Underground Station Design Issues for Light Rail Transit in the Twin Cities Geology

A Report to the Regional Transit Board

From:

Underground Space Center
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Graphic Design and Illustrations:

John Carmody

Funded by:

Regional Transit Board

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Acknowledgments

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Dave Minister, Regional Transit Board  
Randall Halvorson, Minnesota Department of Transportation  
Ken Stevens, Hennepin County  
James Dunn, Hennepin County  
Kathy DeSpiglierie, Ramsey County  
Harvey Turner, University of Minnesota  
Jeff Hamel, Metropolitan Airports Commission

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We appreciate the help of Pam Snopl, who edited the report, and Sara Hanft, who typed much of the manuscript.
Summary

This study is intended to identify and analyze selected design issues for underground transit stations in the Twin Cities geology. The first part of the study consists of six chapters in which key underground station design issues are discussed. The second part includes the development and analysis of conceptual designs for three potential underground station sites: downtown Minneapolis, the University of Minnesota, and the airport. These designs reveal a number of issues related to specific sites and are intended to establish a range of options to be further evaluated by system planners. The report does not attempt to reproduce all station design provisions in the various applicable codes of practice, but does present many design suggestions culled from the authors' experience with underground building design and from the literature on transit station design and safety. A brief summary of highlights and conclusions, where applicable, follows for each chapter.

Chapter 1: Geological and Construction Issues

This chapter describes the geology of the Twin Cities area and the range of possible construction approaches and generic station types, and identifies issues related to system expansion. In downtown Minneapolis, and at the airport, deep mined stations can be constructed in the St. Peter sandstone beneath the Platteville limestone. The downtown stations would be at a depth of approximately 100 feet compared with a 50-foot depth at the airport. Also, the downtown stations are built in the water table whereas the airport station would not be. At the University of Minnesota, deep mined stations are also possible; however, a cut-and-cover alignment beneath Washington Avenue is more appropriate to connect with tracks crossing the Mississippi River bridge.
Chapter 2: Entrance Design and Access Issues

Typical entrances to underground stations can be difficult to find, contribute to disorientation, reinforce negative feelings of enclosure and darkness, and may be inaccessible to handicapped people. This chapter describes several examples of subway entrance designs that alleviate some of these problems, and provides considerations for handicapped access.

One notable design feature to be considered in underground stations is the use of inclined elevators. Although they have rarely been used in the United States, inclined elevators have become common in Scandinavian transit stations and offer some significant advantages compared with vertical elevators. Inclined elevators aid in orientation and personal security since all people enter and exit through the same path. It is particularly beneficial to provide disabled patrons with the same access patterns as others. The main drawbacks to their use are the increased cost from the larger inclined guideway and the lack of experience with their use in the United States.

Chapter 3: Station Layout and Orientation

This chapter addresses the overall layout and spatial arrangement of an underground transit station. The focus here is not on detailed standards and regulations but on the broader design principles that help to create a more desirable station with respect to the users. Problems often arise with lack of orientation in underground stations. Sign systems sometimes are not well designed, further adding to the confusion. In some cases, the layout contributes to a sense of confinement as well.

The chapter discusses several approaches to improving station layout and enhancing orientation. Guidelines for the design of signs, maps, and information systems are provided.

Chapter 4: Interior Design and Station Image

This chapter focuses on interior design elements that make underground stations more acceptable to people. Generally, underground spaces are associated with darkness, coldness, dampness, a sense of confinement, and lack of stimulation and connection to the outside world. Design techniques to offset these negative associations are described and illustrated by successful examples of subway station design. Techniques include appropriate use of color, texture and materials, as well as sculpture, paintings, photographs, alcoves, and lighting to achieve a number of effects. One very important conclusion is that interior
design techniques can be used to make even confined station volumes feel more spacious and attractive. In effect, this means that while large volume stations are desirable for people, they are not necessarily essential to create a positive environment.

The overall image of a transit system is formed based on a variety of factors such as convenience, speed, and safety as well as the visual design of the stations, trains, and graphic information systems. This report addresses only the design of underground stations in the system; however, they are likely to contribute significantly to the overall system image. The underground stations in downtown Minneapolis, at the University of Minnesota, and at the airport will be among the most frequently used stations in the system. For many people, these stations will be the entrance or gateway to these areas of the city, and the station interiors will tend to be predominant visual images for the entire system. Visitors are likely to experience the underground stations as major parts of their experience of the city.

Many different design approaches are utilized in the most memorable and attractive subway systems throughout the world. Design approaches that are generally regarded as successful include the following:

- Create distinctive station designs so each station has its own identity rather than appearing identical to all others. An overall graphic system should still be used to give continuity to the system.
- Incorporate artwork into stations.
- If appropriate, incorporate elements of local interest in the station design.

Chapter 5: Emergency Egress and Life Safety

The safety provisions for dealing with fires and most other emergencies in an underground system involve three major actions: evacuating users to a point of safety as quickly as possible, easing the access of emergency personnel, and limiting the spread of danger from its initial source. This chapter describes fire behavior in underground space and provides several guidelines for design.

A key element of the chapter is a discussion of station evacuation. Safety measures include providing two separate escape routes from the station via stairs in shafts or via the escalators, and the additional possibility of exiting through the running tunnels to the next station or emergency exit. Attention is drawn to operating procedures during fire emergencies in which the central control station takes an active role in directing passengers to places of safety.
This has been shown to be far more effective than simply sounding alarms. The chapter also highlights the advantages of visual display boards for train scheduling and emergency announcements. These boards are very important for the learning impaired as well as for reassuring all passengers in selecting the correct platform and trains.

Chapter 6: Other Design Issues

This chapter provides guidelines and comments on additional issues related to underground station design: security, vandalism, station environment, and operating costs.

Chapter 7: LRT System Characteristics

This chapter summarizes system-wide design decisions already adopted by LRT system planners. These guidelines are the basis for the conceptual designs which follow in chapters 8, 9 and 10.

Chapter 8: Downtown Minneapolis Stations

The final three chapters cover specific design issues for the three potential underground sites. In the downtown Minneapolis geological conditions, several station configurations are possible at a depth of about 100 feet. The St. Peter sandstone is easy to excavate and the Platteville limestone forms a strong roof, conditions that potentially lead to relatively low tunnelling and excavation costs. In the downtown area, however, the sandstone is completely saturated so the mined running tunnels and stations are below water. A typical design approach utilized in many recent systems is a two-level station with a mezzanine level above platforms and tracks. While this configuration is spacious from the interior and provides flexibility in layout, the total station volume is relatively large and the station floor and running tunnels are set deeper into the water table. Because of the increased costs associated with this two-level approach, alternative configurations were developed in this study to explore their feasibility and cost-saving potential. The preliminary analysis indicates that a single-level station cavern with a large shaft provides the necessary operational characteristics while offering significant excavation and structural cost savings. In spite of the smaller station volume, interior design techniques discussed in other chapters can be utilized to create a positive image and interior station environment.
Chapter 9: University of Minnesota East Bank Station

At the University of Minnesota East Bank site, a station can be located along Washington Avenue either partially underground in front of Coffman Memorial Union or fully underground between Church and Union Streets. Both locations would allow for an improvement of the campus connection across Washington Avenue. The Coffman location has more difficult alignment issues, while the Church Street location would allow for access to both the Church Street intersection at one end of the station and the Institute of Technology and Health Sciences complex at the other end. The mezzanine level would provide underground connections and access across Washington Avenue.

Chapter 10: Airport Station

At the airport site, specific locations were not examined in detail but it was assumed that a mined station could be placed beneath or in front of the main terminal. It is anticipated that the running tunnels and the stations at the airport would be located in the St. Peter sandstone to avoid interference with airport operations and to allow passengers to connect directly into the terminal building. The limestone is thinner at the airport site than that downtown but the sandstone is dry to a considerable depth. This should make feasible a mined station with a two-story, one-story, or binocular design. The choice would be made based on the connection opportunities to the terminal, the quality of the limestone, and the location of terminal and ancillary building foundations.
Introduction

Purpose of Project

The project was initiated because of the profound implications of a new transit system on many aspects of the urban environment and, in particular, the special impact of subsurface stations on the cost and public image of the system. Currently, five underground stations are planned for the downtown Minneapolis portion of the system, and it is possible that underground stations may occur at the airport and the University. During the project period, a decision was made not to utilize an underground alignment in St. Paul.

In addition to being designed to be cost-effective and to operate efficiently, the transit stations must be safe, accessible to all people, and designed to maximize a sense of orientation. Designs must focus on alleviating negative psychological associations with underground space, creating a positive image for the city, and providing good transitions from the surface urban environment to the underground stations. Many of the underground stations being planned are quite deep (80 to 100 feet) due to the bedrock geology of the Twin Cities. This presents design issues that are different in some aspects from those found in many transit systems.

The purpose of the project was to provide a comprehensive identification and analysis of selected design issues for underground stations in the Twin Cities geology. The issues to be addressed fell into three general categories:

• station configuration constraints and opportunities in various local geological conditions
• station access and egress concepts (especially in the deep stations)
• station image, psychological perceptions, and relation to the urban environment.
The project naturally divided into two parts: a literature review and issue identification for the selected aspects of the underground station design problem, and the development and analysis of station design concepts for representative geological conditions. The project was not intended to interface directly with the preliminary design process of the LRT system but the advanced status of the Hennepin County portion of the LRT system encouraged some direct comparison of alternate concepts with the station designs under development.

The focus of this discussion is on the design of the underground stations more than on the design of the train running tunnels. Although the two obviously cannot be separated, the cost of the stations is generally the major element of the cost of an underground alignment especially in a relatively favorable geology for tunneling. The stations are also the places that create the impression of the underground system and through which all normal access and egress must occur.

**Brief Description of the Proposed Light Rail Transit System for the Twin Cities Area**

A fixed rail transit system to replace the tram system removed in the 1950s has been discussed in the Twin Cities area for more than two decades. Much of the early discussion was focussed on the relative merits of an underground heavy rail system (patterned after the Bay Area Rapid Transit System and the Washington Metro) versus the upgrading and extension of the bus system. One factor cited in favor of the underground option in the Twin Cities area was the demonstrated low cost of urban tunneling in the St. Peter sandstone (Nelson & Yardley, 1973). The principal factors cited against the heavy rail option were the high cost of the system compared to the low density of the Twin Cities area and the low level of congestion. Both of these factors led to a potentially inadequate initial ridership for the heavy rail investment. A third option was proposed in the mid 1970s — the development of a Personalized Rapid Transit (PRT) system. Although the PRT system was never implemented, its discussion combined with the drawbacks of the heavy rail system resulted in the suspension of consideration of a fixed guideway transit system for the Twin Cities area until 1980, when the state legislature passed legislation permitting the creation of regional railroad authorities. Hennepin County was the first county to create such a body.

In the mid-1980s, several factors combined to reawaken interest in a fixed guideway option for the Twin Cities area. These factors included the success of LRT systems in relatively low densities, the realization that road congestion in
Figure 1: Maximum 10-Year LRT Plan for the Minneapolis-St. Paul Region.

Underground Station Design Issues for Light Rail Transit in the Twin Cities Geology
Table 1: 1991 Capital Cost Estimates for RTB Maximum 10-Year LRT Plan

<table>
<thead>
<tr>
<th>Corridor</th>
<th>1991 Estimated Cost ($1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group A</strong></td>
<td></td>
</tr>
<tr>
<td>Downtown Minneapolis</td>
<td>$125.4</td>
</tr>
<tr>
<td>Downtown St. Paul</td>
<td>28.5</td>
</tr>
<tr>
<td>Central Operations and Maintenance Facility</td>
<td>33.1</td>
</tr>
<tr>
<td>Central Corridor Between Downtowns</td>
<td>$185.5 - $250.5</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>$372.5 - $437.5</td>
</tr>
<tr>
<td><strong>Use</strong></td>
<td>$400.00*</td>
</tr>
<tr>
<td><strong>Group B</strong></td>
<td></td>
</tr>
<tr>
<td>Minneapolis Tunnel Extension</td>
<td>60.4</td>
</tr>
<tr>
<td>Minneapolis Northeast</td>
<td>200.3</td>
</tr>
<tr>
<td>Minneapolis Northwest</td>
<td>128.5</td>
</tr>
<tr>
<td>I-35W (96th)</td>
<td>174.2</td>
</tr>
<tr>
<td>Hiawatha (GSA)</td>
<td>75.6</td>
</tr>
<tr>
<td>St. Paul South (TH 110)</td>
<td>132.9</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
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</tr>
<tr>
<td><strong>Group C</strong></td>
<td></td>
</tr>
<tr>
<td>Minneapolis Southwest</td>
<td>81.9</td>
</tr>
<tr>
<td>St. Paul Northeast</td>
<td>91.7</td>
</tr>
<tr>
<td>St. Paul Northwest</td>
<td>105.3</td>
</tr>
<tr>
<td>Hiawatha Extension to GSA</td>
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</tr>
<tr>
<td>I-35W Extension to TH13</td>
<td>60.6</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>407.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1,579.2</td>
</tr>
</tbody>
</table>

* The cost varies +/-10% depending upon the alignment chosen; this cost estimate will be refined in the future.
The Group B and Group C corridor costs differ from the values in the Development and Financial Plan in two ways: the costs are 1991 dollars versus 1988 dollars and the proportionate share of the downtown distribution systems and operations/maintenance facility are now included in Group A. Capital costs are based on work completed in 1987/1988 and reported in the County Comprehensive LRT System Plans.
the Twin Cities (almost non-existent previously) would become much worse, and the limits on road building options due to environmental and land use concerns. Hennepin County took the initiative in preparing for an LRT system by purchasing an abandoned railroad right-of-way from the edge of Minneapolis downtown to Hopkins. A consultant was hired by the county to begin planning for a county transit system. This effort was later widened to include the whole metropolitan area, and in 1989 oversight of the system was given to the Regional Transit Board (which had been created in 1984). The focus of the early planning efforts by Hennepin County was to establish transit routing and system design criteria at a sufficient design level (approximately 30%) to allow the invitation of turnkey bids from private entities for a design/build and proof of operation contract. Under the Light Rail Transit Coordination Plan (Regional Transit Board, 1990), three options are now considered possible — standard practice (separate design and construction contracts), turnkey (as described above), and a hybrid approach.

