

MUESER RUTLEDGE CONSULTING ENGINEERS
708 THIRD AVENUE. NEW YORK. NY 10017

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SECTIONS OF NYCTA LENOX AVENUE SUBWAY	6-1

CHAPTER 7: SUMMARY AND CONCLUSIONS

7.1 Introduction

More than half of WMATA's eventual 103 mile system will be underground. About one-third of these tunnels lie within crystalline rock of the Piedmont, the other two-thirds within the flat-lying sediments of the Coastal Plain. In addition to the usual problems of water intrusion and hydrostatic pressures impacting underground structures, the geological variety has produced special difficulties with calcification in rock stations and acid inflow in Cretaceous sediments. This investigation concerned four particular subjects affecting structures in the system. Each of these is discussed separately in this chapter under its own heading. While most of the problems are site-specific, some portions of the study have wider implications to transit structures in general. The fifth section of this chapter deals with contacts made with other transit agencies and their experiences with leakage control.

7.2 Water Intrusion Prevention

Leaks in underground transit structures are chiefly the result of cracking of cast-in-place concrete and the ready path for water intrusion created by shafts penetrating from the surface. Either condition is aggravated by the presence of permeable ground surrounding the tunnels and ample recharge from groundwater or leaking utilities. The conclusions from this study are as follows:

1. The feature of overwhelming importance to tunnel leakage is the quality of poured concrete final liner. Those factors that make concreting difficult - long pumping lengths, constricted forms, temperature build up in confined spaces and emphasis on speed of concreting-combine to make tunnel linear concrete particularly subject to cracking. They can be offset to some extent by the use of super-plasticizers, pozzuolanic admixtures and measures to reduce heat of hydration.

2. Records of leakage were evaluated from transit tunnel histories. Analyzing cracks in the concrete, a theoretical permeability of cracked concrete was calculated in this study and compared with the equivalent permeability derived from measured tunnel leakage. Maximum inflow observed from cast-in-place lining is of the order 100 to 300 gallons a minute per 1000 foot length of single tunnel. This corresponds to a maximum equivalent permeability of cracked concrete liner in the range of 1×10^{-3} to 1×10^{-4} feet per minute.

3. Studies of older WMATA stations in rock emphasize that the path of leakage is frequently concentrated at the intersection of penetrating shafts and escalatorways with the main station structure. Excavation for the escalatorway loosens the rock roof and facilitates flow of groundwater from heavily

jointed shallow rock down the top and sides of the penetrating structure to the station. A similar difficulty occurs in a deep tunnel in overburden soil where the penetrating structure allows access for shallow infiltrating water. Consideration should be given to cutting off the penetrating seepage by grouting or by a collar intercepting the direct path of downward seepage.

4. The first line of defense against infiltration is to identify and control the leaks from nearby utility lines at shallow depths. There is some indication that combined sanitary and storm drains which produce a dilute carbonic acid may be a special source of difficulty. Efforts should be made to ensure that the most troublesome leaks from storm drains are sealed and so prevented from aggravating tunnel leakage.

7.3 Hydrostatic Pressures and Pressure Relief

Concern for the effect of calcification in clogging the hydrostatic relief systems of rock tunnels led to field and office studies of the effect of build up of water pressure on tunnel linings, leading to the following conclusions:

1. Tunnels serve to a greater or lesser extent as a large size drain of groundwater. Division of the total hydrostatic head between that lost in impelling flow to the tunnel, and that head which continues to act upon the tunnel liner depends chiefly on the ratio of permeability of surrounding rock to permeability

of the tunnel liner. In some Metro rock tunnels the permeability of surrounding sound rock is low and that of a moderately to badly cracked cast-in-place liner is high and therefore the head acting on the liner is small. A study of leakage through cast-in-place and shotcrete final lining indicates that the equivalent permeability of concrete liner can be as high as $1x10^{-3}$ to $1x10^{-4}$ feet per minute. Permeability of the surrounding rock where unweathered and relatively sound can be $1x10^{-5}$ to $1x10^{-6}$ fpm, roughly 1/10 to 1/100 of that of cracked concrete. Water pressure on the concrete lining would then be no more than about 10 percent of the original head of the surrounding water table.

