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

2002 Water Intrusion Consultant Board Report

Docket ID: **DCA 15 FR 004**

WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY

WMATA WATER INTRUSION CONSULTANT BOARD

INTERIM REPORT

TUNNEL LEAKAGE – RED LINE TUNNELS

Prepared For

Capital Transit Consultants, Inc.

April 2002

INTERIM REPORT

WMATA Water Intrusion Consultant Board

April 15, 2002

I. INTRODUCTION

The Washington Metropolitan Transit Authority, (WMATA), having extensive groundwater leakage in the Red Line Sections commissioned a consultant board of tunneling experts in December 2001. The purpose of the Board, referred to as the *WMATA Water Intrusion Consultant Board,* is to review the tunnel conditions and to develop recommendations for the control or mitigation of the groundwater inflow into the Red Line tunnels. The Board consists of the following members:

Chairman	*Affiliation*
Dr.Tor L. Brekke	Professor Emeritus; University of California, Berkeley.
Vice Chairman	
Dr. Harvey W. Parker	President; Harvey Parker Associates, Seattle, Washington.
Members	
Mr. Drupad B. Desai	Vice President, DMJM Harris, Baltimore, Maryland.
Dr. Alfred Haack	Director, STUVA-TEC, Cologne, Germany.
Mr. Hugh S. Lacy	Partner, Mueser Rutledge Consulting Engineers, New York, NewYork.
Mr. Robert Robinson	Vice-President, Shannon & Wilson, Inc. Seattle, Washington.
Dr. Gerhard Sauer	President, Dr. G. Sauer Corporation, Herndon, Virginia

The Board met in Washington, D.C. twice, and had working meetings in New York, and in Boston to more efficiently complete its work. While in Washington, D.C., the Board received presentations from, and had discussions with various members of the WMATA staff. The purpose of these meetings was to obtain knowledge of the conditions in the Red Line and to review the available technology that would be suitable for the mitigation of the groundwater infiltration in the Red Line tunnel sections. The Board visited the tunnels and one station (Woodley Park-Zoo). The Board has also requested various data from WMATA that was needed for its evaluation.

The Board was assisted by the staff of Capital Transit Consultants and in particular by Henry Russell and Erin Fulton. Mr. Russell and Ms. Fulton provided technical information in regard to the observed leakage in the tunnels and other pertinent technical information that was necessary for the Board to perform its assigned tasks. Mr. John N. Rever provided management support.

This interim report is to provide guidance to the WMATA Staff for the future capitalization and development of a test program to evaluate which materials and methodologies are best suited to mitigate the groundwater infiltration problems on the Red Line Tunnels and Stations. This report is not intended to replace a more in depth report to be developed by the *WMATA Water Intrusion Board* after the implementation of the test section program.

II. HISTORY OF GROUNDWATER INTRUSION ON THE RED LINE

Background

WMATA's Red Line, which contains the system's oldest sections, has experienced an increase in maintenance costs related to electrical and mechanical equipment problems and structural deterioration from exposure to water intrusion. There have also been temporary shutdowns resulting from electrical flashovers and small fires resulting from the water intrusion. There is also some, but currently, an unknown amount of deterioration/corrosion of essential facilities probably all along the system.

The Red Line tunnels were constructed in rock by both drill-and-blast and TBM (tunnel boring machine) with shotcrete or cast-in-place concrete liners. Based on the available data, most of the tunnel leakage appears to be coming from cracks in the concrete or shotcrete lining. Groundwater inflows vary from a glistening surface and intermittent seepage to inflows of approximately 5 GPM. Post-construction grouting of cracks in the tunnel liner by WMATA's maintenance crews has been successful for a limited time but has not solved the long-term intrusion problem.

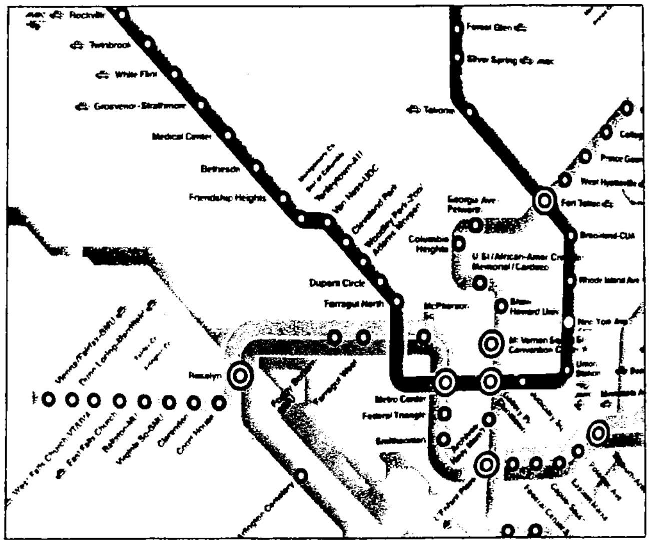


Figure 1. Red Line Location Map

Of the five Washington subway routes (see Fig. 1, Red Line Location Map), the oldest and most troublesome regarding water intrusion is the Red Line. The Board was charged with the scope of addressing water intrusion for the nine-mile tunnel section running northwest, extending from Farragut North Station in northwest Washington D.C. to the rock tunnel termination at the I-495

Wisconsin Avenue interchange in Montgomery County, Maryland (see Fig. 2, Red Line Tunnel Location Plan). This section of tunnels and stations was constructed from 1970 through 1979.

Other than a short cut-and-cover section between the Dupont Circle and the Woodley Park-Zoo stations, all of the Red Line tunnels and crossover vaults were mined in rock. Regardless of the method of construction, all Red Line structures within the nine-mile study section are founded in rock. The construction contract sections within the area described by the nine-mile Red Line tunnels in this study include A-4b through A-11a. The stationing begins at Sta. 56+00 (the beginning of rock tunneling north of Farragut North Station) to Sta. 502+50 (the end of rock tunneling north of Medical Center Station) as shown in Table 1.

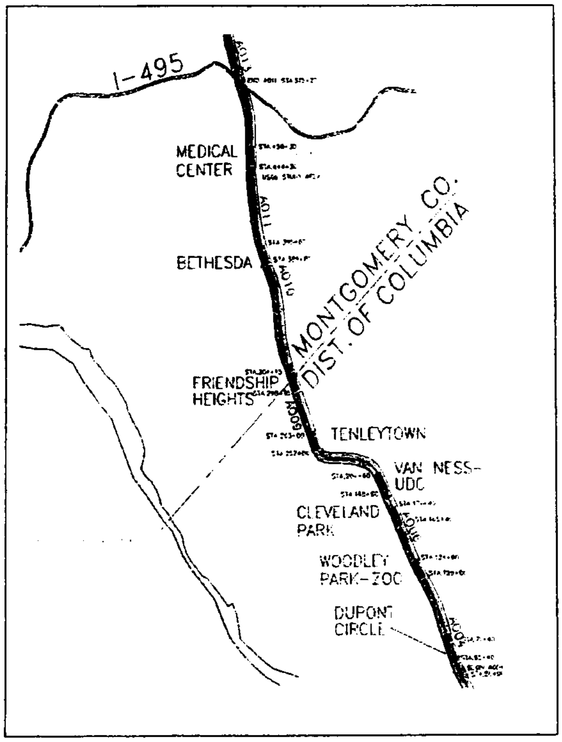


Figure 2. Red Line Location Plan

Geology

The Red Line tunnels north of Farragut North Station lie within the Wissahickon Schist, which is in the Piedmont Physiographic Province (see Fig. 3, Geologic Setting of the WMATA System, Gould, 1988). The tunnels are in Wissahickon Schist, which is overlain by saprolite and Pleistocene deposits. The Wissahickon ranges from low to mid-grade metamorphic Chlorite Schists to higher-grade metamorphic Quartz- Diorite Gneisses. Quartz veins occur commonly in varying thicknesses ranging from less than one-inch to multiple feet and associated minerals in veins and inclusions include hornblende, biotite, muscovite, pyrite, marcasite, calcite, garnet, and chlorite. The rock mass is jointed and heavily foliated. Some faulting exists, many contacts between rock types appear gradational and metasomatic, and shear zones with varying amounts of chloritic clayey gouge are present within the formation.

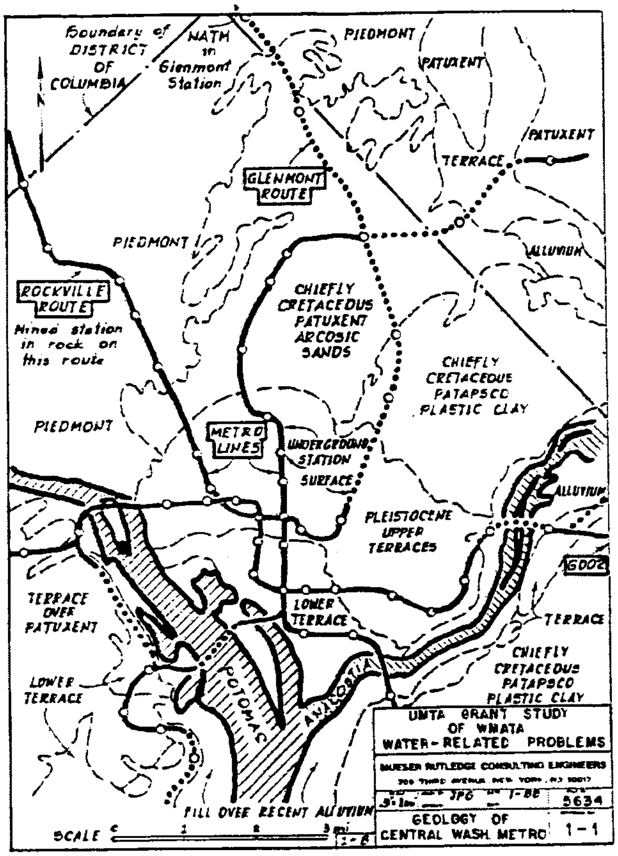


Figure 3. Geologic Setting of the WMATA System, (Gould 1988)

1. Gould, J., "***Water Intrusion In Underground Structures***" UMTA-DC-06-0374-88-01, 1988.

Tunnel Structural Design

The first two WMATA tunnel contracts A-4b and A-4a, totaling 5586 ft, were constructed by drill-and-blast methods while the subsequent tunnel contracts A-6a thru A-11a, totaling 39,926 ft were done by TBM. Table 1, summarizes the contract, stationing, construction dates, liner type and methods used in the Red Line sections. Blasting opens the rock joints and loosens the surrounding rock; creating greater permeability while the TBM method leaves behind an excavated tunnel with less disturbance of the surrounding rock. The results of a tunnel leak survey conducted in Spring 2001 appear to support this as evidenced by the leakage at drill-and-blast shaft -TBM tunnel connections. (Typical tunnel cross-sections are shown in Fig.4 and Fig.5). Some areas along the Red Line tunnels have a Hydrostatic Pressure Relief System, (HPR) installed at water inflow locations encountered during construction and some vaults such as the Medical Center Station Cross-over have an HPR system installed throughout the entire structure.

The HPR systems are susceptible to clogging from calcium carbonate precipitating out of slow-moving calcite-rich groundwater. None of the Red Line tunnels from Farragut North Station to the I-495 portal were specified to have any exterior waterproofing.