Figure 1 shows the 10-year LRT system currently envisaged at the time of writing of this report. The plan includes 83 miles of LRT service and is estimated to cost $1.6 billion (1991 dollars) (RTB, 1990). Table 1 shows the breakdown of the 10-year system into corridor groups with the estimated cost of each element.
Part A: Special Design Issues for Underground Transit Stations

In Part A of this report, a set of special design issues for underground transit stations is presented. Part A is divided into the following chapters:

Chapter 1: Geological and Construction Issues
Chapter 2: Entrance Design and Access Issues
Chapter 3: Station Layout and Orientation
Chapter 4: Interior Design and Station Image
Chapter 5: Emergency Egress and Life Safety
Chapter 6: Other Station Design Issues

The material in these chapters is selected and organized to be useful to LRT system planners. Included are broad design principles, examples from systems throughout the world, and research findings and guidelines related to underground station design. This is not intended to be a set of prescriptive regulations for transit stations. Instead it is a selection of design issues and information that is particularly pertinent to underground stations.
Chapter 1:
Geological and Construction Issues

This chapter contains four main sections. The first is a description of the geology of the Twin Cities area and how this geology affects underground construction. The second discusses how geology and other factors affect the choice of station design, while the third covers construction issues. The chapter closes with a discussion of potential future expansion.

Geology of the Twin Cities Area

The following discussion (with a few modifications) is taken from the Low Cost Tunneling Report (Nelson & Yardley, 1973).

The metropolitan area is underlain by a series of gently dipping to nearly flat-lying sedimentary rock layers which form the Twin Cities structural basin. An inland sea covered southeastern Minnesota in the Ordovician period, from about 500 to 440 million years ago. During this time, sufficient sediments collected to form the 300- to 400-foot-thick limestone, sandstone, and shale sequence of the Twin Cities Basin. These several rock units have been named the Prairie du Chien Group, and the St. Peter, Glenwood, Platteville, and Decorah Formations. Overlying the bedrock surface is a heterogeneous blanket of glacial debris, clay, sand, and gravel collectively referred to herein as drift.

The rock formations of significance in considering a subway system are from the top downwards: Glacial Drift, Decorah Shale, Platteville Formation, Glenwood Shale, and the St. Peter Sandstone.
The Decorah Shale

The Decorah is a grayish green shale with a few discontinuous interbedded limestone lenses. It occurs as erosional remnants on top of the Platteville Formation in a few places in the Twin Cities area. The best exposure is in the quarry of the former Twin Cities Brick Company below Cherokee Park in St. Paul.

The main importance of Decorah Shale to underground construction is that where it is present one can be certain that the underlying Platteville Formation has not been eroded and so the latter's thickness has not been diminished.

The Platteville Formation

The limestone and dolomitic limestone layers that make up the Platteville are more or less continuously exposed along the edges of the Mississippi River Valley from St. Anthony Falls in Minneapolis to Robert Street in St. Paul. The beds are about 30 feet thick in the metro area and are nearly flat-lying. The areal distribution is shown on the Twin Cities bedrock geology map (Norvitch and Walton, 1979). Where the overlying Decorah Shale has been eroded away, the

Figure 1-1: Typical geological section of the Twin Cities along the river bluff.
limestone thickness is less than 30 feet, as parts of the upper beds have been eroded and are loosened and rubbly in appearance. However, in most places it constitutes a strong competent layer that can support itself over large openings. This is evident in some of the natural caves near the river valleys, as for example, the cave near East 34th Street and West River Road in Minneapolis, which is up to 60 feet wide and 900 feet long.

Although a great deal is known about the Platteville in terms of its extent, thickness and layering, much less is known about joints, fractures, and fault zones in it. Where vertical and near-vertical joints have been mapped they are spaced many feet apart — a favorable situation. Bedding-plane joints occur and water can move along joints or other fractures where they have been widened by solution. Such water channels can be sealed by grouting.

Five member-units of the Platteville have been recognized. The lowest member, the 1- to 2-foot thick Pecatonica, is locally, when weathered, rather weak and rubbly and may need to be removed where the Platteville will provide part of a roof structure.

The Glenwood Shale

Between the typical white sandstone of the upper portion of the St. Peter and the lowest massive bed of the Platteville there are a series of beds of soft argillaceous and sandy shale grading to shaly dolomitic layers at the top. These thin layers make up the 3- to 5-foot-thick Glenwood Shale.

The Glenwood is not strong and tends to weaken further when exposed to air and water. It does not provide a safe roof for widths much more than 4 or 5 feet and should not be expected to provide structural strength. In station areas it must be removed at the same time as the sandstone is excavated. It does form a somewhat impermeable layer so that water in the limestone is often perched above it. Many of the joints present in the limestone do not penetrate through the Glenwood. However, it is fractured in a few places and where this is so, it will not provide a dependable water seal.

St. Peter Sandstone

The St. Peter is an unusually pure quartz sandstone. Published analyses show from 98 to 99.8 percent silica in the upper 100 feet. The grains are nearly all in the range of 0.15 to 0.4 mm, are well rounded and most are frosted.

Porosity is high. Schwartz (1960) notes an average of 28.3 percent for ten samples in the Twin Cities area. Although porosity is high, the permeability is
not. This is because of the relatively fine grain size. Any layers with grain size coarser than average will have a higher permeability. This is significant in that the upper five feet or so of the sandrock is slightly coarser-grained than the average.

The coefficient of permeability is near 50 (50 gallons per day per square foot under a hydraulic gradient of one at 60°F (Schwartz, 1960). Tests at the University of Minnesota (six samples) averaged 15.31 Darcy’s and the rock specific gravity averaged 1.85.

The St. Peter is very friable. There is very little non-siliceous material present to provide cementation. It is important to note that where the rock is competent and stands without support, the strength is due largely to compaction by the once heavy load of rocks now eroded away. Only a small part of the strength is provided by cementation between individual grains.

Removal of the small amount of cementitious materials by moving ground water and slight agitation of the grains can result in rapid loss of physical strength. The natural caves near the Mississippi in St. Paul and Minneapolis are a result of this sort of action, where ground water seeping down into the sandstone moved toward the nearby river valley (whose low level created a hydraulic gradient), weakened the sand rock by agitation and solution, and moved some of it out to create the caves.

The whiteness of the St. Peter is due to its purity and the frosted surface of the grains. Locally the sandrock is stained reddish or yellow-brown by iron oxides along certain horizons or in erratic bands.

The joints in the St. Peter are usually quite widely spaced and do not constitute a serious hazard. They do occur and can cause some roof problems where two or more joints intersect a tunnel at certain orientations. They are mostly vertical and occur in sets. Mapping of the joints in several miles of tunnels in downtown St. Paul in the early 1970s has shown that they are usually of no great concern although some extra precautions will be necessary where a tunnel is parallel or nearly so to the main joint directions.

Other Geologic Features

An important geologic feature is the presence of a number of “buried valleys.” These are river valleys cut into the bedrock during the ice age and later buried by water-laid deposits and glacial debris. An example is the Chain of Lakes in Minneapolis, which occupies a series of depressions along a large buried valley. Others have no particular topographic expression to denote their presence. Most were cut down into rock units underlying the sandstone. It is
believed that the major buried valleys in the Twin Cities are now known. However, the details of their edges and of their head ends, and the possibility of unknown smaller tributaries, must be considered.

Wherever the limestone cover has been eroded away, tunneling will be in unconsolidated materials, which substantially increases costs. Therefore, to obtain the lowest costs, tunnel routes should be selected where the larger portions of them will be in the sandstone below a limestone layer and as little as possible in unconsolidated materials.

Another geologic feature related to buried valleys as well as to existing river valleys is the presence of natural caves in the sandstone below the limestone. As noted earlier in the section on St. Peter Sandstone, these caves were created by water moving in the sandstone and removing sand through some opening in the valley wall. Such water movements have also removed some of the sandstone cement, weakening the sandstone in some places to create so-called "soft zones." The type of clay in the soft zones is different from the clay minerals in the harder stronger sandstone. In the soft zones the clay mineral is kaolinite, in the harder sandstone it is montmorillonite or illite.

Groundwater

Perched water tables can be expected, particularly as one nears the edges of river valleys. These occur where an impermeable zone prevents downward drainage. Thus a saturated zone often occurs in the glacial drift and the limestone above the Glenwood Shale, while a zone of unsaturated sandstone exists below it for many feet.

Geological Determinants of Station Design

There are several major possibilities for the design of underground transit stations. The choice of station design depends to a great degree on the geology of an area, especially with regard to the depth of the station below grade level. Due to the bedrock geology of the Twin Cities area, many of the underground stations planned are quite deep (80 to 100 feet). These and other issues are discussed below.
Depth of Station

Stations can be located at shallow, moderate, or larger depths, depending on the area's geology and other factors. The depth chosen will determine the initial construction costs as well as the operational enhancements possible for the station.

For shallow stations in soil or rock, the normal design is to create the station as a cut-and-cover box. The depth to the bottom of the box depends on the necessary grade of the running tunnels and the space required for the relocation of street utilities above the running tunnels. Within these constraints, it is usually desirable to keep the station depth to a minimum to reduce construction costs and to shorten passenger travel times to the platform level.

The stations with the lowest first cost are typically as shallow as possible and have only one level below grade with side platforms. To keep structure costs low, interior columns have also been used to limit roof spans. Although inexpensive in first cost, this type of station has many operational disadvantages and does not provide the kind of urban area enhancement which is possible with other designs.

Operational enhancements to this basic station include the creation of a mezzanine level for circulation and platform access below grade. Aesthetic enhancements include the creation of clear spans within the station box to create a safer and more open environment. Together, these two enhancements create a large two-story box (approximately 40 feet in height) with large clear spans for the roof and sections of the walls (approximately 60 feet for the roof and 40 feet for the walls). These changes have a substantial impact on first cost, and the increase in station volume also increases operating costs for heating and air conditioning.

For stations in rock at moderate depth, it may be favorable to use mined construction techniques if (1) the rock has the capacity to span the necessary openings for station tracks and platform, (2) relocation of surface utilities can be avoided, and (3) there are strong prohibitions on the creation of the large surface excavations necessary for cut-and-cover construction.

As the station depth becomes deeper, the decision on whether to open-cut the station or to create a tunneled or mined cavern is very dependent on the geological conditions and the conceptual design of the station. As mentioned above, many underground stations planned for the Twin Cities will be quite deep. Stations excavated remotely beneath the surface usually follow one of the following general design concepts:
A two-tube station in soil or rock using enlarged sections for the platform
tunnels, with cross tunnels to the platforms providing access and egress
(the binocular station). The main part of the station is on one level
(examples - many London subway stations in clay, many Scandinavian
stations in rock).

A three "ring" station in soil, similar in concept to the three-tunnel station
except the tunnels are not completely separate. Three roof arches span the
station, with thick walls or columns providing intermediate support
(examples - many Russian and East European metro stations).

A single-span station on one level in soil or rock providing a large open
station layout. This can be more economical than the smaller separate
excavations under the right geological conditions (examples - newer metro
stations in Leningrad).

A single-span station enclosing a platform and a mezzanine level within
the mined opening. Roof spans are similar to the single-level one-span
station but the volume of the station wall or arch heights is much greater.
When the station is deep and under-street circulation areas are also
provided, this type of station has two mezzanine-type levels.

A narrow single-span station with platforms and tracks stacked vertically.
Platforms on both sides of the trains can allow through loading, and cross-
platform station interchanges can be designed for quick transfers. Roof
spans are limited but platform access is more complicated.

**Groundwater Conditions**

Tunnels and stations in the glacial drift may be above or in the water table
depending on the depth below grade and the location of the station or tunnel
segment. The tunnels and subway stations in the St. Peter Sandstone in the
downtown Minneapolis area will be constructed below the present water table.
Water pressures will increase as the tunnel moves away from the river to the
south of the downtown area. General local practice for dealing with water table
problems has been to desaturate the area of excavation during construction, and
following completion of the work, permit the water table to return to its original
position.