2. Attention was focused on two of the older stations mined in rock, DuPont Circle and Rosslyn, where it was feared that calcification would eventually plug drains and build up excessive water pressures on the shotcrete liner between the steel ribs. Field tests were carried out in these two stations to measure the exterior water pressures that develop as the shotcrete face was sealed with a test series of brush-on waterproofing compounds. The shotcrete exhibited reflection cracks at the two edges of the outstanding flange of the massive steel ribs in the station arch. Measurements showed that it was not possible to create a pressure-tight seal of the shotcrete by surface plugging of the numerous cracks. Pressure increase measured in this test on the exterior surface of the shotcrete was no more than a few feet of head.

3. Strain gauge measurements were made by the University of Illinois as part of the basic instrumentation on the steel ribs of these rock station permanent linings. Those observations have been translated to thrust and moment and compared to the failure combinations of thrust and moment values for the final lining consisting of shotcrete over heavy steel ribs. The analyses indicate that the stress level only rarely reaches as much as 25 or 30 percent of the yield combinations of thrust and moment. An analysis in this study of the effect of build up of water pressure outside the lining of a rock station indicated that large but uniform pressures would not raise stresses to a dangerous level even under the most conservative assumptions of support conditions.

4. The "New Austrian Tunneling Method" (NATM) scheme appears to offer an answer where hydrostatic pressure relief is necessary. For design of a non-circular section it appears that a significant reduction of total pressure can be assumed because of the relief of water pressures provided by the drainage fabric. Piezometers installed through the NATM lining into the rock of Section B010 tunnel demonstrated that only 2 or 3 psi of water pressure has been built up in several years after completion of the lining. A particularly useful feature of that scheme is the fact that the filter fabric and waterproof membrane are carried continuously from tunnel or station up the shafts and escalatorways so that the intersection of the penetrating structure with the underground tunnel is entirely shielded from

infiltration. It is at the intersection of these structures that the most troublesome leakage traditionally occurs.

7.4 Calcification Cause and Effect

Calcium carbonate precipitate at the point of water intrusion and in drainage systems has been a maintenance problem in WMATA rock tunnels and stations. Concern arose that the clogging of drains could lead to a rise of surrounding groundwater pressures. The problem was studied by MRCE with extensive inspections of precipitation, sampling and testing of inflowing seepage. Use of specialized consultants was supplemented by field tests of waterproofing compounds in two of the older rock stations to determine the build up of water pressures as leaks were sealed. Conclusions are as follows:

1. Calcification is the product of the supersaturation of the inflowing groundwater by calcium carbonate derived from solution of calcite joint filling in the bedrock and enhanced by production of calcium carbonate during rock weathering. Groundwater moving under pressure toward the transit structure deposits carbonates when carbon dioxide is released at atmospheric pressures in the drain or on the inside face of the wall of the structure. The intensity of the precipitate is related to leakage from combined storm and sanitary drains containing dilute carbonic acid and to the degree of weathering and jointing in the

surrounding rock which influence the availability of calcium carbonate.

2. Traditionally, calcification is minimized by confining the inflow under back pressure and avoiding a free surface with the atmosphere until a position is reached where precipitates can be purged. Use of small diameter drain lines of fragile materials is unsatisfactory. Drainage must be arranged to facilitate maintenance and so that drain lines can be penetrated by reaming tools.

3. In the older rock stations structural support consists of heavy steel ribs covered and lagged by shotcrete. The field test of crystallizing penetrating waterproofing products indicated that sealing of the surface by these compounds could not prevent leakage continuing where cracks in the shotcrete exceeded a width of about 0.02 or 0.03 inches.

4. The NATM which installs permeable fabric with waterproofing membrane between the initial shotcrete and the final concrete lining eliminates leakage and also appears to inhibit calcification. Carbon dioxide released from solution would be trapped in the wrap-around fleece and its build up could provide a concentration of gas which inhibits further release within the fleece. Percipitates will then concentrate in the longitudinal collector drains which are arranged to facilitate maintenance.