WMATA Contract	Station	Const. Dates	Tunnel Liner Type	Const. Method
A4b	56+00-65+40	1970-73	Shotcrete/ Ribs	Drill &Blast
A4a	72+10-111+86	1970-73	Shotcrete/Ribs	Drill & Blast
A6a	111+86-221+00	1974-75	Cast –in-Place Concrete	TBM
A9a	221+00-297+78	1975-76	Cast-in-Place Concrete	TBM
A10a	297+00-388+33	1976-78	Cast-in-Place Concrete	TBM
A11a	388+33-511+12	1977-78	Cast-in-Place Concrete	TBM

Table 1. Tunnel Contract and Type of Construction

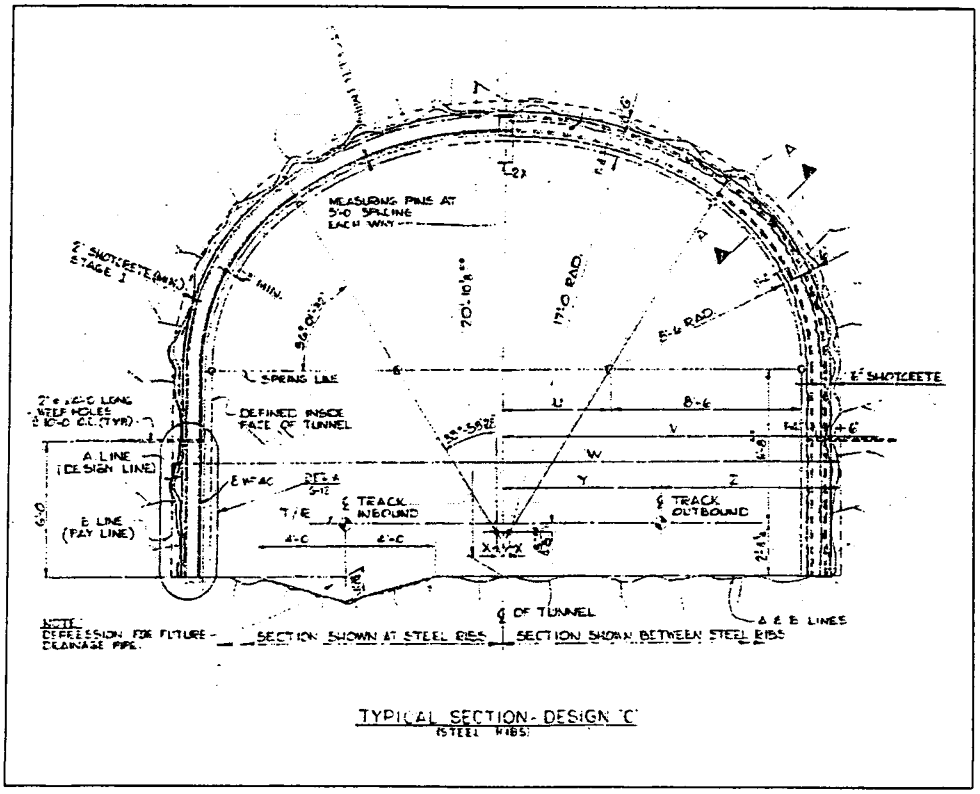


Figure 4. Cross Section of Typical Twin Track Shotcrete Tunnel – Red Line

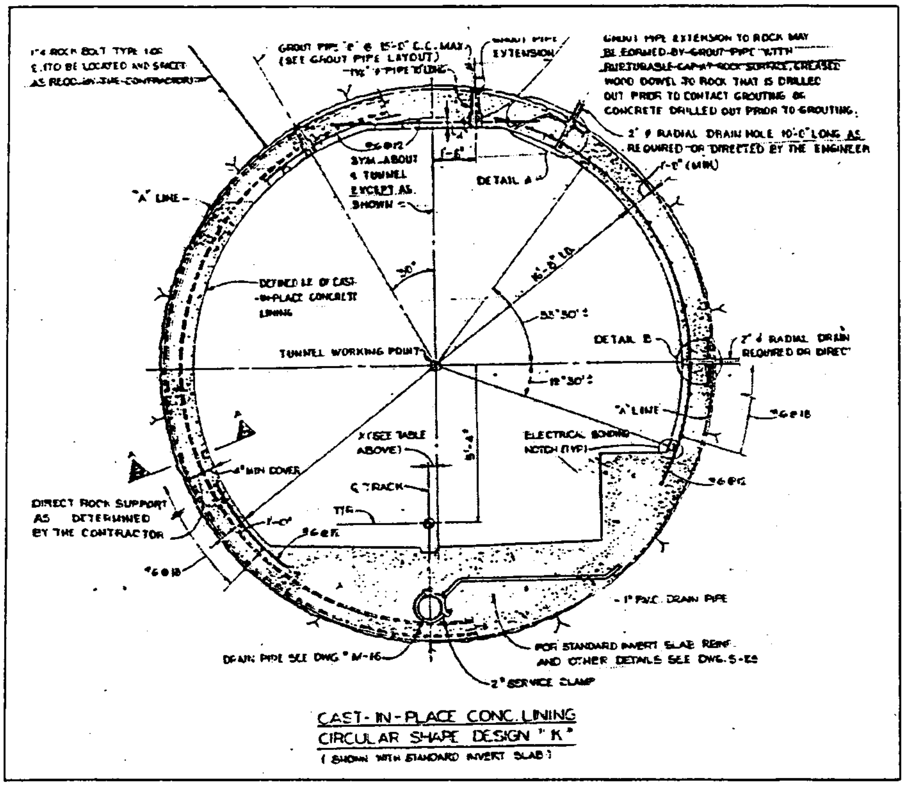


Figure 5. Cross Section of Typical Single Track Bored Tunnel - Red Line

Tunnel Leakage

The majority of water intrusion sources are from shrinkage cracks in the tunnel liner and where the tunnel is subject to thermal changes such as shafts, stations, portals, and adits. Thermal cracking is a result of normal temperature-induced expansion and contraction stresses. In 2001, WMATA instituted an inspection and monitoring program for the purpose of identifying the locations of significant sources of leakage. (Refer to report prepared by Capitol Transit Consultants, Inc titled *Preliminary Water Intrusion Investigation Red Line Tunnel; Stations 456+00 to Tunnel Station 502+80* dated, December 2001.) This survey identified 20 locations in the inbound tunnels and 28 locations in the outbound tunnels with observed inflow rates ranging from slow seepage to an estimated 5 GPM.

Shafts and transitions between different configurations appear to be susceptible to increased leakage. The survey documented that 18 of the inbound and 17 of the outbound leakage locations occur at shafts. The remainder of leak locations are within the tunnel or at station platforms.

In addition to the leak survey performed by WMATA, CTC performed an additional leak survey in December 2001. This leak survey identified many different locations of groundwater intrusion. However, the general locations of the leakage were similar to previous WMATA surveys but the December 2001 survey focused on improving the documentation of the rates and volumes of leakage. In addition to reviewing the formal surveys, the Board visited the site and observed the tunnel leakage on two separate occasions.

Based on the findings listed above, the Board concludes that the source of the majority of the groundwater intrusion is likely a result of shunt flow, water flowing along the exterior walls of the tunnel and the vertical walls of the shafts and appears to be directly responsive to seasonal change. This assumption is largely based on the historical meteorological conditions as shown in the following Table.

Month / Year	Total for Month, Precipitation (inches)	Monthly Departure, Precipitation (inches)
December 2000	2.01	-1.11
January 2001	2.22	-0.50
February 2001	1.83	-0.88
March 2001	3.91	+0.74
April 2001	1.68	-1.03
May 2001	3.71	+0.05
June 2001	4.69	+1.31
July 2001	4.79	+0.99
August 2001	2.98	-0.93
September 2001	1.42	-1.89
October 2001	0.69	-2.33
November 2001	0.55	-2.57
December 2001	1.53	-1.59
January 2002	1.32	-1.89
February 2002	0.47	-2.16
March 2002	3.37	-0.23

Data compiled from the National Weather Service Baltimore / Washington DC, Monthly weather summary for Washington DC, http://www.srh.noaa.gov

Table 2. Seasonal Precipitation for the Washington D.C. Area

Additional information in regard to the Red Line tunnel leakage is described in detail in a report prepared by Capitol Transit Consultants, Inc titled *Preliminary Water Intrusion Investigation Red Line Tunnel; Stations 456+00 to Tunnel Station 502+80* dated, December 2001.

III. UNITED STATES GEOLOGICAL SURVEY STUDY

The United States Geological Survey, (USGS) was retained by WMATA to perform an evaluation of the ground water intrusion in the vicinity of Medical Center Station and crossover in Bethesda, Maryland. The study consisted of a limited hydrological study of the area and a subsequent pump test has determined that the tunnel system acts as a drain. The USGS believes that the gradient of the water at the tunnel could be changed by the installation of various vertical wells to control the groundwater flow towards the tunnel.

The USGS study on the potential for utilizing dewatering wells installed from ground surface supports the concept of relieving water pressures, even in relatively low-permeability fractured rock. We generally concur that water pressures, and resultant seepage inflows can be reduced by the use of a dewatering system. A dewatering system installed from ground surface would require 100 to 200 ft deep boreholes, depending on the depth of the tunnel. Typically wells extend a diameter below adjacent tunnels in order to more fully draw down the ground water levels. Where the groundwater is carried by discrete, continuous near vertical fractures, wells will likely need to be installed at an estimated spacing of about 50 feet along both sides of the station and tunnel alignment. Spacings of as close as 20 feet may be required in some areas and possibly as wide as 50 ft in other areas, depending upon the seepage quantities and locations, and the fracture spacing, orientations and continuity.

The Wissahickon Schist, is a relatively hard impermeable rock material that comprises the rock mass in which most of the Redline transit alignment has been constructed. The Wissahickon Schist is broken by numerous planer fractures, spaced from a few inches to several feet apart. The predominate fracture set is oriented with a strike sub parallel to the Redline alignment, and a very steep westerly dip of 50 to 90 degrees. Experience during construction of portions of the Redline, as well as experience in numerous other tunnels indicates all of the water flow and seepage occurs through various intersecting fractures, rather than through the rock material. Since these fractures are very steeply oriented, they offer a relatively direct flow path for rainwater entering the soil cover, and penetrating the rock to the tunnel horizon. Therefore the orientation, spacing, continuity, and presence or absence of clay fillings of these fractures will control seepage locations and volumes and will also dictate the spacing and productivity of any drainage system.

At some locations, seepage has been reported to relate fairly closely to rainfall. This suggests that infiltrating rainwater flows relatively rapidly along steep fractures in the bedrock. The steepness of the predominate fracture set provides a fairly direct route for rainwater to penetrate the rock mass and enter the tunnel horizon.

It was observed, during construction of the Dupont Circle Station, that seepage was generally associated with fracture zones, shear zones and discrete fractures. A typical geologic cross-section developed for the Dupont Circle Station during construction, portrays a typical fracture spacing and orientation for major features. The cross section depicts the joint fractures are oriented striking sub-parallel with the tunnel alignment and dipping very steeply to the west.