In the airport and perhaps in the University area, construction will be above
the present water table. In the St. Peter Sandstone, problems with water
pressures will be minimized if the tunnel grade is held as close as possible to the underside of the Platteville Limestone. In areas where the St. Peter Sandstone is fully saturated and under a head of water above the base of the limestone, the tunnels and stations will have to resist a substantial water pressure which will increase with depth of the structure below the limestone.

It is not considered likely that tunnels or stations will be able to be permanently dewatered to avoid the need for a pressure-resistant lining. It may be possible, however, to limit the design water pressure in the area of deep stations (in the sandstone) using a controlled amount of drainage from the limestone roof. Small drainage quantities could have the potential to reduce the design head significantly since the limestone is thick and relatively impervious.

When the station must be designed to withstand a substantial water pressure, the cost of the station increases. A high quality waterproofing layer should be used and the floor, walls, and roof must be thickened and more heavily reinforced. Curved structural elements can resist the high water pressures more effectively but are more expensive to construct and may not be as effective in excavated space utilization.

Construction Methods and Costs

Cut-and-Cover versus Tunneled Construction

Unless tunnel grades are deep (more than approximately 40 to 50 feet deep), cut-and-cover construction is usually cheaper in direct construction cost than a tunneled option. However, cut-and-cover construction has a substantial disadvantage in that the traffic and business disruption along the underground route segment is much higher than with the tunneled option. In other projects, this has resulted in many business failures. It has also been true that utility relocation costs, foundation underpinning costs, and temporary decking costs, etc., for the cut-and-cover option have often been underestimated in the past, distorting true comparisons of the costs in the design stages.

In the local geology, tunneling costs tend to increase with depth through the soil and limestone layers but then drop when the favorable St. Peter Sandstone is reached. Tunneling costs are lowest in dry sandstone and typically remain less than in soil even if the sandstone is saturated. As the depth of the tunnel increases below the limestone in areas with a high water table, the costs of the tunneling gradually increase.
Tunneling and large underground constructions always have the potential for some ground settlement above the tunnel or the loss of lateral support to the adjacent ground in a cut-and-cover construction. Proper design and construction methods using the improved tunneling techniques available today are very successful in dealing with this problem. Comparing the major options of cut-and-cover construction, soft-ground tunneling in the soil, and tunneling in the St. Peter Sandstone, tunneling in the St. Peter sandstone offers the least potential for damage to surface structures and streets. It is also not anticipated that drainage into the underground structures will cause any problems with settlement due to drying and shrinkage of the soil in the areas where tunneling is currently contemplated.

Potential Construction Alternates

There are two potential alternates for constructing the LRT system. In the first, the system design may follow the model of a preliminary design, and then a turnkey bid is submitted for the final design and construction. Or, it may follow the model of complete design, followed by bids for construction, services, and equipment. In either case, as much flexibility as possible should be offered to the successful bidder to offer alternate construction techniques that meet system performance goals. This is especially true of the underground portions of the system, since specifying particular configurations too closely (when not required by system performance) can eliminate potentially economic construction methods.

An example of such flexibility might be in permitting a range of finished tunnel sizes from the minimum required for vehicle and equipment clearances to a moderate oversizing for the contractor's convenience. There is a sharp increase in the number of tunnels being constructed by second-hand tunnel boring machines, which typically allow lower prices than the use of new machines. Tunnel size flexibility may allow an existing machine to be used.

If a design/build arrangement is used, the potential need for flexibility in system specifications is greatly increased since existing transit systems (which may be the model for the various bids) can have significantly different design approaches. Because of this need for flexibility, performance standards are generally preferred and prescriptive standards should only be used for essential specifications.

An example of the widely varying system designs is the amount of space allocated for ancillary spaces in underground stations. The Buffalo La Salle station has approximately 10,700 square feet, the Vancouver Bussard station
approximately 7500 square feet (Hatch Assoc. personal communication), and the current downtown Minneapolis station designs between 17,400 and 21,700 feet as a preliminary estimate (PBQD memo 9/15/1990). The reasons for these discrepancies have not been examined in this study, and they may well be justified on the basis of different safety requirements or maintenance provisions. Given the high cost of providing underground station space, it is well worth refining the use of ancillary space as much as possible in design or else leaving the issue of ancillary space organization to a design/build team.

**System Expansion**

If the development patterns of transit systems for major metropolitan areas are examined, it is clear that the Twin Cities system will eventually face the addition of new transit lines and the overloading of certain key segments of the system. Other changes that can be envisaged are a potential desire to upgrade some lines to a higher speed operation to offer better regional service, and the need to provide station interchanges with existing underground stations. Some of the key considerations with respect to initial system design are:

- Can the tunnels initially be designed to physically accommodate a higher speed operation at a later date without significantly adding to the initial cost?
- To what extent should the station length anticipate long-term ridership expectations? Adding platform length to underground stations significantly adds to system cost.
- Is the pedestrian access configuration designed so that additional station entrances can be added in the future without major disruption to operations and without overly complicating the station layout?
- Can the initial station designs reasonably accommodate future station interchanges? If the initial stations in the St. Peter Sandstone are two-story stations, a crossing station would be constrained by track grades either to be excavated into the limestone or soil above the existing track or else extend to depths of 60 to 70 feet below the limestone (140 to 150 feet below the surface). Single-level mined stations usurp far less of the vertical dimension of the urban underground. (Note that the crossing of future utility tunnels is also affected by these issues.)
• How easily can the pedestrian access arrangements for initial stations in a potential interchange location be converted to serve a second station? There are many possibilities for this and no increase in initial costs is likely to be necessary to provide for convenient future access.

• Will underground station designs be amenable to later conversion to a ticket barrier system? This primarily would involve the ability to create sufficient space near the station entrance to house the ticket barrier equipment and a layout of entry points that allows a convenient grouping of entry and exit points.
Chapter 2:
Entrance Design and Access Issues

One of the major differences in the use of underground LRT stations as opposed to surface LRT stations is that, by their nature, the underground stations have access and egress restricted to a few locations, and the station is only visible on the surface at these locations. In addition, the significant elevation changes that are necessary to access the platform level in any underground station make consideration of handicapped accessibility important. Accordingly, this chapter is divided into three parts: (1) entrance design considerations, (2) design approaches and examples, and (3) techniques to provide access for handicapped people.

The focus of this chapter is not on the technical or construction-related problems of creating entrances to underground stations, but on the architectural design issues intended to improve the facility for the users by enhancing the overall system image and accessibility.

The entrance design issues discussed here are intended to complement those related to station layout and interior design presented in the following chapters. There is no precise line within a facility where the entry sequence ends and the internal circulation begins. Internal vertical circulation systems (stairs, elevators, escalators) that occur near the entrance can be correctly regarded as part of the entry sequence as well as part of the building interior circulation. The choice has been made to discuss major vertical circulation elements as part of the entrance sequence since these elements relate so strongly to the need for a clear, efficient, and comfortable downward transition into the facility. Some of the material in this chapter is drawn from Design for People in Underground Facilities by John Carmody within Underground Space Design (Sterling and Carmody, forthcoming).

Figure 2-1: Images of dark, cold, and damp caves contribute to negative associations with underground space.
Entrance Design Considerations

In virtually any building or complex of buildings above or below grade, the entrance has an important role. It gives people a sense of arrival; it can set the mood of a building; it strengthens the orientation on the exterior and interior of the building, and it represents a place of physical and psychological transition between the exterior and interior world (Bain 1990).

In the case of an underground transit station, designing a successful entrance is compounded by two additional factors. First, since the building form is mostly or entirely below grade, the entrance usually cannot be designed in the familiar pattern of a distinct form or opening placed within a larger building mass. In some cases it may be virtually the only visible element of the underground facility. Second, in addition to representing the transition from exterior to interior, it is the transition from above to below grade. This transition potentially can elicit some of the more negative associations with underground space. For example, the movement is usually downward, from light to darkness, from openness to confinement, and from a surface environment with familiar patterns and images to an unknown environment. The key entrance design problems for underground transit stations can be summarized as follows:

1. Because there is no visible building mass, finding the entrance(s) can be difficult and confusing.
2. Because the station is largely not visible, it is more difficult to establish a distinct image.
3. Because there is no object in space that can be perceived as a whole, there is no sense of the overall configuration and size of the facility.
4. Because underground facilities inherently have limited exposure to the surface environment, people in the underground may feel disconnected from what is above grade, leading to problems of disorientation. The entrances may present the only opportunities to establish this connection.
5. The movement at the entrance is usually downward, which potentially elicits negative associations and fears.
6. The necessary use of escalators and stairways to enter some underground facilities forces mobility-impaired people to use secondary means of entry often located away from the main entry sequence.
Entrance Design Approaches

There are several conventional means of entering underground transit stations in urban environments. Each presents constraints and opportunities. Usually the type of entrance is determined by the existing surface development patterns. Typically entrance to an underground station occurs through one of the following:

- a simple, open stairway or escalator
- an enhanced open stairway or escalator using open air structures, courtyards, and other amenities
- an above-grade entrance pavilion
- an above-grade building mass
- as part of a system of underground paths and spaces

In the remainder of this section, several examples of subway entrance design are discussed in order to illustrate techniques to overcome the problems stated previously. The following design objectives for subway station entrances apply to all the approaches discussed below.

- Provide a clear, legible entrance (or entrances) that can be recognized from a distance along major paths of approach.
- Provide a graceful transition to lower levels.
- Make the entrance area and vertical circulation spacious and well-lighted.
- Use the entrance to establish a visual connection between the exterior surface environment and the building interior.
- Provide barrier-free entrances for mobility-impaired individuals. Make these entrances part of the main entry sequence, not a separate secondary path.

Open Stairways and Escalators

The simplest form of entry into an underground transit station is by means of a stairway or escalator placed in a sidewalk or plaza area at street level. While these minimal entrances are practical and minimize disruption of the surface

Figure 2-2: Typical entrances to underground transit stations are often difficult to find and seldom provide a feeling of openness or connection to the surface.
sidewalk space, they are small and tend to reinforce images of entering dark and confining underground spaces.

Generally, an important design objective with underground facilities is to create a graceful transition to lower levels while offsetting associations with darkness and confinement. Where possible, this can be achieved by placing stairways and escalators within small sunken courtyard spaces. Entering through a courtyard has some characteristics that effectively offset some of the negative associations of going downward into an underground building. The downward transition occurs in a more open exterior space with no associations of darkness or confinement. Orientation is enhanced because there is a continuous flow of space from above to below grade, and from exterior to interior environments. Movement is continuous, unlike waiting for an elevator, and people are in visual contact with others, which reduces feelings of isolation and creates a more stimulating environment.

Making the actual transition from the ground level to the entrance level at the courtyard floor is most gracefully done with open stairways, ramps, or possibly escalators. A drawback to this approach is that elevators for mobility-impaired people will often be located away from this main entry sequence since there may be no above-grade mass and the transition occurs outdoors. Moreover, in colder climates exterior stairways and ramps in courtyards exposed to snow and ice can be difficult to keep clear.

Figure 2-3: This stairway entrance to the Les Halles complex in Paris is placed in a small open courtyard area. The entry transition is enhanced by a series of pools with falling water alongside the stairway. From inside the facility, orientation is improved by views of landmarks on the surface.
There are, of course, practical limits to using certain types of vertical circulation. Stairways are limited to serving up to two or three levels before they become too strenuous for many people to use as major circulation, particularly in the upward direction. Also, using stairways as major vertical circulation into and within a station means that mobility-impaired people are required to use other systems. Generally, stairways are used in conjunction with escalators in shallow stations, but seldom as the only means of access in newer transit systems.

Clearly, stairways are not appropriate as major means of bringing people to deep, isolated facilities, but escalators can serve this function. Very long escalators serve subway stations around the world at depths sometimes exceeding 200 feet. Because there is little effort expended by the riders and there is a continuous flow of movement, the transition into and out of an underground facility using escalators can be smooth and graceful.

When escalators must descend to deep isolated facilities such as subway stations, it is often not feasible to place them in a large atrium-like space. Thus, the experience of descending on an escalator in a long narrow tube can evoke some of the worst feelings of claustrophobia and entrapment. In this sense, for some people, seeing the true depth of a subway station through a long narrow tube may be a much more negative experience than descending on an elevator where the spatial relationships are not perceived as well. Similar to entering through a long horizontal tunnel, a long escalator shaft should be designed to enhance spaciousness and provide stimulation through the use of lighting, artwork, sound, and other interior design elements (see Chapter 4). A spacious, well-lighted transition space at the bottom of the escalator will help give a sense of arrival and spatial relief.