7.5 Acid Water Inflow

Acid water intrusion occurred during tunneling in 1977 to 1979 in Section G002 of Addison Route, south of the Anacostia River. The tunnels were mined in Cretaceous sand and clay strata dipping gently southeast. Seepage into partially completed tunnels exhibited pH values as low as 1.5 to 2, corroding steel of the initial lining and attacking permanent concrete in the invert and walls. The concrete lining was cored in 1979 and a study was undertaken of the causes of the acid water intrusion and possible long term effects on the lining. Specialists at the University of Maryland and at University of South Carolina identified the mechanism of acid production. The process is analogous to the production of acidic coal mine leachate which occurs on a much larger scale and which can cause severe environmental damage. In 1983, MRCE sampled groundwater in wells which had been installed in the earlier studies. This was followed by a second round of coring of the concrete tunnel lining and tests and analysis. MRCE performed a computer-based study of the factors contributing to acid production. Conclusions from this study are as follows:

1. The interaction of groundwater inflow with oxygen circulated by the tunnel ventilation system and iron sulfide in the Cretaceous strata produced sulfuric acid and an iron oxide precipitate. Sulfide in its most soluble state in the ground occurs as finely crystalline pyrite, such as marcasite.

2. Section G002 appeared to combine a number of specifically unfavorable circumstances which led to this acid production. These included the presence of a marked interface between sands above and clay below within the tunnel opening upon which seepage concentrated. Also contributing were a delay in tunnel advance, leaving the face and sides of the tunnel exposed to air exchange for a long period, enhancing the oxidation process. Where tunnel advance was the slowest, average rates of two or three feet per day, the lowest pH values were recorded in samples of the seepage.

3. Effective sealing off of leakage by the permanent tunnel lining and the natural processes of groundwater dilution has gradually increased the pH values so that relatively neutral groundwater environment is developing with pH approaching the original pre-construction values.

4. The exterior surface of the cast-in-place lining was attacked superficially by the acid, forming a protective coating of gypsum compounds. This coating appears to be stable over the span of 4 years between two sets of coring of the liner. When leakage continues by active flow through joints in the lining corrosion can continue locally, emphasizing again the importance of control of lining shrinkage and cracking.

5. At present there appears to be no better pre-indicator of potential difficulties than the total sulphur content of soil

samples. Where this exceeds 0.1% by dry weight and the Cretaceous soils are distinctly gray in color and contain finely divided lignite particles, a potential for acid inflow is indicated. Section G002 presented a special combination of unfavorable circumstances which created an exaggerated effect on the tunnel leakage, not as yet duplicated at other locations in the completed Metro system.

7.6 Experience of Other Systems

One portion of this study included contacts with selected transit authorities to determine their experience with water intrusion problems. The principal effort was focused on New York City and London. Lessons learned from these contacts are summarized as follows:

1. Grouting for sealing of leaks after construction has been necessary and utilized in the newer systems, WMATA, Atlanta, Baltimore, Boston, and Buffalo. Use of the recently developed water- reactive polyurethane grout offers a promising procedure for direct crack sealing. A recent (1986-1987) sealing program for old subway sections of Massachusetts Bay Transit Authority has demonstrated the effectiveness of this material.

2. Development in the United States in the last decade of precast concrete segmental liner provides an economical lining which can limit seepage to ordinarily tolerable rates.

Conventional metal liners are considered to be the lining that can be the most nearly watertight of the segmented types. However, metal liners are no longer competitive in price with precast concrete and generally are reserved for the most difficult water-bearing ground or for subaqeous tunnels.

3. Seepage problems have been created in older systems, such as New York and London, by rising groundwater due to termination of industrial well pumping. Water levels rise against box sections which were not designed to be watertight or hydrostatic pressure-resistant. In New York City this problem has been aggravated by the presence of subgrade soils consisting of non- plastic silt and fine sand from glacial outwash deposits which are susceptible to piping into drains and through cracked invert concrete. London Transport may face a similar condition in the future with the rise of groundwater in the Thames valley. However, the terrace gravels on which many of their box section are founded are not susceptible to the piping of fines into underdrains.