Therefore for a drainage system to be effective, it must intercept most or all of these fracture surfaces before they carry water to the tunnel envelope. Even then, variations in clay filling, degree of fracturing and fracture continuity in three dimensions will make the installation of a drainage system that can cut-off or remove all of the infiltrating groundwater impractical. Nevertheless it is possible to remove a large quantity of the groundwater with a dewatering or drainage system.

Vertical wells, as suggested by the USGS presentation, certainly offers one approach to removing substantial quantities of the infiltrating groundwater that eventually seeps into the tunnel horizon. Wells would have to be positioned to encounter the maximum number of fracture surfaces, which is challenging given the steep orientation of most of the water-carrying fractures. Consequently a number of relatively closely spaced vertical wells would be required to pierce most of these fractures and drain the rock mass.

However, experience suggests that dewatering using holes drilled from ground surface could be expensive to install and maintain and would not be the most efficient and cost-effective approach the water pressure reduction. Holes drilled from ground surface would require a large number of holes in leakage prone sections of the underground alignment in order to intercept groundwater before it reaches the tunnel horizon.

Experience suggests that over a 1,000-foot length of tunnel alignment, roughly 40 to 60 holes will be required, spaced 20 to 50 feet apart along both sides of the tunnel alignment. Each hole would require a low volume electric pump at a cost of about $5,000 per pump. Pumps would likely require replacement at the rate of about 20% per year. Pumps would have to be discharged into a header pipe placed in a trench that connects up the various wells and is below the ground-surface. The header pipe would eventually discharge into a storm sewer.

Monthly maintenance would be required for the well system and would likely involve approximately 2 hours per well to check pump operation, clean lines, and replace pump and well components. An acid solution would likely be required to periodically dissolve calcite mineralization.

As an alternative to the use of deep vertical wells it may be prudent to install weep holes, which are similar to the HPR system already in place to reduce the gradient of the groundwater and to allow for a depressurization of the water near the tunnel and thereby control the locations of the groundwater intrusion.

Weep holes may provide a more cost-effective means of reducing groundwater pressures around an underground opening. Weep holes would likely be spaced 10 to 20 feet apart along both walls of the tunnel and in the quarter arch and arch where the lining surface is accessible. Weep holes would likely be drilled at least 2 inches in diameter and 10 to 30 feet deep in order to maximize the number of intersected fractures and accompanying seepage water. Due to their near horizontal orientation, weep holes would encounter a much greater number of steeply dipping fracture surfaces when compared to an equivalent length of vertical well.

Like the surface vertical wells, the weep holes would need to feed seepage water to a piping system that would eventually carry water to a piping system and storm sewer. Weep holes would also need to be adequately maintained in order to promote efficient drainage. Maintenance could include quarterly to yearly jetting of each hole to clear debris, organic growths and calcite precipitation. Where large quantities of calcite precipitate occur, then an acid solution may be required to periodically dissolve calcite precipitate. The weep holes would drain by gravity, no pumps would be required in the individual weep holes, however pumping of water from several hundred weep holes could be accomplished at selected shafts or tunnel portals. Preventing air from entering the weep holes could substantially reduce the rate of clogging of the drains.

IV. CASE HISTORIES OF GROUNDWATER LEAKAGE

As part of this study, available information on tunnel leakage and repair was reviewed. About 106 case histories of water leakage are described in the appendix A of the report of the ITA working group No. 6 "Maintenance and Repair" [9]. Some representative examples of these case histories are shown in Table 3. This is an extract especially for traffic tunnels.

In the appendix A of the ITA-report some general information is given about the tunnel, for example country, tunnel use, excavation method, inner and outer tunnel lining and geology. Also the kind of leakage, the repair method and the degree of effectiveness are described.

About 72 % of the case histories reported in the leakage study of the ITA were traffic tunnels, the others tunnels were used for hydropower, sewer, water and miscellaneous. Most of the traffic tunnels in the report were road tunnels (39 %).

A further 33 % of the case histories of water leakage were railway and subway tunnels.

Another important term, which is described in the report, were different types of tunnel linings. In only a few cases the linings were built with iron (for example iron plate, liner plate and cast iron, all together about 3%) or with brick (2 %). In most of the cases concrete was used for tunnel linings (87 %). In about 71 % of the reported cases the tunnel lining was built with concrete, pre-cast concrete segments were used in 10 %. Only 6 % of the tunnel linings were built with shotcrete or steel fiber reinforced shotcrete.

The leakage is classified according to the following five leakage description terms, defined by the Construction Industry Research and Information Association (CIRIA)[11}:

- Continuous leak (33% from 106 case histories reported in the Appendix A [9]),
- Drip (30%),
- Standing drip (14%),
- Seep (4%),
- Damp patch (2%).

Further details about the classification of the leakage-rates are explained in Table 5 of the STUVA-paper "leakage-rates".

Repair Methods

One of the major causes for the deterioration of tunnel linings is water leakage into a tunnel. In order to protect the tunnel structure, the leakage flow must be controlled or eliminated. In the report of the ITA working group No. 6 the following four categories of repair methods for treating leakage are presented [9]:

(1) Surface Sealing Methods
(2) Conduction Methods
(3) Lining reinstatement
(4) Elimination at source

Surface Sealing Methods

By using the surface sealing methods some special products were applied to the inner surface of the tunnel lining in order to stop the leakage flow. The applied material itself becomes a part of the lining surface. Some examples for the surface sealing methods are coating and spraying of a membrane or fixing waterproof plates and sheets on the inner surface of the tunnel lining (see Table 3). These methods can only be used if the leakage rates are very low.

Conduction Methods

In accordance with the tunnel use it may be acceptable to allow a controlled drainage or channeling of water towards the tunnel invert and along the tunnel towards a sump for disposal. This conduction method can only be used if the installation and maintenance of the waterproofing system does not cause some negative effects to the operational effectiveness of the tunnel.

In 24 of the 106 case histories the water leakage of the tunnel lining was repaired with one of the three following conduction methods:

- Channeling of leakage water (9 cases),
- Inner shell (10 cases),
- Sprayed membrane or inner protective lining (5 cases).

It must be taken into consideration, that these waterproofing systems should be protected against damage for example caused by vehicle impact, fire or vandalism. Furthermore there must be an insulation against freezing temperature in order to avoid drainage water to freeze. The freezing drainage water because of the rising pressure and the growing up weight can cause a collapse of the waterproofing system.

In the following sections the three conduction methods are described.

The repair method 'channeling of leakage water' involves the installation of strips of drains and gutters at leaking cracks or joints in order to build a channel to collect the leakage water and conduct it to the drains at the tunnel invert. The sealing of the edges of the drains and gutters is achieved for example by mechanical compression or by the use of adhesives. The waterproofing system can be installed during the nighttime to minimize the interference to the tunnel use. The effectiveness of this system depends on the quantity and the sediment content of the drained water. Calcite deposits or frozen water may block the channels.

The next repair method, which uses a waterproof sheet membrane fixed to the existing intrados, is called 'inner shell'. This membrane drains the leakage water towards the tunnel invert and the collecting system. In order to protect the waterproofing membrane against perforation and damage an inner protective shell for example made of shotcrete is necessary. The protective shell also can be built with frame structures and prefabricated concrete elements. For the whole drained surface this method of repair is very efficient. Dependent on the quality of the leakage water the drainage collector system could be blocked. To avoid blockading a waterproofing membrane with studs towards the existing intrados can be used. These studs act as spacers and form channels for the water to flow through.

The last conducting method is called 'sprayed membrane or inner protective lining'. A special mortar, reinforced by fibers or welded mesh is fixed by spraying to the existing tunnel lining. The mortar must be sufficiently dense to reduce the migration of water and to control shrinkage cracking. Leaking cracks and joints must be sealed for example by injection, so that the mortar is sprayed on the dry tunnel surface. This method of repair can be used if the leakage flow is very low (seep or standing drop) and in the case of active leaks, where these can be sealed by injection of grouts.

Lining Reinstatement (Repair)

In order to establish or re-establish the impermeability of the tunnel lining leakage cracks, joints and fissures can be injected or grouted (e.g. repair methods "crack and fissure injection" in Table 3). The selection of the injection or grouting material and the application procedure depend on the specific leakage rates. Further details about the material and the leakage-rate are shown in Table 5. There are a number of factors relating to the selection of grouting procedures and materials, which must be taken into account to achieve success.

Elimination at Source

Another repair method of a leakage in the tunnel lining is the control of groundwater infiltration into the tunnel. For grouting and injection of the surrounding ground outside the tunnel in order to stop the water infiltration there are particle and chemical grouts available. The success of this repair method depends on many factors so that there is not one universal solution to control the leakage. The selection of the appropriate method (for example permeation grouting, displacement grouting and replacement grouting) to control the infiltration is site and operationally specific.

Conclusions

Sometimes one of the four categories of the methods of repair (explained in the sections entitled Surface Sealing Methods through Elimination at Source) may be used in conjunction with one another and additional methods, developed for specific conditions.

Normally the surface sealing methods involve the simple application of special products, but it only can be used by very low rates of leakage. The other three categories of repair methods are more difficult in their application and so require special skill.

Success of the Repair Methods

The effectiveness of the repair methods can be taken from the appendix A of the ITA report [9]. The effectiveness is classified in four categories:

- Effective,
- Somewhat effective,
- Limited effectiveness and
- Temporary measure.

The success of the repair methods according to category of leak is shown in Table 4. For the larger leaks (standing drip to continuous leak) the percentage of successful repairs varied from 47% to 60% [9].

The repair method "conduction of water leakage at the surface and disposal" was reported as 54% successful, 32% reasonably successful and 5% poor success. The other repair methods "sealing of leakage" were in 59% successful, in 29% reasonably successful and 4% poor success [9].

Summary

It can be taken from the ITA report that water leakage is the principal cause of damage to and degradation of tunnel linings. About 106 case histories of water leakage were reported in the ITA-report [9]. The major percentage of the case histories were traffic tunnels (roadway-, railway- and subway-tunnels). In most of the cases significant leaks (continuous leak and standing drip) were described. The favorite lining material was concrete.

In order to control the water leakage, four categories of method of repairs (Surface Sealing Methods, Conduction Methods, Lining Reinstatement and Elimination at Source) were introduced. In 57 % of the cases these repair methods were successful, this depends on the repair method, the leakage rate and other specific conditions.

(References for Section IV: Case Histories of Groundwater Leakage can be found in the back of this document.)