Vertical and Inclined Elevators

While escalators and stairways can provide graceful and efficient transitions into underground stations, elevators are likely to be present in all stations to provide handicapped accessibility. In some cases, elevators are utilized as the only means of access to subway stations; however, this is usually in very deep stations with limited passenger loads. A clear asset of elevators is their accessibility to all people. In most existing deep subway stations, there are typically two means of entrance available—long escalators in inclined shafts, and conventional elevators in vertical shafts. While accessibility can be provided with vertical elevators, they are often located away from the main entry sequence and for this reason may be less secure as well as more disorienting and more
difficult to find. An inherent problem with elevators is the manner in which they spatially disconnect the surface entrance level from the lower levels of the station. The experience of entering the confined space of an elevator, descending to a below-grade level, and then getting off on a floor with no spatial connection to the above-grade environment seems to have the potential to exacerbate problems of orientation and has few redeeming characteristics to ease the downward transition into the station.

One design approach to providing vertical circulation in underground facilities is the use of glass-enclosed inclined elevators. These elevators are commonly used to provide accessibility to mobility-impaired people in subway systems with deep stations—Stockholm and Helsinki are notable examples. Glass-enclosed inclined elevators run adjacent to the bank of escalators. The same entry sequence is used for all people and the glass-enclosed elevators relieve the feelings of confinement and disorientation found in conventional vertical elevators.

Figure 2-5: Glass-enclosed inclined elevators are commonly used adjacent to escalators in Scandinavian subway stations. These help in maintaining orientation and improve security as well.
Open Air Structures Over Entrance Stairways and Escalators

Two common entrances to underground stations in urban settings are a simple opening in the sidewalk or plaza or a small sunken courtyard containing a staircase or escalator. While functional and unobtrusive, these entrances can be difficult to recognize, especially from a distance, and thus tend to lack a distinctive image when they are approached. To some degree, signs and logos help direct people to these entrances, but an open air structure over these openings is more recognizable and has a distinct image. An excellent example are the arch-shaped trellis structures over the open air entrances to the Les Halles underground complex in Paris. Any distinctive roof form supported on columns, a space frame, or a tent structure can perform a similar function.

While a primary purpose of these open air structures is to create a recognizable form, they also tend to enhance the experience of making the transition from the exterior surface to the interior subsurface. Rather than an abrupt entry through a door into an entrance building or simply disappearing into a stairwell, an open air structure like a trellis is partially enclosed and serves as the zone that provides a necessary psychological transition between two somewhat disconnected worlds. Another advantage of open air structures over open stairways and escalators is that they may provide shelter from rain, although trellises and space frame structures do not necessarily do so.

Figure 2-6: An open air structure over the entrance stairway to an underground facility.

Figures 2-7 and 2-8: Arch-shaped trellis structures over the entrances to the underground Les Halles complex in Paris create a transition between the exterior and interior environments. They are recognizable from a distance and establish a distinct image for the entire complex.
Enclosed Above-grade Entrance Pavilions

Another common subway entrance design utilizes an above-grade structure or pavilion that encloses the means of vertical circulation into the station below. An above-grade entrance pavilion has some characteristics of a conventional entrance—it can be seen from a distance, and if designed appropriately, it can have a distinct image that communicates something about the transit system. It has the practical advantages of providing enclosure from the weather and may be designed to accommodate mobility-impaired people through the main entry sequence.

By its nature, an entrance pavilion is relatively small and gives little indication of the size or extent of the facility below. This is not desirable in helping people form a mental image of how a facility is organized, and the limited size of the structure may make it more difficult to recognize as one approaches from a distance. The familiar image of an entry form or opening against the background of a larger, visible building mass is missing.

Since the predominant function of an above-grade entrance pavilion is to get people in and down into the main spaces below, making this downward transition in a positive manner is an important aspect of its design. Frequently, the minimal size of the entry pavilion does not permit this transition to occur gradually or within a larger open space such as an interior atrium or exterior sunken courtyard. Any efforts to create open multilevel space extending from the surface entry level to building floors below are desirable, along with the use of natural light and exterior views during the downward movement on stairs or escalators.

Entrance through an Above-grade Building

In many subway systems, station entrances are incorporated into existing or new above-grade buildings. It is more recognizable from a distance and a distinct image can be more easily created because there is a visible mass to work with. Also, it may be possible to integrate other components of the station such as ventilation shafts into the surface structure.

Where a station is placed adjacent to historic buildings of distinct character, this design approach can be extremely unobtrusive as evidenced by some entrances to the Washington, D.C. metro. Entry pavilions in sidewalks or visible building service outcroppings can sometimes be eliminated. Depending on the situation, of course, entering one building to get to another can be confusing. Recognition of the station entrances both outside and inside the building usually
depends on a distinctive system of signs and logos.

When station entrances occur through an above-grade building, opportunities exist not only to create a legible entrance and distinct building image, but also to connect the surface and subsurface environments with multilevel open spaces (see Chapter 3 examples from Toronto and Montreal).

**Pedestrian Access Considerations**

An additional factor in designing entrances for underground stations is providing sufficient space at pedestrian access and queueing points to prevent congestion. Certain areas may become congested for several reasons. First, due to the expense of providing escalator and elevator shafts together with under-road passages and connections to nearby building basements, the number of access points is generally limited to the minimum necessary to serve the main traffic generation points around the station. Also, it is not generally desirable to provide too many access points to improve station security. Some considerations in locating and designing entrances are described below. Other requirements related to pedestrian movement and queueing within the station are presented in Chapter 3.

- Entrances should be located slightly away from major pedestrian congestion points so that access to the station is not impeded. Street intersection corners are generally the most congested pavement areas. If entrances are to be located at the corners (which is good for visibility and wayfinding), pavement widening at the corner may be necessary.

- Street hardware often inhibits pedestrian movement in congested areas. Street corners typically have the greatest concentration of street hardware such as traffic signals, lamp posts, and newspaper vending machines (Fruin, 1971). The location of street hardware including the permitted locations for vending machines should be reviewed and agreed on with the appropriate authority for each station entrance to reduce peak pedestrian congestion.
Design Considerations for Handicapped Accessibility

Access for mobility-impaired people at entrances to underground stations requires special attention. Although this must be addressed for all buildings, underground facilities by nature require vertical circulation at the entrance. Stairways and escalators characteristically make efficient and spacious transitions to lower levels but they are not easily accessible. Creating secondary elevator entrances away from the main approach area may not be a desirable solution, because the front entrance is symbolic and denotes a certain status. Mobility-impaired individuals prefer to use main entrances and they tend to feel dependent, disoriented, and degraded when access is not available (Bain 1989). It is this sense of dignity that Bain has identified as one of the characteristics of a successful entry.

Many reports have been written about the accessibility of transit systems (see among others Am. Pub. Transit Assoc., 1980; Trans. Research Board, 1980; Hunter-Zaworski, 1988; Gelick, 1975; Kangas, 1974; Dougherty, 1975). The focus of the discussion here is to highlight those issues that are particularly important for underground stations and to summarize the more general design recommendations that do not necessarily appear in the prescriptive design requirements for systems. References to the source of the recommendations are provided as appropriate. The recommendations range from major layout issues to minor detailing issues, and the discussion is intended to complement rather than replace the LRT system guidelines already established and the relevant codes of acceptable practice. The types of people with physical challenges considered in this discussion include the visually impaired, hearing impaired, wheelchair users, other physically impaired pedestrians suffering from walking or balance impairments, and the elderly who may suffer to a greater or lesser extent from a combination of diminished faculties. It is important to understand and resolve the conflicts that may occur when improving conditions for people with one set of disabilities can adversely affect another group. One example of such an issue is the provision of curb cuts at street corners which are essential for wheelchair users but impair the ability of the blind to find the edge of the sidewalk.

Issues in design for improved access for the physically impaired include the following:

- Provide elevator access to all public areas of the station. If a single elevator is used, alternate arrangements must be planned for times when
the elevator is out-of-service and physically impaired passengers arrive from another point on the system.

- Avoid doors as much as possible, especially revolving doors.

- Large open spaces are difficult for the visually impaired to understand and cross. The old style side platform station with narrow corridors is the easiest for blind people to understand and use (Uslan, 1990).

- Use identification markings at critical points for the visually impaired, for example, warning strips at platform edges and adjacent to escalators and stairs, roughened hand rail sections and special stair edge details at the top and bottom of stairs. Use internationally accepted detailing as far as possible (Hunter-Zaworski, 1988). Good lighting and the use of high contrast colors without surface glare is important for the visually impaired (Uslan, 1990). Tactile system and station maps, tactile trails, auditory pathways and auditory beacons are being introduced on some systems to aid travel for the blind and visually impaired (Uslan, 1990).

- The large number of hard surfaces impairs auditory feedback to the visually impaired and distorts public address announcements. Rough walking surfaces can cause cane bounce (Hunter-Zaworski, 1988).

- Keep routes for physically impaired users as integrated as possible with the main passenger traffic flow. This makes the transit system more understandable for the handicapped since they do not have to find remote elevator entrances. It also improves the safety of the elevator users and the ease of maintaining station security. This issue is particularly important in deep underground stations because the horizontal offset between a vertical elevator and a long escalator can be significant (Transportation Research Board, 1980).

- Provide “slow lanes” for the physically impaired, i.e., space for slower moving pedestrian traffic (SCAG, 1976). Pedestrian routes serving the elevators should not have to cross the main traffic routes to reach ticket vending machines, etc.

- Use a minimum number of elevation changes within the station. Avoid the use of ramps within the station as far as possible because they cause difficulty for some pedestrians, especially when not clearly visible (SCAG, 1976; Gelick, 1975).
• Use 48-inch-wide escalators and automatic doors at least 36 inches wide for public use (SCAG, 1976).

• Limit the height of elevation changes using only stairs (and handicapped elevator) but without escalator provision. Projecting nosings should not be used on stairs (Fruin, 1971). Extra horizontal travel sections of escalators at boarding and alighting points can be used to ease transition problems for the physically impaired.

• Make warnings regarding danger points for pedestrian traffic both tactile and visual; for example, the colored tactile strips along the platform edge in many transit systems. The visual and tactile warnings should be consistent and conform as far as possible to national and international standards (Uslan, 1990).

• Make station and system announcements both visually and audibly as far as possible (SCAG, 1976). Centrally controlled electronic display boards can be very effective for both train arrival information and special messages (see the emergency egress discussion in Chapter 5). Audible announcements should be consistent and clear even under crowded conditions. Station announcements helpful for the visually impaired should include information on trains stopping or standing at platforms and the direction of trains. Train announcements should include on which side of the train the doors will open (Uslan, 1990).

• The space between LRT cars can be dangerous to the visually impaired because it may resemble a door opening.

• Station furniture should be consistent in layout as far as possible — locations on center and side platforms, number and length of seats, location of waste bin, etc. (Hunter-Zaworski, 1988).

• One source reviewed recommends intermediate emergency access to elevators in a shaft at vertical intervals of no more than 36 feet. For the deep stations in downtown Minneapolis this recommendation would greatly increase the cost of providing vertical elevators in isolated vertical shafts.

• Inclined elevators in the same inclined shaft as the station escalators should be seriously considered for the elevator access system since they solve many security and wayfinding considerations. They are used effectively in transit stations in Sweden and Finland and were evaluated
favorably by a U.S. study in 1978 (DeLeuw Cather, 1978). The principal drawback of the inclined elevator is the additional cost stemming from the longer inclined guideway for the same vertical rise. A second concern is that very few inclined systems are currently operating in the United States.
Chapter 3:
Station Layout and Orientation

This chapter addresses the overall layout and spatial arrangement of an underground transit station. The focus here is not on detailed standards and regulations but on the broader design principles that help to create a more desirable station with respect to the users. The chapter is divided into three sections: First is a brief discussion of station layout considerations with an emphasis on spatial orientation. The second section presents some design concepts used to improve layout and orientation problems. Finally, guidelines for the design of information systems are presented since they are an important aspect of maintaining orientation underground. Some of the material in this chapter is drawn from Design for People in Underground Facilities by John Carmody within Underground Space Design (Sterling and Carmody, forthcoming).

Station Layout Considerations

For most building types, the designer has a wide range of opportunities to enhance underground facilities by creating courtyards, interior atriums, as well as spaces of many sizes and shapes. A transit station, however, is usually quite different from a building containing any other function. Its layout is strongly dictated by the functional requirements of moving people efficiently onto and off of long trains. It is further shaped by significant geological, economic, and surface planning constraints. Thus, the layouts of most transit stations are derived from a few basic patterns. Nevertheless, it is important to recognize that underground facilities in general present special problems that should be considered in developing the overall layout of a station. The key design problems related to layout and spatial configuration are:
Figure 3-1: This drawing of the Les Halles development in Paris illustrates the complex geometry often found in urban underground facilities. This complexity and the inability of people to visualize the overall form and layout contribute to problems with spatial orientation.

1. Because the overall mass and configuration of the building is not visible and the lack of windows reduces reference points to the exterior, there can be a lack of spatial orientation within underground facilities.

2. Without windows to the exterior and because tunnel dimensions are often limited, there can be a sense of confinement.

3. Because there are no windows, there is a loss of stimulation from the natural and manmade environments on the surface.

The first problem, lack of spatial orientation, is the most important in an underground transit station. People must find their way easily and quickly for the system to function effectively, and a sense of orientation contributes to a feeling of safety and comfort. Because relatively little time is spent in a station by most people, offsetting problems such as lack of stimulation or a sense of confinement are less important than they might be in spaces that are occupied for...
long periods of time. Nevertheless, a stimulating and spacious environment is desirable to improve the image of the system.