4. An extreme example of seepage aggravated by highly pervious water-bearing sedimentary rocks combined with leaky cast-in-place liner was evident in a section of the Buffalo Light Rail Transit System where inflow was as great locally as 1 gpm per running foot of single tunnel. Despite the high volumes of inflow, this problem was finally controlled by a comprehensive grouting program using a variety of grouts.

LIST OF REFERENCES

CHAPTER 1: INTRODUCTION AND BACKGROUND

1-1 Tiedeman, H.R. and Graver, J., "Groundwater Control in Tunneling, Volume 2 - Preventing Groundwater Intrusion into Completed Transportation Tunnels", U.S. Department of Transportation, Report No. FHWA/RD-81/074, April 1982.

1-2 Russell, H.A., "A Technical Manual for the Inspection and Rehabilitation of Transit Tunnels", a report to Career Development Committee, Parsons, Brinckerhoff, Quade & Douglas, Inc., October 1987.

CHAPTER 2: WATER INTRUSION PREVENTION

2-1 Technical Committee on Tunnel Lining Design, "Guidelines for Tunnel Lining Design", Underground Technology Research Council of ASCE Technical Council on Research, New York, NY, 1984.

2-2 Tillman, E.A. and Desai, D.B., "Baltimore Metro, Tunnels that Weep but Don't Leak", preprint of paper presented at ASCE Convention, Boston, MA, October 28, 1986.

2-3 Parks, P., Francis, J., Gorlov, A., Gorlova, E., Guertin, J.D., "Water Intrusion Problems in Transit Tunnels", U.S. Department of Transportation, Report No. MA-06-0156-86-1, May 1986.

2-4 Noble, G.E., "Circumferential Cracking of Concrete Linings in Soft Ground Tunnels", Concrete International, ACI, October 1984, pp. 31-34.

2-5 Anderson, B., "Underground Waterproofing", Earth Integrated Technics, Inc., published by WEBCO Publishing, Inc., Stillwater, MN, 1983.

2-6 Rudolf, J, "Concrete Waterproofing by Crystallization", informational briefing, WMATA Board of Engineering Consultants, March 16, 1982.

2-7 Russell, H.A., "Field Trip to MARTA", internal memorandum to Parsons, Brinckerhoff, June 1, 1987.

2-8 Gould, J.P., "Water Control and Waterproofing for Buildings and Tunnels", notes for BSCE lecture series, "Waterproofing and Groundwater Control Techniques for Underground Structures", Boston, MA, February 5, 1987.

2-9 ACI Committee 504, "State-of-the-Art Report on Sealing Joints in Tunnels", Report No. ACI 504.IR-82, Concrete International, June 1982, pp. 17-29.

2-10 ACI Committee 515, "A Guide to the Use of Waterproofing, Dampproofing, Protective, and Decorative Barrier Systems for Concrete", Report No. ACI 515.IR-79, Concrete International, November 1979, pp. 41-81.

2-11 Welsh, J.P., "Control of Water Infiltration by Injection Techniques for Underground Transportation Structures", notes for BSCE lecture series, Waterproofing and Groundwater Control Techniques for Underground Structures", Boston, MA, February 19, 1987.

2-12 WMATA, "Contract Specifications, Leak Repairs, A Route Tunnels, Contract 1B909K", August 1982.

2-13 Baker, W.H., "Improved Design and Control of Chemical Grouting, Volume 3 - Engineering and Practice of Chemical Grouting", U.S. Department of Transportation, Report No. FHWA/RD-82/038, February 1982.

2-14 WMATA, "Section 712, High-Density Polyethylene Waterproofing", Contract and Specifications for Contract 1E0011, Greenbelt Route, 1983.

2-15 Heflin, L.H. and LeFevre, G.T., "NATM Construction of WMATA's Wheaton Station and Tunnels", Tunneling Technology Newsletter, U.S. National Committee on Tunneling Technology, Washington, DC, June 1985.

2-16 Leonard, G.A., "Control of Groundwater as Employed by the NATM", preprint of paper presented at ASCE Annual Convention, Boston, MA, October 28, 1986.