COUNTRY	USE	EXC_ METHOD	LINING1	LINING2	GEOLOGY	LEAKAGE	CLASSIFY	METHOD_REP	EFFECTIVE	YRS.
Australia	Roadway	Mined	In-situ-concrete		Massive sandstone	Drip	Conduction	Crack Injection/ water conduit	Effective	#N/A
Austria	Roadway	Mined	Shotcrete/partly	In-situ-concrete		Drip	Conduction	Waterproof sheet	Effective	#N/A
Belgium	Subway	Cut-and-cover	Slurry walls		Sand	Drip/ continuous leak	Stoppage	Crack Injection	Effective	#N/A
Canada	Subway	TBM	Ribs w/ wooden laggings	Cast-in place-concrete	Glacial till	Drip	Stoppage	Crack injection	Limited effectiveness	10
Canada	Rail Tunnel	Bored excavation	Shotcrete	Cast-in place-concrete		Varies	Conduction	Water conduit	Somewhat effective	
Canada	Railway-LRT	NATM	Ribs w/ shotcrete	Concrete	Wet sand	Continuous leak	Stoppage	Channel cut & Filling	Limited effectiveness	
France	Roadway	#N/A	Shotcrete		#N/A	#N/A	Conduction	Sheet/drainage/ shotcrete	Effective	#N/A
Germany	Roadway	Road header	Shotcrete	In-situ-concrete	Glacial deposits	Seep	Stoppage	Joint injection	Somewhat effective	12
Germany	Subway	Mined	Shotcrete	In-situ-concrete	Anhydrite/ sand stone	Seep	Stoppage	Joint injection/ fissure injection	Somewhat effective	10
Japan	Subway	Cut-and-cover	In-situ-concrete		Sand	Standing Drop/drip	Conduction	Water conduit	Temporary measure	#N/A
Japan	Railway	Mined	In-situ-concrete		Tuff	Standing Drop/drip	Conduction	Channel cut	Somewhat effective	#N/A
Japan	Subway	Shield	Pre-cast concrete		Sand	Standing Drop/drip	Stoppage	Crack injection/ channel cut + fill	Effective	7
USA	Subway	Cut-and-cover	In-situ-concrete		Soil and rock	Drip/ continuous leak	Stoppage	Crack injection	Effective	1
UK	Railway	Shield	Cast iron		Clay	Drip	Stoppage	Crack injection	in construction	

Table 3: Summary of Leak Sealing Case Histories Collected (Extract from the Appendix A [9])

Type of leak	No. of Cases	% Degree of Success		
		Successful %	Reasonably successful %	Poor Success %
Continuous	35	60	23	9
Drip	32	53	31	3
Standing drip	15	47	33	7
Seep	4	100	–	–
Damp patch	2	100	–	–
Others	18	50	4	6

Table 4: Degree of Success in Treating Different Types of leaks [9]

Procedure to apply	Types of Repair Materials for specific rates of leakage			
	Moisture Leakage at Apex/Faces of Cracks			
	Dry	Damp	Steady Flow	
			Free Flow	Pressure Flow
Close	EP-perm	EP-perm^{1}		
	EP-inj	EP-inj^{1}		
	PUR-inj	PUR-inj	PUR-inj	PUR-inj^{2}
	CP-inj	CP-inj	CP-inj	CP-inj^{3}
	CS-inj	CS-inj	CS-inj	CS-inj^{3}
Seal	EP-inj	EP-inj^{1}		
	PUR-inj	PUR-inj	PUR-inj	PUR-inj^{2}
	CP-inj	CP-inj	CP-inj	CP-inj^{3}
	CS-inj	CS-inj	CS-inj	CS-inj^{3}
Rigid bond	EP-inj	EP-inj^{1}		
	CP-inj	CP-inj	CP-inj	CP-inj^{3}
	CS-inj	CS-inj	CS-inj	CS-inj^{3}
Elastic bond	PUR-inj	PUR-inj	PUR-inj	PUR-inj^{2}

Table 5: Application of materials [9], according to ZTV-RISS 93 [14]

Legend:

EP-perm	Permeation with epoxy resin
EP-inj	Injection with epoxy resin
PUR-inj	Injection with polyurethane
CP-inj	Injection with cement paste
CS-inj	Injection with microfine cement suspension

Superscripts:

1	only water tolerant materials
2	previously inject rapid acting foam
3	previously reduce water flow

V. SOURCES OF WATER AND TYPES OF LEAKAGE

There are several sources of water that must be considered to fully understand the water intrusion problem, and thus, their solution. There are also different types of leakage. All these issues, plus all the different types of construction and subsequent maintenance, must be addressed not just individually but also in the overall interaction with each other. See Fig 6, Schematic of Sources of Water and Types of Leakage as the sources of water and types of leakage are described below. As a convenience and to facilitate communication, names and abbreviations of these sources are suggested.

Sources of Water

Soil Flow (Swf)

The ground water table in the soil layer at the surface has been reported to be high but does not change much seasonally (at least not in the Medical Center testing by USGS). The soil is reported to be relatively impermeable and thus cannot contribute much water very fast to the underlying rock.

However, we did see the relatively high flow into the shaft at Woodley Park-Zoo station. This water was reported to be entering the liner at about the soil-rock interface. It is very important to check this location or to check that the pipe was not bringing water from somewhere else. It is possible that leakage from utilities etc. and some groundwater from the soil is leaking directly down into the shafts by vertical shunt flow as described later.

Flow through the soil will be called Soil Water Flow (Swf) for convenience.

Rock Flow (Jf)

There is essentially no primary permeability in the rock; therefore there is essentially no flow through the rock itself. Water flow through rock always passes through the rock joints and is governed by the head and what is termed the rock mass permeability. However, based on recent USGS studies, the rock mass is also reported to have a very low permeability. Therefore, it seems somewhat unlikely that excessive flows are coming directly and solely from the rock mass.

The USGS reports that their testing indicates that the tunnel is acting as a drain, and the ground water table in the rock is reported to change about 5 ft seasonally in the vicinity to the tunnel at the Medical Center station test location. It is unknown how the head changes, with each rainfall. More frequent monitoring by the USGS could obtain this data.

These observations indicate that there is some seasonal changes in pressure head which indicates that the rock is a major potential source of the water leakage into the tunnel is reported to be seasonal. However, it is not likely that all the flow into the tunnel and through the lining comes is sourced form this relatively impermeable rock.

The water flow within the rock mass is to be referred to as joint flow (Jf).

Utility Trench Backfill Flow (Uf)

One potential source that has been overlooked until now is the water that resides in the backfill of all the trenches for those utilities beneath sidewalks and streets, which were intercepted by shaft construction. Frequently these backfills are comprised of sand or fine gravel, to ease construction and, although clean sand and fine gravel is not the cheapest (and thus not the most likely) backfill, even if poorer backfill were used, there are abundant ways through settlement that paths for open flow into the shaft construction areas are likely to exist. Many of these utility trenches were affected by shaft construction and it is likely several utility trenches could be a relatively easy source of significant quantities of free-draining water at the shafts.

It is expected that this source may provide a significant amount of water; since many of these trenches may be under the relatively high water table. Unless they were blocked off or sealed during construction, those old trenches could quickly transmit rainwater to the shaft areas. The water would then pass vertically down by means of Shunt Flow behind the lining of the shaft (See subsequent paragraphs for description of shunt flow).

Direct Inflow into the Tunnel

Rainwater and surface drainage does enter the tunnel through the portals, shafts, elevators, stations, and other openings. This flow obviously varies with rainfall and thus could be a significant contributor to water in the tunnel under drains and sumps.

As seen in Woodley Park-Zoo Station, water was entering the shaft through the lining at a rate of about 5 gpm. This was a continuous flow that appeared to have been flowing similarly for years. Given the number of shafts, only a few of them leaking in this manner would contribute considerably to a wet tunnel and significant pumping at the sumps.

At any location, where a shaft lining has a defect that allows water through the lining, this water would provide direct Inflow into the tunnel similar to rainwater and surface drainage.

Water Brought in by Trains

It may not seem like much but during rainstorms, considerable quantities of water are brought in to the tunnel by the wet trains themselves. Considering the number and frequency of trains, this source may not be insignificant.

Condensation of Moist Air

Again, a somewhat unappreciated source is the condensation of moisture in humid air may not be insignificant either. In fact, the air conditioning systems themselves produce significant quantities of moisture, which eventually enters the track, drain system.

Leaky Water Pipes in Tunnels and Stations

Another source is from water service piping in the tunnels and stations themselves. Even a small leak builds up over time and likely there are several leaks throughout the 9-mile length of the Red Line.

Shunt Flow Down Shafts and Along Tunnel Behind Linings (Sf)

Shunt flow is defined as flow parallel to or along a shaft or tunnel that takes place behind the liner in the annulus between the bedrock and the tunnel liner and in the zone of blast-damaged loosened rock. Sources where this may occur are illustrated in Figure 7 which is a schematic of a drill and blast tunnel illustrating zones that may have higher permeability or where artificial paths develop due to deterioration of wood blocking etc.

These water paths could be caused by shrinkage between the rock and the shotcrete, by deterioration of the wood blocking, and/or the more permeable blast damaged zone. Where the lining has defects, leakage may occur at those points but otherwise, there would be tendency for flow to occur down-gradient parallel to the tunnel and vertically at the shafts.

Shunt Flow moves down-gradient parallel to the shaft or tunnel. If however, there is a defect or a crack in the lining, i.e. cracks or joints in the invert or tunnel liner, some of the Shunt Flow might find its way through the lining and in to the Track Drainage system (Tf). This may have been what we saw in the drainage sumps at the shaft at Woodley Park-Zoo station.

Shunt Flow is given the abbreviation of Sf.

Types of Construction Effecting Leakage

The type of tunnel leakage is dependent on the material of the liner and the configuration of the structure. The following types of construction exist, each of which may have its own type of leakage and thus a different type of remedial solution. They are:

- Running Tunnel
    - Cast-in Place lining
    - Shotcrete lining
- Crossover Structures
- Shafts
    - Vent Shafts
    - Escalator and Elevator Shafts
    - Cable and Auxiliary shafts
- Station Structures
- Transitions between these types of structures

It is likely that different solutions may be required for each type or combination of structure, leakage type, and degree of severity of leakage It has been reported that the largest, or at least most troublesome, water intrusion in the Red Line occurs in the transition structures between different types of structures and the shotcrete lined crossovers and tunnel line sections.

Types of Tunnel Leakage

Where a specific crack or defect creates a small water path in a lining, water will seep through it as a point source leak. This might be individual leaks (such as those that result in stalactites) or along leaky cracks or joints. The latter are usually from a line source but the seepage flowing from the crack flows down the wall and gives the appearance of being a non-point source leak. Point sources can be treated by grouting of the liner or, where the head acting on the back of the lining is low, by a coating on the wall, which creates a barrier to the water flow.

Where a zone of lining is honeycombed or porous in nature, a general source of leakage exists (Non-Point Source) and specific grouting of the lining becomes very difficult to implement. The same is true in the instance of numerous closely spaced specific sources of leaks through the lining. This requires a different remedial approach to control the leakage.

Several of the Red Line structures were provided with High Pressure Relief (HPR) holes to provide drainage to reduce water pressures acting on the lining to values consistent with the structural capacity of the lining.

Any type of leakage that enters the tunnel, it will flow is generally directed through piping, to the Track Drainage System.

Flow in the Track Drains will be called Track Drainage (Td) as shown in Fig. 6.