Designing an environment so that people can maintain spatial orientation and find their way is a basic requirement in all buildings. Disorientation is not only an inconvenience—it is potentially quite stressful. In The Image of the City, Kevin Lynch emphasizes this negative impact on people:

...let the mishap of disorientation occur and the sense of anxiety and even terror that accompanies it reveals to us how closely it is linked to our sense of balance and well-being. The very word lost in our language means much more than geographical uncertainty: it carries a tone of utter disaster (Lynch 1960).

Lynch emphasizes the importance of “legibility” in the design of a city, which he defines as “the ease with which its parts can be recognized and can be organized into a coherent pattern.” He further states:

The need to recognize and pattern our surroundings is so crucial, and has such long roots in the past, that this image has wide practical and emotional importance to the individual. ...a distinctive and legible environment not only offers security but also heightens the potential depth and intensity of human experience (Lynch 1960).

While Lynch is primarily addressing the design of cities in his discussions of legibility and forming mental images, the same concepts can be applied to individual building design. The spaces, corridors, and architectural elements of a building can be analogous to plazas, streets, and landmarks in a city. In his book, Wayfinding in Architecture, Romedi Passini discusses the fact that architectural form and space can help or hinder a building’s legibility. One key is designing an environment with “imageability,” a term that refers to “the ease with which a place can be mentally represented.” These mental images then can be incorporated into an overall cognitive map to maintain orientation (Passini 1984).

Passini suggests that forming a good mental image of a place is facilitated by several factors. One of the most important is that the internal organization principle of the facility must be detectable. This refers to understanding the overall system—for example, that the street pattern of a city is a grid, or that all stores in a shopping center face a single multistory atrium. Arranging an underground layout with a clear, understandable organizing principle is
essential. Many examples exist of convoluted labyrinths of underground passageways in transit stations as well as adjacent commercial areas that are virtually impossible to comprehend, requiring visitors to rely completely on signs to find their way. According to Passini, certain major underground commercial developments in Montreal are avoided by people who fear getting lost.

While the focus of this discussion is on the physical layout and arrangement of space as a means of improving orientation in underground buildings, a system of signs and other interior design elements must complement and reinforce a clear internal organizing principle. Passini has found that people appear to process wayfinding information in two main ways. To some extent, people approach the problem in a linear fashion and seem to rely mainly on signs. In addition, however, they depend on developing a spatial understanding of the setting. To maximize the legibility of an environment for the majority of people, both the organization of architectural space and sign systems must be clear.

The following is a list of design objectives related to improving orientation and enhancing the spatial arrangement in an underground transit station.

Figure 3-2: A typical problem in underground, windowless buildings is orientation. With no reference to the outside environment, people are easily confused in complicated and sometimes monotonous corridors of many urban subway systems and commercial developments.
• Create an interior layout that is easy to understand, thereby enhancing orientation as well as emergency egress.
• Provide visual connections between the interior and exterior environments whenever possible.
• Arrange spaces and building circulation to enhance a feeling of spaciousness through the facility by providing extended interior views as much as possible.
• Provide a clear, attractive system of signs and maps (if necessary) to facilitate orientation.

Design Approaches and Examples

Design concepts related to station layout and spatial arrangement apply to three different scales: (1) the entrance and connecting corridors, (2) the actual station platform and mezzanine spaces, and (3) interconnecting networks of underground facilities that include subway stations as one component.

Entrance and Interconnecting Corridors

Typical corridors in many modern buildings are long, narrow and monotonous. In an underground facility, using typical corridors for circulation reinforces feelings of confinement and an understimulating environment. Due to the lack of visual cues to the outside (an occasional window or a glimpse into a space with a window), underground corridors can also be disorienting. One approach is to design major circulation arteries within underground facilities as thoroughfares—an indoor street larger than a conventional corridor.

In mass transit stations, standards ensure that major entrance corridors are sufficiently wide to handle the volume of people required. It is often corridors leading to secondary entrances that result in feelings of confinement and monotony. In addition to the size of the corridors, the simplicity of their layout is a factor in embracing orientation. Very direct routes with a minimum number of turns is desirable. Corridors that curve or turn at angles other than 90 degrees will tend to disorient people. Likewise, orientation will be improved when the direction of travel and choices are obvious.
Main Station Spaces

In most cases, the basic layout pattern of the main station spaces is dictated by geological and other cost-related considerations. The most common types are two cavern (binocular) stations or single cavern stations that may be one or two levels high. The binocular station has the disadvantage that the spaces are more constrained, and there are interconnecting corridors not in open view.

The single cavern stations have the following advantages: the entire space can be comprehended at once which aids orientation, and the larger volume and longer views enhance a feeling of spaciousness. Also, if a center platform is used, the waiting area is more spacious and flexible.

Naturally, a two-level station provides much greater ceiling height and can offset feelings of confinement underground. On the other hand, two-level caverns usually include a mezzanine over part of the platform and the areas under the mezzanine are often dark with relatively low ceilings. Nevertheless, the long views from mezzanine balconies overlooking the platform below aid significantly in an overall comprehension of the space.

While two-level stations with mezzanines clearly provide opportunities to create larger volumes, there are many interior design and lighting techniques that can create feelings of spaciousness in one-level stations (see Chapter 4). While a two-level design has definite amenities, techniques to improve orientation and create a spacious feeling in one-level stations may be quite important if excavation volumes can be reduced.

In one-level stations, an important strategy to offset feelings of confinement is to increase the ceiling height even slightly more than the minimum required. According to Menchikoff (1975), height dimensions are more often overestimated than horizontal dimensions, which implies that increasing the ceiling height in a room will have an impact on perceived spaciousness that is greater than a similar increase in other room dimensions. The effect of increased ceiling height on improving feelings of spaciousness is reflected in a study by Cochran and Urbanczyk (1982), which found that people needed more personal space when ceiling height was reduced. In a similar study, Savinar (1975) found that increased ceiling height reduced feelings of crowding even though floor space remained constant.

Some specific requirements for pedestrian movement and queueing space within stations are described below:

- Queueing space is required for people waiting to get on an escalator or stairway and adequate landings should be provided. Typical
recommended minimum distances include: stair to wall, 10 feet; stair to stair, 25 feet; escalator to escalator, 40 feet; escalator to stair, 30 feet; escalator to end of platform, 30 feet. Lighting levels should be at least 6 footcandles at stairways and escalators (APTA, 1980).

- The optimum stair slope for comfort has been assessed at approximately 27° (Fruin, 1971). The vertical clearance for stairs should be preferably 8 feet or more. Stair treads should be 11 to 14 inches wide. Stairs wider than 88 inches should have intermediate handrails. A stair landing at least 6 feet deep should be used at intervals of no more than 16 steps (Hoel, 1976).

- Adequate space must be provided on the platform for comfortable conditions during maximum occupancy. APTA (1981) recommends the provision of 8 square feet per person after deducting a strip of 1.5 feet along each platform edge. APTA (1981) also recommends that distances from platform edge to obstructions such as stairs or escalators should be a minimum of 5 to 8 feet.

- Many passengers tend to stay close to their arrival point on the platform when waiting for trains APTA (1981). Frequent system users, however, tend to go to a point on the departure platform that will be most convenient for exit at their destination station. Good distribution of access/egress points to the platform and variation of the access/egress points among stations will tend to even train passenger loading.

- Center platforms should be at least 20 feet wide, side platforms at least 13 feet wide (Hoel, 1976).

Large-Scale Layout of Underground Complexes and Circulation Networks

In most cases, underground buildings are experienced primarily from the interior. With limited connection to the surface, it becomes important that the circulation system within the building is understandable to help people maintain orientation. Beyond being clear, though, the layout of the building should create a distinct image or a sequence of distinct images that further aid in forming mental maps of a facility as well as making the experience of passing through the facility more stimulating. To achieve this, the layout of an underground facility should be viewed like the plan of a city rather than a building. Traveling through the public areas of the building should not be similar to passing through
a series of enclosed monotonous corridors and elevators. Instead, it should be more like a stimulating, memorable city where there is a legible system of paths (or streets) that are lively and distinct in character. Within the city (building), notable, special features establish variety while enhancing image and orientation.

In *The Image of the City*, Kevin Lynch identifies the five elements that improve imageability: paths, landmarks, nodes, districts, and edges (Lynch 1960). Romedi Passini has taken Lynch's analysis for cities and applied it to buildings or complexes of buildings (Passini 1984).

Creating a system of paths, zones, nodes, and landmarks is a particularly appropriate approach for large building complexes as well as interconnected groups of facilities. In addition, an overall system of circulation and spatial organization within an underground facility must be regarded as an extension of similar systems occurring in the above-grade environment.

This concept of organizing an underground environment in a similar way to a city is most easily visualized in underground developments with circulation systems that are, in fact, on the scale of a city, such as Montreal and Toronto.
Although both underground cities have areas that are not very legible to people, there are portions that function quite well as a hierarchical system. In Montreal, for example, several downtown blocks have a named complex, often with a central atrium and a distinct design theme. As one passes through the subsurface corridors (paths) connecting these places, there is a sense of arrival at each complex that is reinforced by the atrium itself and other landmark architectural elements. Subway stations are associated with several of these major complexes and are entered through lower levels of these centers.

Multilevel Atrium Spaces

An interior atrium in an underground building is one of the most powerful and versatile design patterns available. It can provide extended views, visual stimulation, a sense of orientation, sunlight (in some cases), and a focus of activity within the facility.

With respect to orientation and image, the atrium space often is the central landmark within an underground building and establishes the major image of the facility. In his study of wayfinding problems in several underground complexes in Montreal, Romedi Passini found that buildings containing a central open space are generally well understood. “Such an opening ... gives visual access to the different floors of the building and allows one to sense at least part of the building volume. A single perspective of the space contains much information that in a closed floor arrangement has to be organized from a number of separate experiences of individual floors. Visual information is easily accessible, the legibility of the space is enhanced” (Passini 1984). Atriums have two applications to underground station design. Occasionally, an atrium can be used in a station as a large central space containing vertical circulation and even providing natural light. This is more common in shallow cut-and-cover stations, but an open cut atrium is a possible approach for deeper stations as well. Secondly, atriums may be an important part of a larger interconnected network of underground facilities.

Zones of Distinct Character

In his analysis of cities, Lynch (1960) identified “districts” as one of the key elements that enhanced the ability to form mental images and thus improve orientation and wayfinding. A district is defined as “medium to large sections of the city ... which are recognizable as having some identifiable character.” Continuing the analogy between city and underground facility, a district is

Figure 3-5: As people follow this below grade concourse in the underground pedestrian network in Toronto, Canada, they arrive at Eaton Center. Similar to landmarks within an above-grade street system, the multistory atrium and fountain are notable features that enhance orientation in the underground environment. The subway station is entered from this lower level of the atrium.
similar to a zone within a building complex. Large building complexes often contain zones that are distinguished by function—for example, a complex may contain apartments, offices, a hotel, shops, theaters, and a transit station. The inherently different appearance of some of these functions and the type of activity they generate create zones of distinct character in many cases.

Within an underground facility, zones of distinct character will certainly enhance the ability to differentiate areas and contribute to better orientation. The point here is to develop a layout and spatial configuration in conjunction with detailed architectural elements that define and reinforce zones of distinct character. The zones should have meaningful names and clear boundaries with identifiable gateways or entrance transitions.

Signs and Maps

An important aspect of interior design is the system of signs, graphics, and maps that people use to find their way in transit stations. Spatial orientation is a particular problem in underground facilities because many of the normal visual cues provided by windows (i.e., a glimpse of the ground plane, the sky, or surrounding landmarks) are missing. Moreover, the exterior form and extent of the building is often not clear, leading people to feel they are in a labyrinth of convoluted passageways. These problems can be alleviated to some extent by making the layout and organization of an underground station as clear as possible. But even in well-organized, legible facilities, clear signs and maps are necessary to reinforce and assist people.

Romedi Passini (1985), who has analyzed problems in orientation and wayfinding in complex underground facilities in Montreal, states:

"Signs and maps, it appears, are not second class supports for badly designed settings, but information systems which complement information obtained from other environmental sources. Signs in particular are relied upon by a large segment of the population which finds it difficult to mentally represent complex indoor settings. A given sign ... has a good chance to be perceived only if it occurs at a moment when such information is sought."

The key problems with many sign systems are: (1) the information is not accessible, (2) the information is unclear or ambiguous, and (3) the information cannot be distinguished in an overloaded visual environment.
The following guidelines will assist in designing a system of signs to aid orientation and wayfinding (Passini 1984, 1985):

1. The signs pertaining to wayfinding must be visually accessible from relevant circulation routes.
2. The signs must be sufficiently differentiated from the general background.
3. The signs must have consistent design features so they can be easily recognized, particularly in complex settings.
4. The signs must be in consistent and predictable locations, particularly in complex settings.
5. The wayfinding signs must be differentiated from other types of signs such as advertising.
6. The message on signs must be sufficiently large to be read from a distance, particularly from an obvious point where a decision must be made.
7. The information on signs must be visually structured in small packages of three or four components.