CHAPTER 3: HYDROSTATIC PRESSURES AND PRESSURE RELIEF

3-1 DeLeuw, Cather and Co., "Effect of Hydrostatic Pressure on Stresses in WMATA Rock Station Structural Linings", report submitted to MRCE, November 1983.

3-2 Van Sint Jan, M.L., "Ground and Lining Behavior of Shallow Underground Rock Chambers for the Washington, D.C. Subway", submitted as doctoral thesis, Department of Civil Engineering, University of Illinois at Urbana-Champaign, 1982.

3-3 Ferguson, P.M., Reinforced Concrete Fundamentals, Second Edition, John Wiley and Sons, Inc., 1965.

3-4 Schleiss, A.J., "Design of Pervious Pressure Tunnels", Water Power and Dam Construction, May 1986, pp. 21-26.

CHAPTER 4: CALCIFICATION, CAUSE AND EFFECT

4-1 Einstein, H.H., Assouz, A.S., McKown, A.F., and Thompson, D.E., "Evaluation of Design and Performance-Porter Square Transit Station Chamber Lining", RETC Proceedings, Volume I, 1983.

4-2 Ambric Testing and Engineering Associates of Virginia, "Metro Tunnel Hydrostatic Pressure Relief System", February 5, 1976, report submitted to DeLeuw, Cather and Company.

4-3 DeSanto, R.S., "A Preliminary Consideration of the Calcite Concretions in the Washington, DC Subway System", report to MRCE by DeLeuw, Cather and Company, East Hartford, CT, February 23, 1984.

4-4 White, W.B., "Secondary Mineral Deposition in Washington Metro Tunnels", report to MRCE, February 17, 1985.

4-5 Goldberg-Zoino & Associates, Inc., "As-Built Report, Geotechnical Instrumentation, Tunnel Leakage Study", January 17, 1984.

CHAPTER 5: ACID WATER INTRUSION, CAUSE AND EFFECT

5-1 Bechtel Associates, Geotechnical Group, "As-Built Geologic Report of Tunneling Conditions, Addison Route, Contracts G-1, G-2, G-3", report prepared for WMATA, pp. 36-52, October 1979.

5-2 Kim, G., Heisey, B.C., Kleinmann, R.L.P., and Deul, M., "Acid Mine Drainage: Control and Abatement Research", Bureau of Mines Information Circular 8905, 1982.

5-3 Caruccro, F.T. and Geidel, G., "The Identification of Acid Producing Horizons in the Tunneled Zone of Unconsolidated Sediments of Metro, Washington, DC", report submitted to MRCE, October 6, 1979.

5-4 CARGEID, "An Evaluation of the Acid Production Potential of Selected Samples from Sections F-003 and F-004 of the Washington Metro System", report submitted to MRCE, April 30, 1980.

5-5 Wagner, D.P., Fanning, D.S., and Foss, J.E., "Identification and Source Materials for Acid Leachates in Maryland Coastal Plain", Transportation Research Record No. 892, 1983.

5-6 Hime, W.G. and Erlin, B., "Study of Water and Concrete from Washington Metro System", report submitted to Geraghty and Miller, August 21, 1979.

5-7 Martinek, R.A., "Limited Petrographic Studies of Concrete Cores and Supplementary Report, Petrographic Studies of Concrete Cores", Erlin, Hime Associates, Inc., Northbrook, IL, report submitted to MRCE, November 3, 1983.

CHAPTER 6: CONTACTS WITH OTHER RAPID TRANSIT SYSTEMS

6-1 Carmody, D., "Consulting Report Says 63rd Street Tunnel is Sound", New York Times, October 30, 1985, pg. B3.

6-2 New York City Transit Authority, Engineering Department, "Study for a Permanent Solution to the Ground Water Inflow Problem on the Lenox Avenue Line (IRT Division), Borough of Manhattan", October 1978.

6-3 "A Royal Command Performance, Sagging Rail Tunnel at Heathrow Airport Fast-Track Fix", Engineering News Record, March 20, 1986.