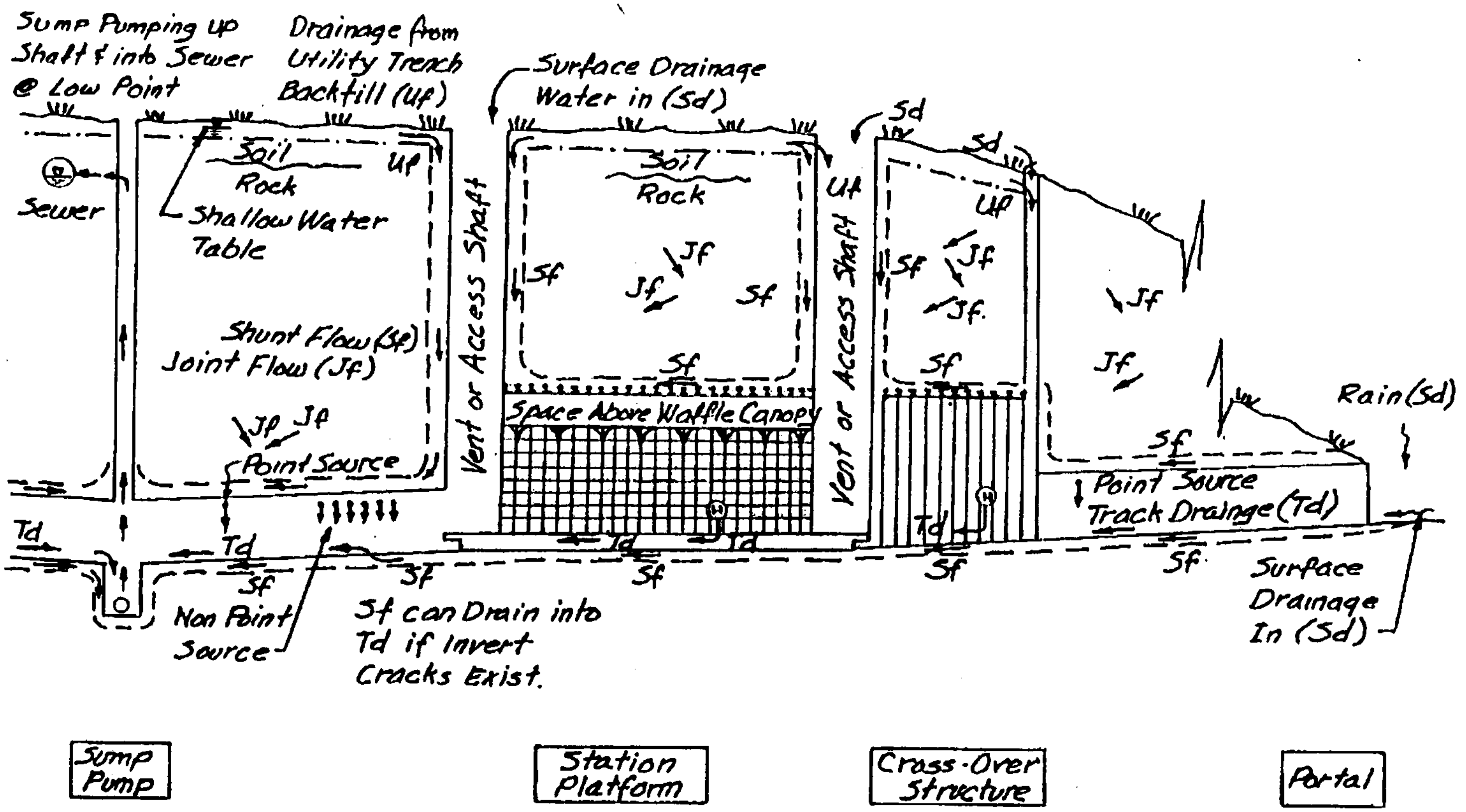
Severity of Leakage

Fig 7 illustrates the possibility of the tunnel acting as a drain, with some pressure head acting on the base of the wall and on the invert of the tunnel. Where this pressure exists, water may find its way through very small but tight cracks. In locations where there is not much pressure, such as in the crown, water will only find its way through open cracks. However, these need only be a few hundredths of an inch wide.

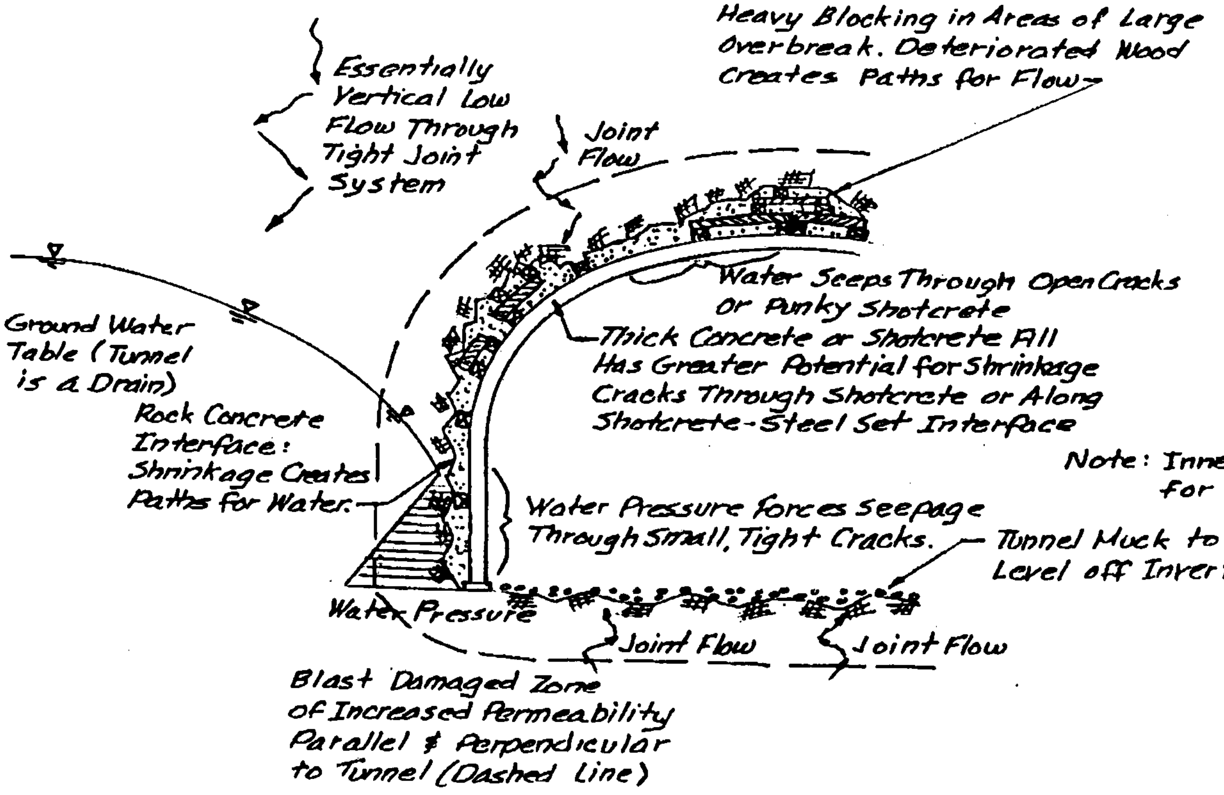
A rule of thumb used in Europe is that cracks with little pressure will leak excessively if they are 0.2 to 0.3 mm while cracks under moderate to high pressure will leak at 0.1 to 0.15 mm wide.

It is likely that different sources and types of leakage will have different solutions but a higher severity (volume) of leakage (for otherwise same conditions) will require different remedial actions. For example, leakage that is clearly under high pressure probably should be controlled by a wall coating capable of withstanding the pressure whereas low pressure seeps may be controlled by the use of a penetrant or other simple coating.

One should be careful to evaluate whether the coating will prevent so much seepage that higher water pressures would build up behind the lining and jeopardizes the success of the coating. Any proposed remedial ground water control program should take these effects into account.



WMATA Water Intrusion Consultant Board
Figure 6
Source of Water Leakage



Schematic of Potential for Shunt Flow and Increased Paths Through Lining.

WMATA Water Intrusion Consultant Board
Figure 7
Shunt Flow Diagram

VI. Mitigating Measures

The control/ elimination of the groundwater infiltration in the Red Line tunnels can be categorized as follows:

- Elimination of the groundwater inflow at the tunnel liner.
- Control of the groundwater inflow within the tunnel (negative side waterproofing).
- Combination groundwater control/elimination within the tunnel.

Each of these general categories requires site-specific adaptation of the existing groundwater mitigation systems to be effective within the Red Line Tunnel. The materials to be used must be non-flammable, have low flame spread, and be non-toxic when exposed to fire. In addition they must be easy to construct with minimal disturbance to the operating system, while providing the best long-term economic value. This discussion will focus on the types of inflow, general types of mitigation and a detailed description of the materials and procedures required to provide an effective groundwater control system.

Elimination of Groundwater Inflow

The elimination of groundwater inflow at the tunnel liner has been the traditional method preferred by most tunnel operators. This process requires the sealing of the liner at point source leaks and at locations where the liner is porous. Point source leaks are those that occur where the liner has provided a clear path for water to pass through. Typical point source leaks are shrinkage and thermal cracks, pipe penetrations and joints in various types of construction. In these tunnels where shotcrete and rib linings were used, leaks are generally where cracks have formed at the contact between the ribs and shotcrete. Point source leaks are generally repaired/sealed with the use of particle or chemical grouts.

Many tunnel liners also allow ground water infiltration through the concrete or shotcrete mass itself. This occurs as a result of poorly placed cast-in-place concrete or instances of high air entrainment. The presence of these pore spaces within the concrete/shotcrete allows water to pass through the liner in the form of vapor and condense on the interior of the liner. In the case of shotcrete, depending on the amount of rebound or other voids within the shotcrete liner water will pass through the liner and develop moist areas on the surface of the liner. This type of leakage is sealed by the use of microcrystalline coatings, waterproof cementitious coatings, polyurea, or the addition of a new waterproof membrane that is often backed up with a shotcrete layer or cast-in-place interior liner. These interior membrane liners often require the use of small weep holes to relieve the hydrostatic pressure, and prevent rupturing of the membrane.

Control of Groundwater Inflow Within the Tunnel

The control of ground water inflow within the tunnel has been the most commonly used maintenance method for minimizing the impacts of groundwater damage at site-specific locations within the tunnels that require the protection of equipment. The control of the leakage is often done with pipes, drain pans, interceptor gutters at the liner wall, liner shields, and diversion drains to the invert and the track drains. The control of groundwater leakage within the tunnel provides for the localized protection of electrical and mechanical equipment. However, it does not provide protection for the structural elements that are located within the tunnel liner. These drainage control devices are often used on older structures pre 1930's, where the tunnel was not designed for the full hydrostatic head. The Red Line Tunnels have been designed with the installation of high-pressure relief (HPR) ports installed to prevent the hydrostatic head buildup.

Combination Elimination and Control of Groundwater Intrusion Within the Tunnel

The Combination systems are a hybrid system that utilizes both the methods for elimination of flow and water diversion techniques. This is often performed using localized grouting and drainage pans to carry water away from locations that may pose a safety hazard or inconvenience to the riding public. The most common use of the combination systems is to perform grouting, and interior coatings in association with specialized piping and pans to divert water away from the electrical equipment and passenger platforms.

Groundwater Control Materials/Systems

Grouting

Various grouting measures have often been proposed for sealing fractures in the rock and tunnel lining in order to reduce seepage. Fracture grouting is as much an art as a science and generally requires a multi-phased grouting program in order to "chase" seepage areas down toward tunnel invert. Furthermore, as a grouting system incrementally seals off sources of seepage, then water pressures will tend to build up around the tunnel. This often leads to the development of new seeps and leaks in previously dry areas. The Corps of Engineers performed a study to assess how accurately the cost and extent of grouting programs could be predicted and designed. They found that grouting programs were often up to 300% more expensive than predicted and originally designed.