Figure 3-6: In Tokyo subway stations large photographs of the buildings just above the exit help people maintain their orientation.
8. Identification and directional signs should be easily distinguished from each other.

9. Sign messages must be unambiguous so they can only be read with one meaning.

10. Well-known terms should be used. (In one Montreal complex, "floors" were referred to as "sections" leading to considerable confusion.)

Maps can provide an overview of the facility and assist people both in finding an appropriate route to their destination as well as giving them an understanding of the overall organizing principle of the building. Just like sign systems, maps must be designed and located to avoid the following problems: (1) inaccessibility, (2) ambiguous, unclear information, or (3) too much information leading to overload. The following guidelines will assist in designing useful maps in an underground setting (Passini 1984, 1985):

1. Maps must be visually accessible from the relevant circulation routes.

2. Maps must be aligned with the surroundings so people do not have to make complicated mental rotations to orient themselves.

3. The information must be packaged according to content. For example, major destination and functional zones (i.e., offices, commercial, parking) should be distinguished.

4. Information must be packaged in small units of not more than three to four names to facilitate reading at a glance.

5. Messages must be unambiguous so they can only be read with one meaning.

6. Maps should not be overly complicated. Information not required for wayfinding should be minimized.

7. Maps should emphasize the key recognizable elements that contribute to forming a strong image of the facility: key circulation paths, activity codes, landmarks, zones, and the overall boundaries of the building.

In addition to using conventional signs and maps, other graphic devices that aid orientation in underground environments can be used. Subway stations in Stockholm, Helsinki, and Osaka have compass patterns set into the floor indicating the cardinal directions. Signs near exits from Tokyo subway stations sometimes include wall-size photographs of the above-grade scene just outside.
that particular exit. Not only do the photographs help passengers visualize where the exit will lead, they also are a visually attractive addition to otherwise very plain interior spaces.

Particularly in an underground setting where spatial orientation is a potentially greater problem, effective systems of signs and maps are important but must be part of an overall design that is easily understood. As Passini (1985) notes:

Wayfinding design does not only concern itself with signs and maps, but includes also the conception of space and the use of architectural elements. We should be thinking of wayfinding from the very beginning of the design conception...

Information System Guidelines for Transit Stations

In addition to the general guidelines discussed previously for signs and maps, some guidelines related to transit station information systems in particular are listed below.
• Color code transit lines. This can be continuous and include the station entrance, internal wayfinding directions to the platform and correct track, to its reinforcement on the train itself.

• Keep essential information for basic use separate from more detailed information.

• Provide information at every decision point along a route.

• Provide frequent checks so that choices are made correctly.

• Make station names on platforms clearly visible whether people are seated or standing and with or without crowds. This implies (1) frequent repetition of the station name on both sides of the track and (2) that on the platform side the station name can be seen above the people waiting on the platform. Design differences among stations also help in station identification as do frequent route maps within the vehicles.

• Use consistent coloring for normal exit signs not used elsewhere in the system.

• Identify routes not leading to exits as such and preferably block them if not for public use.

• Use compass arrows to orient passengers.

• Provide visual references to surface locations where possible (exterior photographs of station entrances are used in some stations in Tokyo to help passengers find the right exit from the station).

• Indicate the direction of train travel on the platforms.

• Keep the same type of information in as consistent a location as possible.

• Use the same names of places and routes consistently and ensure that the system staff use the same terminology as the signage. The signage should be adjusted fully and quickly as system conditions and configurations change. Examination of operating systems indicates that this is not automatic (Proulx and Sime, 1989).

• Avoid pedestrian traffic conflicts which create confusion and limit the time available for wayfinding decisions. Provide a standing area from which the wayfinding information can be studied that is not going to interfere with other passengers under crowded conditions.
Chapter 4:
Interior Design and Station Image

Interior design in its broadest sense can include virtually any aspect of the interior environment of a building. In this study, the focus is on design techniques to enhance underground transit stations to make them more acceptable for people. Therefore, this chapter addresses a selection of interior design elements and systems that are particularly important in this context.

Interior design typically includes predominantly visual elements such as the use of lighting, color and pattern, materials, furnishings, artwork, and other notable elements such as plants and fountains. Graphic information systems, which are often considered part of interior design, are discussed in Chapter 3, where design to improve orientation is presented. Some of the material in this chapter is drawn from Design for People in Underground Facilities by John Carmody within Underground Space Design (Sterling and Carmody, forthcoming).

Interior Design Considerations

In conventional buildings, the general goals of interior design include providing functional, comfortable, and attractive spaces. Because of some of the negative attributes and associations with underground, windowless environments, the designer must not only achieve these general goals, but must consciously attempt to offset particular negative perceptions. The key design problems related to the interior of underground buildings can be summarized as follows:

1. In underground space there are often associations with darkness, coldness, and dampness.
2. Because there are no windows and tunnel dimensions are often constrained, there can be a sense of confinement.

3. Without windows to the exterior, there is a loss of stimulation from and connection to the natural and manmade environments on the surface.

Images of Dark, Cold, Damp Spaces

Caves are generally regarded as dark, cold, damp, and poorly ventilated, and manmade underground structures such as tunnels, mines, and many unoccupied basements have similar qualities. Windowless underground spaces that are to be occupied by people can be mechanically ventilated, heated, cooled, and dehumidified just like most conventional buildings with or without windows. Nevertheless, it is the associations with these qualities that present design concerns for underground space.

Figure 4-1: High-quality materials, fixtures, and furnishings create a positive image of the 70-meter-deep subway stations in St. Petersburg, Russia.
Confinement

The feeling of confinement associated with underground, windowless buildings implies that interiors should be designed to feel “spacious.” Creating spaciousness in interiors will be made easier when the station layout provides large spaces and high ceilings with views from balconies overlooking platform areas below. Enhancing spaciousness, however, has many aspects beyond simply making spaces larger and creating long interior views. The quality of spaciousness can be created with visual illusions involving light, color, pattern, and texture, and it is also influenced by the arrangement and design of furnishings within a space.

Stimulation and Variety

A stimulating and varied interior environment has many components. It involves the visual aspects of the space—shape, size, color, texture, furnishings, and artwork, for example—as well as the acoustic, olfactory, and thermal aspects of the environment. Moreover, an interior is a place of human activity, not a static visual image. This implies that other important aspects of a stimulating environment include the movement and activity of people, and the changes in the environment over a period of time.

Given the lack of stimulation inherent in a windowless space, providing variety in the environment is an important goal, but it is not necessarily desirable to maximize stimulation in all spaces. A reasonable, comfortable amount of variety in the environment must be viewed as a balance point on a spectrum between extreme understimulation and extreme overstimulation. This suggests that the designer should seek a moderate amount of stimulation and variety in the environment, but within a predictable framework. This quest for a moderately varied environment leads many researchers to identify nature as an ideal model. Anita Olds (1985, 1987) writes:

When the environmental stimulation and movement are predictable, yet involve moderate degrees of change and contrast, the nervous system can function optimally and the person experiences a sense of ‘being comfortable.’ Nature is often perceived as a ‘healer’ precisely because of the soothing qualities of ‘difference within sameness’... Natural elements, such as babbling brooks, gentle breezes, and sunlight dancing on leaves, are always undergoing fairly predictable yet fascinating changes. They prevent boredom, as subtle fluctuations in their movement periodically reawaken all the senses.
The obvious implication is to attempt to replicate the essential qualities of patterns from the natural environment in the design of windowless, underground environments. A second related implication is actually to use elements from nature within the interior environment. Natural elements such as plants, water, and rocks embody the quality of desirable visual complexity, and also evoke direct associations with the natural world. Actual natural elements, their use in artwork, or even projected views of natural settings have been shown to have relaxing and restorative effects on people (Ulrich 1983, 1986; Wohlwill 1983).

The concept of providing variety in the interior environment certainly is applicable to transit stations even though people spend relatively little time there. A stimulating environment is likely to contribute to a favorable system image, and can enhance relatively monotonous experiences like descending a long escalator or waiting on a platform.

Issues Related to Station Image

The overall image of a transit system is formed based on a variety of factors such as convenience, speed, and safety as well as the visual design of the stations, trains, and graphic information systems. This report addresses only the design of underground stations in the system; however, they are likely to contribute significantly to the overall system image. The underground stations in downtown Minneapolis, at the University of Minnesota, and at the airport will be among the most frequently used stations in the system. For many people, these stations will be the entrance or gateway to these areas of the city and the station interiors will tend to be predominant visual images for the entire system. Visitors are likely to experience the underground stations as major parts of their experience of the city.

Combined with the design of station entrances, layout, and graphic information systems (addressed in Chapters 2 and 3), the interior design forms the station image. An interior design can be regarded as a set of distinct decisions about colors, materials, lighting, and furnishings. However, these elements are detailed parts of a broader interior design concept that shapes the image of the station, the system, and the city.

Many different design approaches are utilized in the most memorable and attractive subway systems throughout the world. Key questions in overall station design are:
• Should all stations in a system be similar in design or should they be distinctive?
• Should stations incorporate art into their design?
• Should advertising be allowed and if so, how can it be incorporated into the station design?
• Are there themes or elements of local interest that can be incorporated into the designs?

Consistency versus Variety

There are numerous examples of systems where all stations are designed in a consistent, almost identical manner. The arguments in favor of this approach include familiarity by the users, and a very clear consistent image. An example is the Washington, D.C. Metro where interior design elements in each station are virtually identical. Passing through a series of stations viewed from the train, the only distinct element characterizing each station is its name on a sign. While the overall system has a clear image, variety and any reflection of local interest are missing. When individual stations do not have distinct images, orientation and wayfinding may be hindered.

On the opposite end of the spectrum are systems like those found in Montreal or Stockholm where each station is intentionally designed differently. In both cases artwork is used to create distinctive station images, although in Montreal the architectural character as well as the artwork in many stations is unique. Distinctive stations are easier to recognize when passing through on the train, and the overall image of these systems is stimulating and colorful. In all cases however, the graphic information systems and some interior elements such as furnishings or lighting remain consistent. Recognizable logos and colors to identify lines within a system are nearly universal techniques to establish a coherent system image even though individual station designs vary.

Public Art

Several transit systems throughout the world have incorporated special programs to include public art and artistic input into the design of the transit system. Financial set asides, as much as one percent of the construction budget of the system, have been made for this purpose (e.g., Seattle Bus Tunnel). Public art programs have been successful in many locations of the world, and many

Figure 4-2: A positive, stimulating interior environment is created in subway stations in Montreal, Canada. Each station is designed differently, but most utilize colorful artwork and high-quality materials.
underground transit systems serve as public monuments in addition to their transit function. Examples of special civic, artistic, or monumental designs in transit systems include:

Stockholm Metro: The interior design of each station on the newer lines was done by a different artist. The designs ranged from bold painted designs on the rock cavern roof to the use of archaeological artifacts as sculptures on the walls of the station.

Mexico City Metro: The stations are designed as important civic monuments using archaeological excavations along the route to provide a living museum for the artifacts and ruins found.

Moscow/St. Petersburg Metros: Almost all the stations are monumental in design celebrating the location of the station, famous historical figures, and famous events. Ornate or dramatic designs, expensive materials, and a high quality of workmanship are common.

Advertising

Divergent views exist on the desirability of advertising in transit stations and vehicles. On the one hand, advertising can spoil the aesthetic simplicity of transit vehicles and station halls. On the other hand, it can add color, interest and vitality to the environment. Advertising can also provide some additional revenue towards system operation.

Should advertising be permitted, the following issues should be considered in the adoption of advertising regulations.

- Advertising adds to the visual clutter of a station and vehicle interior and, if not controlled, may reduce the ability of a passenger to pick out important directional and safety signage. This has been dealt with in Shinjuku Station, Tokyo, for example, by only allowing directional signage to be placed perpendicular to the direction of passenger movements. Advertising is placed along the walls parallel to passenger movement.

- Unsold advertising space can be used for public service messages and for programs such as "Poetry Underground" on the London Underground (in this program, short excerpts of poetry are displayed for the passengers). Another possibility would be a school art display program which would help schoolchildren and their parents take "ownership" of the system.
Local Relevance of Station Design

Much of the interest in developing monumental transit station designs and including public art stems from a desire to create civic pride in the transit system. It appears from experience around the world that such a feeling of community or civic pride helps attract ridership and can also greatly reduce crime and vandalism within the system. It is also possible to further enhance local pride in the system by involving local communities in the design of some of the ancillary features of their local station and in choosing or creating some of the artwork or items of local relevance to be displayed. This requires a genuine openness on the part of the designers and artists involved in the program but can be very successful in getting the public to see the system as their own and something to be cared for. One example of this kind of successful participation is the new Seattle bus tunnel stations. Within the many art projects and special design elements included in the system development was a project that involved art classes in the local schools creating ceramic tiles of their own design which were then mounted into a mosaic display outside of one of the stations. This is a particularly good example of a low cost means of involving many parts of a community in the system creation, and has been received very well.

As discussed above, there are two schools of thought regarding the extent of individuality of each station design. The uniform design approach perhaps best exemplified by the Washington Metro often includes very little expression of local relevance in each station design. However, this does not have to be the case. It is possible to create a similar identity for station operational design elements without creating stations that look almost identical and can only be differentiated by the station name.

Proposed underground stations in the Minneapolis area include the Art Institute, the Convention Center, the central downtown Minneapolis business and shopping district (7th and Marquette), the Minneapolis Public Library, the University of Minnesota, and the airport. Each of these station locations has a particular identity and history that could be reflected in the station design. For example, the Art Institute station could display sculpture or paintings similar to the Louvre subway station in Paris. Another approach to creating a local character in station design is to provide images that reflect the city as a whole rather than to create a direct connection with the station location. For example, large scale photographs or murals that portray Minneapolis as the City of Lakes could be a theme in several stations.
Design Techniques and Examples

In this section, a series of interior design elements are discussed with respect to underground transit stations. The focus is on elements that offset problems of negative imagery associated with underground facilities.

Color

Color is a powerful element in interior design that can affect the overall attractiveness and acceptability of an environment. It can also be applied in a space to create feelings of warmth and spaciousness—two key issues in underground design.

In an extensive review of color-related research, Rikard Kuller states that the presence of color gives rise to positive evaluations of the environment while the absence of color is generally considered to be negative. While there are many studies of color preferences and mood associations with colors, Kuller states that hue, lightness, and chromatic strength will not affect the pleasantness of the

Figure 4-3: Brown-colored, richly textured bricks add warmth to this corridor in the Montreal subway system. In many cases underground corridors are simply left unfinished with gray concrete walls that feel cold and reinforce images of low-quality basement space.
interior space in any consistent way (Kuller 1981). In effect, it is the presence of color that seems desirable, but any number of color schemes can potentially be successful.

The presence or absence of certain colors in underground space may have a special significance. Some negative reactions to working in underground facilities occur in spaces with unfinished gray concrete walls (Sterling and Carmody 1990). This may be attributed to the association with undesirable basement space, but its cold and colorless character is most likely a factor. The effect of color depends on many factors and it must be viewed in the context of the overall environment, which typically consists of many colors in combination.

One possible use of color in underground environments is to help offset the associations with coldness and dampness. Generally, many colors with longer wavelengths (i.e., red, orange, yellow, brown) are considered to be associated with warmth, while those with shorter wavelengths (i.e., blue and green) are considered to be "cooler." These associations seem to be consistent with research findings. In one set of experiments, occupants of a blue-green room felt that 59°F was cold, whereas the occupants of a red-orange room felt cold only after the temperature fell to 52° to 54°F (Itten 1970). Similar results were found in a Norwegian study where people tended to set the thermostat four degrees higher in a blue room than in a red room (Porter and Mikellides 1976).

Another important use of color in underground environments is to create a feeling of spaciousness. A widely believed rule of thumb states that warm colors (red, for instance) advance toward the viewer, while cool colors (i.e., blue) recede. Thus, the conclusion often drawn is that blue or green surfaces will create a greater feeling of spaciousness than red or orange. The perception of depth related to colors, however, is much more complicated and other factors can make this rule of thumb untrue.

Contrary to the previously mentioned rule of thumb, some researchers have concluded that hue does not have a strong effect on the perception of distance (Wise and Wise 1987; Tiedje 1987). Spaciousness is enhanced by increasing lightness of the enclosing surfaces. High value colors reflect more light, and lighter spaces are generally perceived as larger and more open. In addition, saturated (high chroma) colors appear closer than less saturated, grayer colors. Thus, the perceived depth or distance to a color is relative to the color of the surfaces around it and the properties of the light falling on it. Enhancing spaciousness using lighter colors on enclosing surfaces will be most successful with higher levels of illumination directed on these surfaces.

Because a spacious design approach with color is not necessarily restricted to a particular set of hues, there seems to be no inherent conflict in designing a
space to be both warm and spacious. Even if the designer chooses to use light, cool colors on walls and ceilings to enhance spaciousness, warm-colored furnishings and artwork may be used to offset associations with coldness. It is important to remember that color is only one component of the visual environment and its use is multifaceted. Although color can be used to create effects of warmth and spaciousness, the greatest psychological effect associated with color may simply be that it is stimulating and attractive. Frank and Rudolph Mahnke (1987) warn against using a single color in a space to create a particular effect:

Taking all research collectively, it is safe to conclude and suggest that color variety is psychologically most beneficial...there must be colors in changing degrees of brightness, temperature, and chromatics, and the complement of the dominant color should be present to some extent. Maximum favorable color effects depend on variety and contrast, within reason.

Applied Lines, Patterns, and Textures

Surfaces within a space have many possible attributes including color, texture, and applied line and pattern. All these characteristics can contribute to the creation of a more varied, stimulating space, and they can also enhance the perception of spaciousness. Line, pattern, and texture actually can increase spaciousness in two ways. First, patterns and textures make an environment more complex, with more visual information to explore, and this tends to make a space actually seem larger because it cannot be comprehended at a glance. Second, because lines suggest direction while patterns and texture suggest scale due to the size of the repetitive elements, they can influence the perception of distance and therefore spaciousness.

In a survey of techniques to increase spaciousness, Beverly Tiedje identifies several design strategies (Tiedje 1987). First, the application of line enhances size in the direction of the application. Thus, vertical lines on walls make the ceiling appear higher. This approach is particularly effective because people overestimate vertical dimensions, exaggerating the effect even further. Horizontal lines increase width and decrease height, an effect that seems less desirable than increasing height in underground space. Diagonal lines are particularly space enhancing; they suggest dynamic movement and draw attention to long diagonal views in a space. Diagonal patterns applied to floors are particularly effective in making the space appear larger.

A second technique to enhance spaciousness is to apply patterns to surfaces
in order to make them recede. Generally, a smaller, finer pattern size and spacing appears farther away than larger, bolder elements. Also, less distinct objects or surfaces appear farther away. This presumably occurs because distant objects are not as clear as close ones in an actual three-dimensional view. Thus, a ceiling with large, bold elements will appear lower than one with a finer pattern. Tiedje suggests manipulating the pattern effect by decreasing the pattern spacing on the upper portion of a wall near the ceiling. A similar optical illusion could be created by decreasing the pattern size and spacing along the edges of a tile floor or carpet.

Texture on surfaces has some of the same effects as applied line and pattern. For example, vertical ribs formed in a concrete wall can increase the illusion of height, while the size and spacing of texture in stucco or plaster can make a wall appear nearer or farther away. Texture, however, is three dimensional and in some cases can be used to create a higher level of visual interest than lines and patterns. For example, complex patterns of light and shadow can result from lighting a heavily textured surface. Textures can also connote warmth and stimulate other tactile associations.

Using texture, applied line, and pattern in interior design to enhance spaciousness must be done in moderation. The designer must avoid too much visual pattern and seek a balance between overstimulation and understimulation.

Natural Elements and Materials

Using natural elements and materials in underground facilities is perhaps one of the most obvious, but also one of the most powerful, techniques for creating a positive environment for people. Many of the negative associations with underground windowless spaces are related to the lack of connection with the natural world on the surface. Furthermore, in seeking design approaches to create a stimulating, comfortable artificial environment, nature is often identified as the ideal model.

In many types of underground facilities, the use of plants, water pools, and fountains is a very positive interior design feature. However, these elements are less likely to be applied to central platform and mezzanine areas of transit stations since space is limited and people stay there a relatively short period of time. These elements may be appropriate in underground commercial areas and corridors connected to the transit station.

In addition to plants and water, the use of certain "natural" materials to improve the underground environment is an effective strategy. Wood, more
than any other material, seems to fit this definition since the pattern and texture of wood grain is so distinct, its natural colors are warm, and it was once alive. Rock and soil are also clearly from the natural world. Natural rock walls or rough textured stone applied to an interior are distinctly recognizable as being in a natural state.

Some geological conditions present the opportunity to expose the rock walls and roof that form the enclosure. Exposing rock walls has been a successful design technique for many types of underground facilities. In some cases, the irregular texture of the rock has all the powerful qualities of other natural materials—it is from nature, and it is visually fascinating with its very rough, irregular and sometimes colorful appearance. Unlike any other natural material, however, it is an honest expression of the actual enclosure of the underground facility. Rather than creating a comfortable artificial environment by using “natural” elements from the surface, exposed rock surfaces emphasize the unique (but natural) quality of being underground that cannot easily be replicated anywhere else. Some of the finest examples are found in Norway and other Scandinavian countries where sections of the granite rock walls are exposed, but much of the ceiling and other wall areas are finished in wood. This sets off the sections of rock as if they are sculptures or natural settings to be viewed in place of an exterior view. This effect is enhanced by indirect lighting from above that emphasizes their texture. In some cases rock walls are painted white to reflect light. In other cases, the actual rock is either not attractive or must be covered by a sprayed-on layer of concrete for structural reasons. Although this coating lacks the completely natural color and texture of the rock, the rough hewn shape of the cavern enclosure is often preserved. While exposing the sandstone walls completely is not feasible in the Twin Cities deep stations, it may be possible to expose and highlight small sections of the rock, or to expose the rough texture of the sprayed-on concrete lining in places.

**Sculpture**

The use of sculpture in underground spaces has the potential to enrich the environment in many ways. Usually, sculpture is a focal point, such as an isolated art object in contrast with its surroundings, although it may be seamlessly integrated into the overall environment. The range of objects that falls under the category of sculpture can best be represented by some examples. The most traditional placement of sculptural objects is within wall recesses or in a central location, much as they would be displayed in a museum.

An intriguing and powerful use of sculpture in underground space can be
found in the 800-foot-long pedestrian concourse at O'Hare Airport in Chicago. A multicolored neon sculpture is constantly changing overhead as people pass through the underground corridor on moving conveyors. A mirrored ceiling reflects the neon tubes so that they appear suspended in a much higher space. The visual stimulation of color, form, and movement is further enhanced by the sound of musical tones that seem to correspond with the changes in the sculpture. The resulting effect of this multimedia use of sculpture is quite stimulating but also pleasant and relaxing, not overloading.

A particularly interesting design approach in underground environments is to utilize archeological structures and artifacts that are encountered during construction. In the construction of subways in Mexico City and Rome, such structures were encountered unintentionally but incorporated into the station designs. During excavation of the underground addition to the Louvre in Paris, the original foundation walls around the fortress were revealed and have now been incorporated into an archeological exhibition. Artifacts and sculptures not necessarily found in the actual construction can also be used to create images with archeological associations that seem uniquely suited to an underground setting. In the Kungstradgarden Station in Stockholm, archeological artifacts are used and sculptural figures appear to emerge from the rock walls of the station.

Figure 4-7: In this long underground corridor at O'Hare Airport in Chicago, stimulation is provided by a multicolored neon sculpture overhead. The neon tubes flash on and off in patterns synchronized to music.
Mirrors

The use of mirrors in underground, windowless interiors can have a great effect on the perception of spaciousness. Mirrored walls and sometimes ceilings are a well-known technique for creating the illusion that there is space extending beyond the actual surface of the mirror. Unlike using a painting with an exterior view to create the illusion of depth beyond the wall surface, a mirror is optically correct from any angle and the view changes as one walks around the space. Basically, the form of objects, their color, and the amount of light are not significantly altered by a high-quality flat mirror, resulting in an extremely realistic illusion. In addition to appearing to extend the view, mirrors actually lighten space since they are highly reflective and can make surfaces appear transparent, reducing the massiveness of columns or other architectural elements.

Alcoves and Window-like Recesses

In windowless spaces, it is desirable to provide elements in the interior environment that have some of the qualities of an actual window view. These visual qualities include providing stimulation and a connection to the outside world, as well as enhancing spaciousness. Sometimes referred to as “surrogate windows,” these design techniques can include alcoves or wall recesses containing objects of interest, pictures or photographs, or even projected or transmitted views of the exterior or other scenes.

An alcove or recessed area in a wall is a three-dimensional indentation of the wall surface. It may be nearly the size of the entire wall or it may be a small niche. In some cases a recessed wall area may have a glass window over it similar to a commercial display window. While an alcove seldom if ever creates the illusion that it is an actual window with an exterior view, its depth breaks the plane of the wall and suggests space beyond the surface.

Successfully creating an alcove that enhances the interior environment depends on the contents of the alcove and its lighting. Plants and rocks in an alcove provide a connection with nature and may even give the illusion of looking into a small courtyard. This effect is enhanced by a bright, hidden light source in the ceiling of the alcove. Light that is the color of natural light can appear to be a skylight, and the higher level of light at the perimeter of a room tends to make it appear more spacious. Manmade objects, such as sculpture, artifacts, or even the display of two-dimensional artwork in alcoves or wall recesses, can provide visual stimulation and enhance spaciousness. Some
alcoves or wall recesses may not actually contain anything of visual interest. They may simply exist to break up the wall plane or in some cases to create the illusion of a window.