Nevertheless, grouting has proven to be effective for sealing discrete fractures, construction joints, and fracture zones in concrete and rock. Epoxy resin, polyurethane, cement, and sodium silicate grouts are but a few of the possible materials used to seal and preclude leakage. Each of the various grouting materials has attendant benefits, drawbacks, and limitations for their application. For discrete well-defined leakage areas, grouting may offer one of the least expensive alternatives for reducing and possibly eliminating leakage, but should be combined with a water pressure relief system to reduce the potential for new leaks developing elsewhere in the tunnel.

Grouting is the injection of a fluid-containing particle or chemical compounds that will cure over time and fill any voids that exist within the tunnel liner or in the case of rock tunnels the rock formation or the annulus between the rock and the tunnel liner. Grouts consist of two basic types: particle grouts and chemical grouts. Particle grouts are those grouts, which are a finely divided powder such as cement and cement mixtures. Chemical grouts consist various chemical compounds and are either hydrophobic or hydrophilic grouts. A hydrophobic grout requires a catalyst to react while hydrophilic grouts use water to act as a catalyst.

Rock Grouting

Formation grouting is the process of filling the voids outside of the tunnel with grout. The most common grout used for this process is particle grout. Chemical grouts are also often used for the grouting of the exterior of the tunnel liner. However, due to economic considerations they are often not used unless rapid set time is required. Particle grouts are typically of cement, cement/flyash, and microfine cement. Chemical grouts are typically polyurethane acrylamide acrylate resin and acrylic gel grouts, and sodium silicate. These grouts are available in both hydrophilic and hydrophobic formulations. The use of acrylamide is not advised due to the high toxicity of the grout. The most commonly used chemical grout for exterior lining grouting is polyurethane grout. Formation grouting is the primary method of cutting off shunt flow at shafts and tunnel lines section by creating a collar around the exterior of the tunnel.

Tunnel Liner Grouting

Chemical grouts are the most commonly used grout for the injection and sealing of tunnel liner cracks, joints and point source leaks. The chemical grouts are used since the width of the typical crack or joint are often too small or tight, for effective grouting of particle grouts. The grout is typically injected through drill holes that are set at an angle to the tunnel wall and have injection ports installed. The drill holes intersect the tunnel defect at approximately mid wall and are flushed with fresh water and then injected with the chemical grout. Hydrophillic grouts are most commonly used unless there is little or no presence of water at the time of injection and a hydrophobic grout is used since it does not need water to complete the catalization of the grout. The set times of chemical grouts can be varied depending on condition and they are very flexible and have extensive elongation, which makes the use of chemical grouts for sealing tunnel cracks and other defects an excellent choice. The most commonly used chemical grouts are single component water reactive polyurethane grouts, with acrylate gel grouts used for very fine cracks.

Coatings

Coatings are negative side waterproofing systems that are applied to the interior side of the concrete /shotcrete tunnel liners and are adhered to the tunnel liner. These coatings are of three basic types:

- Cementitious coatings
- Sprayed/hand applied membranes
- Penetrating coatings

Cementitious Coatings

Cementitious coatings are coatings that are applied to the interior (negative) side of the tunnel liner. They are typically comprised of high Alumina cements and additives that allow for workability and assist in the curing of the coating. The coatings are generally less than ½ inch in thickness and are applied by toweling or spraying with a hopper gun. These coating have been used with success at depths similar to that of the Red Line tunnels.

Sprayed/Hand Applied Membranes

Sprayed/hand applied membranes are membranes that are applied directly to the concrete liner on the negative side and are of two basic types; those that have sufficient tensile and bond strength to withstand the hydrostatic head and those that require a back up coating of either shotcrete or other material to provide tensile resistance to the hydrostatic head.

The use of a sprayed cold applied neoprene coating with shotcrete as a backing material will provide an effective interior waterproofing membrane. The concrete is cleaned and the membrane is sprayed to the interior side of the wall in a layer of approximately 60 mils in thickness. Prior to the spraying steel "J" hooks are attached to the wall and during the membrane application are covered with the membrane making the membrane a continuous sealant of neoprene. After the coating is applied welded wire mesh is attached to the "J" hooks and the entire membrane is sprayed with a low volume wet process shotcrete. The neoprene provides the waterproofing and the shotcrete will provide suitable resistance to the hydrostatic pressure. In some instance it may be necessary to install relief wells depending on the depth of the tunnel to reduce the thickness required for the shotcrete reinforcement.

In addition to the reinforced membranes, recent developments in the use of polyurea waterproof coatings have allowed their use in tunnel applications. The recent developments are in regard to making the polyurea fire retardant and have a low flame spread that has allowed the materials to be installed in coal mines in the United States. Polyurea is an excellent product for a waterproofing membrane, it has extensive elongation, bridges small cracks and has very high tensile and bond strength. The material is applied hot by spraying, and is very easy to install as the cure time is less than two minutes and it does not need a shotcrete reinforcement to withstand high the hydrostatic pressures.

Penetrant Coatings

Penetrant coatings are applied to clean concrete/shotcrete surfaces the penetrant coating are comprised of two basic types the silane based and microcrystalline penetrants. The silane penetrants form a surface seal that is acceptable for low heads applications where the hydrostatic head is less than 75 feet. The microcrystalline penetrants react with the free lime in the concrete/shotcrete and grow crystals in the pore spaces of the concrete, which reduce the pore space to less than one angstrom and thereby prevent the passage of water through the concrete/shotcrete liner. Microcrystalline coating has been successfully used in many harbor-crossing tunnels.

Shields

Shield systems have been used to successfully deflect small to large quantities of seepage to wall drains and invert drains for numerous highway and railway tunnels. These shields consist of semi-rigid sheets of plastic, stainless steel, or metal clad polyurethane foam or other material suspended on a stainless steel, coated steel or plastic frame to deflect seepage water to the side to wall drains. These shields have proven effective for drying up sections of tunnel in fractured rock. The suspension of shield elements from a frame permits access to the gap behind the shields and easy replacement of damaged or corroded shield elements, and servicing of the sidewall drains. The smooth surfaces of the shields are aesthetically pleasing and easily cleaned for a lighter, more reflective tunnel surface.

The use of shields generally requires the bolting of a supporting frame to the liner. Attachment of the frame to the shotcrete or concrete surface may be accomplished with 6-inch long epoxy grouted stainless steel dowels placed in shallow drill holes. The frame and shields generally require a minimum gap of about 6 inches, and consequently construction of the waterproofing shields may reduce the tunnel clearance by 6 inches to a foot, or more, depending upon the irregularity of the tunnel surface. If enough sidewall clearance is available then utility piping may be left in place, and the shields placed over the piping. Partial shields have also been used in some instances to shed seepage water to the sidewalls rather than dripping directly down on the track structure.

Several shield suppliers are available, primarily in Europe. Shield suppliers are scarce in the U.S., but waterproofing shields have been constructed for several railroad tunnels in Pennsylvania and several tunnels in Alaska where even minor seepage can contribute to serious ice buildup on tunnel arches, walls and invert.

Shields are a large variety of systems that provide an umbrella type shield between the liner and the tunnel or station area. Shields may be very complex installations or as simple as the installation of drainage pans and gutters to divert water flow. The shields are installed by attachment to the tunnel liner or by being supported by internal structural supports. The shield may be made up of porcelain steel panels, waterproof geomembranes, preformed concrete panels or other composite panels. All shield systems require a drainage system to be installed to carry the water from the shield and into the tunnel drain system. Some shield systems use geotextiles to drain the system between the shield and the liner while other rely only on sheet flow of water over the shield to carry the water to the drain system. All shield systems usually require extensive disruption to the operations of the tunnel for installation and in some instance are cost prohibitive.

Hydrostatic Pressure Relief (HPR) Drains

Dewatering systems are used in most railway and highway tunnels to relieve groundwater pressures on the tunnel lining. Dewatering systems may also be desirable and necessary in conjunction with grouting or surface sealing systems to reduce the buildup of groundwater pressures that might otherwise lead to increased liner loads as well as leakage at new locations in the tunnel liner.

Typically weep holes are drilled 5 to 10 feet deep, 2 to 4 inches in diameter, and spaced 10 to 40 feet apart in order adequately relieve water pressures. However, with time many of these weep holes clog-up and require periodic maintenance to clear out debris, calcite, and biologic build-up. Clogged weep holes can lead to increasing hydrostatic pressures that would add additional load to the lining.

Evaluation:

Table 6 is a comparison of all of the systems discussed in more detail. The comparison also included installation issues, safety and cost information and is intended to be used for comparison purposes to evaluate the various systems as applicable to the WMATA systems.

Table 6: Remediation Options

Formation Grouting (Rock Grouting)

Particle Grouts

Remediation Options	Success		Installation Ease	Maintain-ability	Toxicity	Flamability		Const. Duration	Operations Impact	Cost	Total Rating
	Short Term	Long Term				Flame Spread	Flamable				
Cement	3	3	1	1	5	5	5	2	2	4	31
Cement / Flyash	3	3	1	1	4	5	5	2	2	4	30
Sodium Silicate	4	4	2	1	2	5	5	2	2	2	29
Microfine Cement	2	2	2	1	2	5	5	2	2	1	24

Chemical Grouts - Hydrophobic

Remediation Options	Success		Installation Ease	Maintain-ability	Toxicity	Flamability		Const. Duration	Operations Impact	Cost	Total Rating
	Short Term	Long Term				Flame Spread	Flamable				
Polyurethane grout	4	4	5	5	4	5	5	3	3	3	41
Acrylamide grout	2	2	2	1	1	5	5	3	3	4	28
Acrylate Resin Grout	2	2	2	1	2	3	3	3	2	3	23
Acrylic Gel Grout	3	3	2	3	3	3	3	3	3	2	28
Structural Epoxy Grout (Amine, Polyester, Vinyl)	1	1	2	1	2	2	2	3	3	2	19

Chemical Grouts - Hydrophillic

Remediation Options	Success		Installation Ease	Maintain-ability	Toxicity	Flamability		Const. Duration	Operations Impact	Cost	Total Rating
	Short Term	Long Term				Flame Spread	Flamable				
Polyurethane gel grouts (water reactive)	4	4	4	5	4	5	5	3	3	3	40
Polyurethane gel grouts (hydro-active)	4	4	4	4	4	4	4	3	3	3	37

Remediation Options	Success		Installation Ease	Maintain-ability	Toxicity	Flamability		Const. Duration	Operations Impact	Cost	Total Rating
	Short Term	Long Term				Flame Spread	Flamable				
Acrylate Gel Grout	2	2	3	2	2	2	2	3	3	3	24

Tunnel Liner Grouts

Particle Grouts

Remediation Options	Success		Installation Ease	Maintain-ability	Toxicity	Flamability		Const. Duration	Operations Impact	Cost	Total Rating
	Short Term	Long Term				Flame Spread	Flamable				
Cement	3	3	1	1	5	5	5	2	2	3	30
Cement / Flyash	3	3	1	1	5	5	5	2	2	3	30
Microfine Cement	2	2	2	1	5	5	5	2	2	2	28

Chemical Grouts - Hydrophobic

Remediation Options	Success		Installation Ease	Maintain-ability	Toxicity	Flamability		Const. Duration	Operations Impact	Cost	Total Rating
	Short Term	Long Term				Flame Spread	Flamable				
Polyurethane grout (multi-component)	4	4	4	5	3	5	5	3	3	3	39
Acrylamide Grout	1	1	2	1	1	5	5	3	3	3	25
Acrylate Resin Grout	3	3	2	2	3	3	3	3	3	3	28
Acrylate Gel Grout	3	3	2	2	3	3	3	3	3	3	28

Hydrophillic Grouts

Remediation Options	Success		Installation Ease	Maintain-ability	Toxicity	Flamability		Const. Duration	Operations Impact	Cost	Total Rating
	Short Term	Long Term				Flame Spread	Flamable				
Polyurethane Gel Grout (water reactive)	5	5	5	3	3	5	5	3	2	3	39
Polyurethane Gel Grout (hydro-active)	5	5	5	3	3	5	5	3	2	2	38

Tunnel Liner Treatment - Negative Side Waterproofing

Adhesive Coatings

Coatings

Remediation Options	*Success*		Installation Ease	Maintain-ability	Toxicity	Flamability		Const. Duration	Operations Impact	Cost	Total Rating
	Short Term	Long Term				Flame Spread	Flamable				
Cementitious Microcrystalline Coatings	4	4	3	4	5	5	5	3	3	3	39
Waterproof Cement Coatings	4	3	4	4	5	5	5	3	2	4	39

Remediation Options	Success		Installation Ease	Maintain-ability	Toxicity	Flamability		Const. Duration	Operations Impact	Cost	Total Rating
	Short Term	Long Term				Flame Spread	Flamable				
Polyurea Coatings	4	4	2	4	5	5	5	3	3	2	37

Cold applied Membrane with Shotcrete

Remediation Options	Success		Installation Ease	Maintain-ability	Toxicity	Flamability		Const. Duration	Operations Impact	Cost	Total Rating
	Short Term	Long Term				Flame Spread	Flamable				
Neoprene	3	4	3	2	4	3	3	4	4	2	32
Bituthane Fluid applied Membrane	3	2	2	2	2	1	2	1	1	3	19

Remediation Options	Success		Installation Ease	Maintain-ability	Toxicity	Flamability		Const. Duration	Operations Impact	Cost	Total Rating
	Short Term	Long Term				Flame Spread	Flamable				
Hot applied Membrane with Shotcrete	2	2	1	2	1	1	1	1	1	4	16

Remediation Options	Success		Installation Ease	Maintain-ability	Toxicity	Flamability		Const. Duration	Operations Impact	Cost	Total Rating
	Short Term	Long Term				Flame Spread	Flamable				
Hot applied Membrane with C-I-P	2	2	1	2	1	1	1	1	1	2	14

Non-Adhesive
Composite Shields (Cladding)

Sheet Membrane with Shotcrete

Remediation Options	Success		Installation Ease	Maintain-ability	Toxicity	Flamability		Const. Duration	Operations Impact	Cost	Total Rating
	Short Term	Long Term				Flame Spread	Flamable				
HDPE	4	5	1	1	2	2	2	2	2	1	22
Polyethylene	4	5	1	1	2	1	1	2	2	2	21
PVC (Polyvinyl Chloride)	4	5	1	1	0	1	1	2	2	2	19

Sheet Membranes with C-I-P concrete

Remediation Options	Success		Installation	Maintain-	Toxicity	Flamability		Const.	Operations	Cost	Total
	Short Term	Long Term	Ease	ability		Flame Spread	Flamable	Duration	Impact		Rating
HDPE	4	5	1	1	2	2	2	1	1	2	21
Polyethylene	4	5	1	1	2	1	1	1	1	1	18
PVC (Polyvinyl Chloride)	4	5	1	1	0	1	1	2	1	1	17

Sheet Membrane with Shield

Remediation Options	Success		Installation	Maintain-	Toxicity	Flamability		Const.	Operations	Cost	Total
	Short Term	Long Term	Ease	ability		Flame Spread	Flamable	Duration	Impact		Rating
Steel panel (galvanized, stainless, porcelain, epoxy coated, enameled)	3	2	3	5	5	5	5	4	2	5	39
Aluminum Panel	3	1	3	3	3	5	5	4	2	5	34
Fiberglass Panel	3	4	3	5	2	3	3	4	2	3	32

Controlling Water Leakage

Remediation Options	Success		Installation	Maintain-	Toxicity	Flamability		Const.	Operations	Cost	Total
	Short Term	Long Term	Ease	ability		Flame Spread	Flamable	Duration	Impact		Rating
Diversion Drains	5	2	3	3	5	5	5	5	3	3	39
Drip Pans	4	3	2	4	5	5	5	4	3	2	37
HPR Piping	4	1	2	1	5	5	5	4	3	3	33

External Groundwater Control

Remediation Options	Success		Installation	Maintain-	Toxicity	*Flamability*		Const.	Operations	Cost	Total
	Short Term	Long Term	Ease	ability		Flame Spread	Flamable	Duration	Impact		Rating
Dewatering	4	1	1	1	5	5	5	2	5	1	30
Water Cutoff	2	1	1	1	5	5	5	2	5	1	28

VII. DEMONSTRATION TEST SECTIONS

In order to better evaluate the best site-specific methodology for the elimination/control of groundwater, the Groundwater Intrusion Board has concluded that the most prudent approach for the Red Line tunnels is to perform various demonstration test sections. These demonstration test sections will be performed to evaluate the effectiveness of the materials and methodology used to seal or control the infiltration of the groundwater. The selection of each test section will include detail mapping of each location, evaluation of quantities of groundwater leakage, and the locations of utilities, and operating equipment present in the area to be tested. Each test section must be typical in regard to the existence of utilities, access, and groundwater infiltration. In addition close attention will be paid to the ease in installation, impact on operations, maintainability, and long-term effectiveness. The duration of the test sections should be approximately one year after installation.

The Board has concluded that the following are the best-suited materials for further investigation and use in the demonstration test sections. They are:

- External water cut off collars for the control of shunt flow.
- Polyurea coating
- Microcrystalline cementitious coating.
- Cementitious waterproof coating
- Shields

Based on our knowledge of the Red Line tunnels, we believe that the test sections should be located within the shotcrete lined tunnel sections. The reasoning for this is that the shotcrete sections are more susceptible to leakage and will be a better location for the demonstration test sections. This decision is based on our observations indicating that the majority of the observable leakage is located within the shotcrete tunnel sections and the shotcrete crossover cavern and stations.

The demonstration test sections will each be approximately 150 linear feet in length and will be circumferential with the exception of the invert portion. It is our opinion that the invert does not have significant groundwater leakage and it would be a prudent economic decision not to treat the invert sections with the interior coatings or to grout the invert for the shunt flow collars. Leaving the invert slab free to "breathe' will also prevent the build up of hydrostatic pressure and will assist in the success of the interior coatings. In regard to the shunt flow collars it is our opinion that there is little potential for shunt flow along the invert, due to full contact of the concrete liner with the bedrock.

External Water Cut off Collars Demonstration Test Sections

The control of the ground water along the exterior of the tunnel line sections and the shafts is best performed by the installation of a grout collar. The grout collar is to be constructed by the injection of a chemical grout by the use of a minimum of three lines of injection ports. The injection ports are to be installed approximately twelve inches apart, with the drill holes drilled with a minimum penetration into the bedrock of three feet. The injection of a non-shrink expanding chemical grout shall be performed using traditional chemical grout pumps with grouting pressure established to be a minimum of ten PSI less than the hydrostatic head at the test section. The grouting shall be performed with a minimum of two passes for each grout line and the grouting shall continue until no measurable grout take is observed. As stated earlier, the entire circumference of the tunnel will be grouted except for the invert portion where we believe there is full liner contact with the bedrock.

Based on our observation we propose to have two test sections for the shunt flow control. One located within the 200 feet of the outbound portal and the other at a shaft location to be determined at the time of installation. The tunnel test section will be 500 feet in length with two seals being installed one at each end of the test section. The shaft test section will have a collar installed below the saprolitic layer at a minimum of 20 feet within the competent bedrock. It is anticipated that the shafts will only have one collar installed at approximately 30 feet above the crown of the tunnel.

The Coating Demonstration Test Sections

During the design phase of the demonstration test sections a materials demonstration test will be performed. The purpose of this test is to observe a small quantity of the material placed on a liner section so that the application may be observed to better understand the operations required for the installation of the demonstration test section. It is anticipated that this materials test section will be performed in late April or May 2002.

The demonstration test sections for the various coatings will be similar in nature and will be approximately 150 feet in length. Each test section will be selected for similar utility locations to best duplicate the installation comparison. The coatings will be installed on the interior circumference of the tunnel shotcrete liner at the manufacturer's recommended thickness. The invert of the tunnel will not be coated for the reasons stated above. Each coating will require the preparation of the existing surfaces to be power washed clean prior to application of the coating and will have any flowing leaks controlled immediately prior to the application of the coating. All of the coatings will be applied as per the manufacturer's recommendations and will be applied by the use of a hopper gun for the cementitious coatings and with special spray equipment for the polyurea.

The exact locations of the test sections will be determined within one month of the start of the test demonstration program. This is necessary to ensure that the demonstration test section will be representative of the groundwater intrusion. We propose to do the coating sections next to each other to eliminate the variable of the geology and the difference in pressure head. The test sections will be installed in conjunction with weep holes at the invert to allow for drainage and to assist in the performance of the coatings. Therefore the total test section will be in the order of four hundred and fifty feet in length and will have weep holes placed at a spacing of twenty feet. The demonstration test sections will be comprised of polyurea, cementitious and microcrystalline materials.

Shields Demonstration Test Sections

At this time, the Board does not believe that a shields test section is viable based on the disruption to operations and the relatively high cost. However, the Board does recognize the viability of such a system for use in the annulus between the precast station finishes and the rock cavern for the stations. Providing funds are available a test section for the use of shield type cladding could be performed above the pre-cast concrete segments in Woodley Park- Zoo station.

Instrumentation for Test Sections

In addition to the test section it will be necessary to better evaluate the quantities of flow within the tunnel therefore a groundwater infiltration monitoring system must be implemented in association with the materials demonstration test sections.

Monitoring Systems

Groundwater seepage inflow rates and groundwater pressures around the tunnel opening can and should be assessed qualitatively and quantitatively. Where test sections are used to assess the effectiveness of various seepage control systems, a monitoring system is essential to determine the effectiveness of these seepage control systems. Qualitative monitoring systems involve the use of visual classification systems to estimate the type and quantity of inflow and have been discussed in the Preliminary Water Intrusion Investigation, Red Line Tunnel prepared by Capitol Transit Consultants, Inc. However, qualitative measurements require repeated site visits by a trained observer to record his observations as a function of time. This type of qualitative measurement is essential, but should be augmented with a less subjective and more continuous quantitative monitoring system. Quantitative groundwater monitoring systems include piezometers and flow meters.

Borehole Piezometers

Piezometers are pressure sensitive and calibrated gages, typically placed in boreholes or seepage storage tanks to measure water pressures or water levels. These piezometer gages can be read either periodically with a portable readout device or they can be hooked up to a virtually continuous monitoring automatic data acquisition system (ADAS). The ADAS can provide a nearly continuous record of water pressures.

Electrical piezometers or standpipe observation wells should be installed in a few boreholes in and around underground openings to assess groundwater pressure changes as a function of the various leakage treatment methods. Vibrating wire piezometers can be selected to measure piezometric levels equal to one foot to over several hundred feet of water and can be tied into an ADAS for frequent, easy remote monitoring, particularly where instruments must be located below busy streets in order to be near the alignment. Changes in water levels can be easily monitored to ± 0.1 ft of water.

Flume Flow Monitoring Systems

A flow monitoring system should also be used to assess drainage water quantities entering and leaving various sections of tunnel in order to assess the current leakage rates as well as the effectiveness of remedial measures. The flume monitoring points should be installed to either side of each of the test section in order to assess the effectiveness of the seepage control system. For normal monitoring of the Red Line, a seepage monitoring system might be placed near each of the invert drain collection points where water is pumped out of the tunnel.

Demonstration Test Section Costs

The following costs were derived using recent bid prices and based on a limited work widow of 4 hours and an extended work window of 8 hours. WMATA costs for flagmen, electricians, and other WMATA personnel required to provide access to the work areas were not included in the cost.

System	Relocate			Clean Surface	Weep Holes	LF Cost	
	Cables	Lights	Miswiring			Install Window	
						4hr	8hr
Shield System NATM Type	Yes	Yes	Yes	Yes	No	$7,078	$3,593
Microcrystalline coating	No	Yes	No	Yes	Yes	$1,992	$996
Waterproof Cement Coating	No	Yes	No	Yes	Yes	$1,616	$808
Polyurea	No	Yes	No	Yes	Yes	$2,952	$1,476
Steel Shields	Yes	Yes	Yes	No	Yes	$6,000	$3,000
Weep Holes	No	No	No	No	No	$ 200	$ 100

NOTES:

1. Costs do not include WMATA costs for operational impacts, power services etc., or engineering costs. Costs for test sections based on all coating sections having weep holes and shield sections with piping and headers. A 12% engineering cost for design not included in estimate. Construction Phase Services for documentation is not included.
2. All costs are based on difficult access and limited working time; the 8-hour window represents 6 hours of actual working time; the 4-hour window represents 2 hours of actual working time. It is anticipated that the final costs would be less depending on the contactors staging, and experience.
3. All systems are based on the relocation of tunnel lighting fixtures, with the NATM Type system requiring the relocation/replacement of electrical cables.
4. The typical test section for costing is a 60-foot arch, twin track shotcrete lined arch, with 10 electrical cables, 2 wave-guide antennas, two sets of tunnel lighting. No provision was made for misc. wiring or signal equipment.

VIII. CONCLUSIONS

- The following conclusions are based on a review of existing conditions, available data on as-built construction, and WMATA and the Board's experience with sealing leaks and published information on controlling tunnel leakage:

- The Red Line, Section A rock tunnels, were designed to provide hydrostatic pressure relief (HPR) by drilling drain holes. Leakage was directed away from the architectural lining in stations using metal pans. Piping systems embedded in concrete linings drained HPR holes to the invert in crossover chambers, stations and running tunnels. As-built drawings indicate that HPR holes were eliminated in shafts and in sections of tunnels where the tunnels appeared dry.

- Calcium carbonate precipitates from leakage is evident throughout tunnel system causing drainage systems to clog and drainage to leak into the tunnel system at other locations. Uncontrolled leakage and clogged drainage has caused more rapid deterioration of track fasteners, electrical and mechanical equipment and structural support members.

- Conditions have deteriorated to the extent that there is an urgent need for a more thorough inspection and prioritization of deficiencies. The current tunnel maintenance program needs to be re-evaluated given the 25± years age of this part of subway system. Our inspections indicate that a more extensive and focused maintenance program, that may include total replacement of some elements, such as the station drip pans, has become necessary to avoid deterioration of tunnel elements that could eventually impact operational reliability and safety of subway passengers.

- An investigation by the USGS of area geology and hydrology to establish groundwater flow trends within the rock has demonstrated that groundwater flow from west to east through the bedrock towards Rock Creek has been interrupted by leakage into the subway tunnel which runs sub parallel to Rock Creek. The USGS also performed a pumping test in one of their wells to investigate the possibility of permanent exterior groundwater pumping as a method of reducing groundwater intrusion into the subway. Our initial conclusion is that this method may be marginally effective at some spot along the subway. However, this pumping test indicated that closely spaced wells would be necessary at this location to be effective. The short and long-term costs including surface disruptions, well maintenance to limit clogging and environmental impacts may make this alternative unattractive at most locations. We are also concerned about potential vandalism to the drainage system. In addition, this method has a high risk that higher volume open joints will not be intercepted by the wells. To attain a better understanding of further pump tests by USGS, piezometers should be installed from the Medical Center crossover.

- Sealing all leaks to exclude infiltration is impractical due to the high cost and impacts on subway train traffic. However, sealing leaks in exposed station areas and to reduce concentrated flows at or near electrical/signal/mechanical systems is a practical way of reducing future MEP maintenance.

- Drainage observation indicates higher flows at shafts than other parts of the subway. Monitoring of pumping rates reveals striking correlation with rainfall records. Considering the low permeability of the Saprolite overburden and modest variation in the perched overburden groundwater levels, it appears that shunt flow in fractured rock from blasting left behind concrete linings in shafts, caverns and the drill and blast tunnel sections. However, it is noted that running tunnels were mined using TBM north of Woodley Park-Zoo Station representing most of the running tunnel in rock included in this study. In addition, flow through the tunnel portal may be contributing to pumping fluctuations.

- Ponded water in crossover and other areas appear to be the result of clogged invert drainage.

IX. RECOMMENDATIONS

- We recommend improving WMATA's maintenance program to adequately maintain the current track drainage system free and clear of any debris. This will significantly improve the quality of drainage and eliminate corrosive deterioration of fastening system. The first step will be a video inspection of the drains embedded in the concrete invert and a thorough cleaning.

- Determine a means of establishing off revenue and off peak operation to provide at least eight-hour maintenance windows to assure quality maintenance and improve constructibility conditions for corrective measures to be implemented.

- Pre-qualify specialty contractors, who will be invited to perform the tasks. An organized, scheduled maintenance program under the direction of WMATA staff should be implemented and carried out by one or more of these specialty contractors.

- Reduction of flow at shaft's where significant flow has been observed is an important element in reducing the impact of groundwater intrusion. Grouting a collar zone of shattered rock around selected shafts should materially reduce shunt flow outside of linings and leakage into the subway. This will require careful planning at each shaft to determine the most practical means of access for equipment and crews with minimum impact on subway operation.

- The effect of groundwater intrusion on the condition of the outside flanges of the ribs supporting the roof of station and crossover cavern needs to be examined requiring removal of shotcrete at several test locations where seepage is occurring.

- The Demonstration Test Sections should be performed as an engineering study and as such may be contracted by The General Consultant (CTC)) as a direct cost to their existing contract. CTC will select the contractor to do the work by a competitive pre-qualified bid process and will develop suitable specifications and plans for the implementation of the test program this is necessary to allow for modifications of the test program, as it develops and to control the test program costs. The demonstration test sections should also have CTC personnel perform the record keeping and evaluation of the installation, and develop a performance report on the test sections.

References

[1] Washington Metropolitan Area Transit Authority: Preliminary Water Intrusion Investigation, Red Line Tunnel, Tunnel Station 56+00 to Tunnel Station 502+80; Capital Transit Consultants, Inc., December 2001

[2] U.S. Department of Transportation: Water Intrusion in Underground Structures, Final Report; October 1998

[3] Sala, A.: Erfahrungen mit einschaligen Spritzbetonverkleidungen bei Tunnelsanierungen in der Schweiz; 6. Internationale Fachtagung des BMI, Innsbruck-Igls, 1999, Tagungsband, Seite 77-83

[4] Girnau, G. / Haack, A.: Tunnelabdichtungen; Forschung + Praxis U-Verkehr und Unterirdisches Bauen Nr. 6, Herausgeber: Ministerium für Wohnungsbau und öffentliche Arbeiten NRW und die Studiengesellschaft für unterirdische Verkehrsanlagen e.V. STUVA

[5] Mergelsberg, W. / Gall, V. / Sauer, G.: Achieving dry-cut-and-cover stations – A membrane based waterproofing system for underground structures; North American Tunnelling '96, Balkema, Rotterdam, 1996, Tagungsband, Seite 353-361

[6] Garrett, R.: Pittsburgh Berry Street Rebuild; North American Tunnelling Ausgabe Juni 1997, Seiten N19-N23

[7] Dr. G. Sauer Corporation; Informationen zu diversen Tunnelprojekten

[8] Haack, A.: Maintenance and repair of underground structures and tunnels; Proceedings of the World Tunnel Congress '98 on Tunnels and Metropolises; Sao Paulo, 25.-30. April 1998, Herausgeber: A.A.Balkema/Rotterdam/Brookfield 1998; Tagungsband, Seite 459-475

[9] ITA Working Group No. 6 Maintenance and Repair: Study of methods for repair of tunnel linings, June 2001

[10] Sager, H.-J.: Entwicklung für einschalige Bauverfahren mit Anwendungsbeispielen beim Stadtbahnbau in Bochum, III. Kolloquium des Lehrstuhls für Bauverfahrenstechnik und Baubetrieb der Ruhr-Universität Bochum,13.02.1985, Seite 73-86

[11] CIRIA Report 81: Tunnel Waterproofing; Construction Industry Research And Information Association, London, April 1979; ISBN 086017-125-6

[12] Haack, A. / Schreyer, J. / Jackel, G.: State-of-the-art of Non-destructive Testing Methods for Determining the State of a Tunnel Lining, Tunnel and Underground Space Technology, Vol. 10, No. 4, 1995, Seite 413 – 431

[13] ZTV-RISS 93: Zusätzliche Technische Vertragsbedingungen und Richtlinien für das Füllen von Rissen in Betonbauteilen, Bundesministerium für Verkehr, Abt. Straßenbau, Bonn 1993

[14] Russel, H. A. / Iske, B. J.: The control of groundwater in underground structures, North American Tunneling '00, Balkema, Rotterdam 2000, Seite 1 – 9

[15] de Hesselle, J. / Hornig, U.: Nachträgliche Bauwerkabdichtung durch Gelinjektion, Grundbautaschenbuch (Entwurf 19.10.2001)

[16] ZTV-Tunnel: Zusätzliche Technische Vertragsbedingungen und Richtlinien für den Bau von Straßentunneln, Teil 1 Geschlossene Bauweise (Spritzbetonbauweise), Bundesministerium für Verkehr, Abt. Straßenbau, Bonn 1995

[17] RABT: Richtlinien für die Ausstattung und den Betrieb von Straßentunneln, Forschungsgesellschaft für Straßen- und Verkehrswesen, Arbeitsgruppe Verkehrsführung und Verkehrssicherheit, Ausgabe 1994

[18] Ril 853: Eisenbahntunnel planen, bauen und instandhalten; Fassung vom 1.10.1998; Deutsche Bahn AG,
Modul 10: Abdichtung und Entwässerung, Seite 1 – 31
Modul 22: Wartung, Instandsetzung und sonstige Baumaßnahmen an bestehenden Tunneln, Seite 1 – 11 sowie Anhang 1 und 2