Paintings and Photographs

Paintings and photographs on the walls of an underground, windowless space can provide color, beauty, and visual stimulation just as they can in any interior environment. The size, depth of field, and content of a painting or photograph can also affect other important issues in underground design such as spaciousness and connection with the outside (and natural) world. Creating a sense of spaciousness is most strongly related to the perspective or depth of field in a painting. A wall-size mural that appears to extend the space of a room can be an effective optical illusion. A notable example of such a painting is found at the end of a concourse in the below-grade Smithsonian Museum offices. On the end wall of a long, narrow space, a one-point perspective clearly draws the eye into the painting and beyond the plane of the flat wall. Presumably a mural-size photograph could create a similar effect.

Figure 4-8: An alcove containing sculpture is the focal point in a St. Petersburg subway station. The landscape painting behind the sculpture in the alcove creates the illusion of an outside window view.
It has been suggested by numerous researchers that images of natural settings (with vegetation and water in particular) have relaxing and restorative effects on people. The possibility of providing images related to the local station area may influence the choice of paintings or photographs as well.

While natural landscapes appear to be preferred and beneficial compared with other visual images, abstract paintings also have the power to influence feelings of spaciousness, provide visual stimulation, and establish connections with the natural world. A remarkable set of examples of paintings in underground settings can be found in Stockholm subway stations where completely abstract as well as naturalistic elements are painted directly on the rock walls and ceilings. Likewise, photographic or painted images of people, animals, or manmade settings with positive associations can enhance the interior environment. Unlike windows, however, all photographs and paintings are static. Opportunities to change artwork over time may also be an effective strategy. Visual images in the interior environment need not be static. Projected slide images or high-definition video images can create a “surrogate window” that is quite dynamic.

Figure 4-9: This wall-size painting at the end of a concourse in the underground Smithsonian office area is designed to create the illusion that the space extends beyond the wall.

Figure 4-10: In Stockholm subway stations artists have painted designs directly onto the exposed rock caverns.
Backlighting of Translucent Skylights and Wall Panels

The illusion of natural light can be enhanced by placing artificial lights with natural characteristics above skylights with translucent panels. If the panels are not flush with the ceiling but project upward, then spaciousness as well as visual interest are enhanced. Since skylights often are translucent but not clear, this illusion can be quite close to a real skylight.

A similar approach can be applied by placing artificial lights behind translucent walls or wall panels. Usually to enhance visual interest, the backlighted wall is composed of glass block or colorful stained glass, making the wall a significant decorative element. One notable example of this technique is found in an underground pedestrian concourse at O'Hare Airport in Chicago.

Figure 4-11: In this train station at O'Hare Airport in Chicago, undulating glass block walls are backlighted in different colors.
Colorful, backlighted panels line the concourse, and their shapes and patterns are intended to emulate the form of a row of trees. Elsewhere in the same airport, undulating glass block walls, also lighted from behind, line the subway station platform.

**Uniform Indirect Lighting on Perimeter Walls and Ceilings**

Indirect lighting that uniformly washes the walls of a space appears to be a consistently effective technique to increase the perception of spaciousness in a room (Flynn et al. 1988; Boyce 1980). In a series of experiments in 1973, Flynn found that rooms with indirect peripheral lighting were always perceived as more spacious than rooms without it. Spaciousness is enhanced by a higher illumination level and by adding some diffuse overhead lighting to the peripheral lighting. In a similar fashion, indirect lighting of the ceiling makes that enclosing surface appear farther away as well. According to Aubree (1978), indirect lighting of walls and ceiling periphery by fluorescent lamps was preferred over other systems. The soft, diffuse character of indirect light seems to provide adequate illumination without the contrast and glare characteristics of visible bulbs.

The effect of making a space appear larger by brightening the peripheral enclosure may seem contradictory. Generally, a brightly lighted object against a more dimly lighted background will appear to advance or become closer than if the lighting were reversed. However, when the entire periphery is uniformly lighted to a bright level, this figure-ground contrast does not exist and the brightness draws attention to the periphery, making the overall enclosure seem larger (Tiedje 1987).

In addition to enhancing spaciousness and having a preferred quality of light, indirect wall and ceiling lighting appears to contribute positively to some more subjective design problems in underground space. For example, by simply raising the overall level of illumination, associations with darkness are offset. In addition, by using full-spectrum light sources, indirectly lighted walls and ceilings can appear to be naturally lighted since the light source is not visible. In some cases, indirectly lighted ceilings create the feeling of being under the sky rather than a ceiling.

One drawback to this approach, as evidenced in the Washington, D.C. Metro, occurs when walls are lighted from below. Unless cleaned frequently, the lights are gradually covered with dirt and grow dimmer over time.
Peripheral Surfaces in Darkness

In apparent contradiction to the previous recommendation to use high, uniform illumination on walls and ceilings to increase spaciousness, some designers and researchers have suggested that spaciousness can also be enhanced if the enclosure or periphery of a space is in darkness and thus its boundaries cannot be clearly perceived (Tiedje 1987; Ankerl 1981). In a museum or church setting, objects in the foreground are placed under bright light while the room periphery remains dark. This creates a feeling of awe and mystery as objects appear to float in a black void (Flynn et al. 1988). Brightly lighted objects in the foreground advance in relation to the dimly lighted background.

Figure 4-13: The brightly lighted floor, signs, and furnishings in this Stockholm subway station appear to float in a void. The dark background of the rock cavern is ambiguous and can appear to be infinite.
A notable set of examples of this design approach are the rock cavern subway stations in Stockholm, Sweden. Suspended light fixtures direct high levels of illumination downward to the floor, while the ceiling and walls of the caverns are dimly lighted. Attention is focused on the floor and furnishings which appear to some extent to float in an undefined dark cavern.

While this approach does seem to create an illusion of infinite space which is desirable in creating a spacious environment underground, it also creates a predominantly dark space. Darkness, particularly in a cave-like setting, is one of the characteristics often associated with negative imagery in underground facilities. Using this approach to create an unusual, mysterious environment may be quite stimulating and thus may be acceptable in a setting where people do not spend long periods of time (i.e., a subway or a museum), but relying on darkness to improve the habitability of windowless settings where people spend long periods of time seems to be a questionable strategy.

Patterns of Light and Shadow

It is important in lighting design to recognize the multifaceted role lighting plays at various scales within a building. With respect to lighting, a building interior will be more stimulating, more legible, and ultimately emulate the desirable characteristics of the natural world if there are variations in the lighting design. This does not imply variation simply for the sake of it, but variation to reinforce the definition of pathways and spaces as well as to create special places and reflect different functions.

In *A Pattern Language*, Alexander et al. (1977) address this issue in a number of ways. “In a building with uniform light level, there are few ‘places’ which function as effective settings for human events. This happens because to a large extent, the places which make effective settings are defined by light.” The authors suggest that people are naturally attracted to light, and thus it can be used to direct movement by increasing light levels at major destination points along a pathway. In effect, the system of paths, activity nodes, and landmarks described in Chapter 3 can be reinforced by light patterns of varying intensities. The key point is that the definition of space using light can only occur if there are corresponding areas of darkness.

Natural Light

In underground stations near the surface, skylights can provide natural light that significantly alleviates many of the negative characteristics associated with
The natural light spectrum enhances visibility while daylight provides a calm constant source of illumination without the flickering characteristics of fluorescent lighting. Moreover, sunlight connotes warmth and a connection to the natural world. Sunlight provides information about time of day and the weather, and there is the subtle but constant stimulation created as light patterns change throughout the day.

The fact that many shallow underground stations are beneath roads precludes the opportunity to place skylights over the central station area itself. However, even small openings in sidewalks can often provide light to the station perimeter. For all types of stations at any depth, natural light can usually be provided near the entrances.

When natural light enters an underground facility through skylights, it can be reflected off surfaces and other devices to maximize its penetration and distribution in the space. In deeper, more isolated spaces, it is possible to use systems that transmit or reflect natural light into the station through shafts, conduits, or cables.
Chapter 5:
Emergency Egress and Life Safety

A major design consideration for underground transit stations is their safety in an emergency requiring rapid station evacuation. The most likely emergency is from fire — in the station itself, in an LRT vehicle in the underground system, or in the running tunnels connecting the stations. Other emergencies may involve terrorism, explosions from accumulated flammable gases, water ingress from ground or surface water, and earthquakes (an extremely low probability in the Twin Cities area). On the other hand, underground stations may provide safety from some types of emergencies such as severe storms and aerial bombardment (for example, the use of the London tube system for civil defense shelters in World War II).

The safety provisions for dealing with most emergencies in an underground system are similar to those for fire safety. They involve three major actions: evacuating users to a point of safety as quickly as possible, easing the access of emergency personnel, and limiting the spread of danger from its initial source. For this reason, the following discussion is restricted principally to the issue of fire safety.

Code Requirements

Codes and specifications relating to fire and life safety are numerous. They include building codes, insurance industry certifications, hazardous material storage and handling requirements, and fire protection codes. General building codes usually do not allow for the special needs of transit systems and also have ambiguous definitions when underground multiple-use facilities are considered (Sterling et al., 1988; Frost, 1985). The State of Minnesota and the Twin Cities...
area use the Uniform Building Code as their base for state and local building requirements. The City of Minneapolis has also developed a life safety code for large mined commercial developments which resolves the principal uncertainties about what is required or permitted in terms of exiting, fire protection systems, and emergency service access in a large underground system. Some of the provisions examined in this code are of interest in the underground LRT station designs.

The National Fire Protection Association (NFPA) recently released NFPA-130 (1990), a model code for the design of life safety systems for fixed guideway transit systems. It is intended that the Twin Cities system will meet the criteria (or their equivalent) included in this code.

NFPA-130 requires sufficient exit lanes to evacuate the station occupant load from a platform in four minutes or less and to a point of safety in six minutes or less. The point of safety need not be outside but must be determined to be a safe refuge by engineering analysis of configuration, distance, and/or separation materials. The peak occupant load on a platform is based on the peak 15-minute period of operation. Exit lanes are 22 inches wide. The assumed travel speed and capacity of some exit lane configurations are shown in Table 5-1. Escalators are assumed stopped for these calculations, and cannot account for more than half the exit lanes at any one level (a 48-inch-wide escalator is assumed to be two exit lanes).

While code requirements should and must be met regarding physical facilities for the stations and the running tunnels, there are still many design, operation, and emergency response issues which must be resolved for the Twin Cities system. These include alternate means of satisfying code provisions, proposal of equivalent safety features if individual circumstances warrant, and the recognition of the experience of other systems in emergency situations which is not yet codified.

The design issues listed in this chapter do not cover all the various code

Table 5-1: Travel speed and capacity assumptions for exit lanes

<table>
<thead>
<tr>
<th></th>
<th>Capacity (persons/minute)</th>
<th>Travel Speed (feet/minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platforms/corridors</td>
<td>50</td>
<td>200 (horiz)</td>
</tr>
<tr>
<td>Stairs/escalators - up</td>
<td>35</td>
<td>50 (vert)</td>
</tr>
<tr>
<td>Stairs/escalators - down</td>
<td>40</td>
<td>60 (vert)</td>
</tr>
</tbody>
</table>
requirements pertaining to life safety. The critical issues for the Twin Cities underground LRT system are stated together with observations from studies of fire safety and actual fire experience in similar environments.

**Life Safety Design Issues for Underground Structures**

**Fire Behavior In Underground Spaces**

*This discussion is taken from several sources including Degenkolb (1981), NFPA (1991), SFPE (1988), Sterling et al. (1988), and others.*

Fires in underground space behave differently than above-grade fires in several important ways. All fires produce heat and smoke and consume oxygen. In a confined underground environment the heat buildup from an unconstrained fire is potentially more rapid than in a free space. Likewise, the smoke has no avenues of escape other than the enclosed spaces, tunnels, and shafts that serve the system. Although the confined environment eventually limits the oxygen supply to a fire, this does not occur until the fire is well established. The oxygen-depleted atmosphere that results is more toxic in combination with the smoke and airborne pollutants from the fire. In addition, when new oxygen suddenly becomes available there is a high danger of explosion (termed “blowback”).

Fires are typically fought by venting smoke and heat away from the source of the fire to allow fire fighters to approach the fire and extinguish it. Excessive heat, toxic emissions, and poor visibility due to smoke all restrict the ability to do this. As a result, the design of fire and life safety systems for underground transit must include provisions to limit fire and smoke buildup, provide access for fire fighters, and allow rapid evacuation of system users (including the mobility-impaired) to a place of safety.

Although egress and alarm systems are important life safety elements for all buildings, they assume particular importance in underground space, for several reasons. First, by being underground people may become more disoriented and uncertain of proper evacuation routes. Also, most people in underground stations are simply passing through briefly and thus are unfamiliar with their surroundings. The complex nature of stations may lead to wayfinding problems even in normal situations, which are then compounded in an emergency.

With these factors in mind, the following recommendations and guidelines are intended as a summary of the two major safety issues for underground space: egress and evacuation, and alarm and communication systems.
Egress and Evacuation

- Emergency exits must be clearly and consistently marked using a reserved color scheme. Doors not leading to exits should also be clearly marked as such. Open passageways not leading to an exit should be closed off at the public area.

- In addition to the designated station exits, operational procedures may direct passengers to board the next available train coming into the station as an alternative to evacuation through the normal fire exits. Large numbers of people can be evacuated quickly with this procedure and it is particularly useful when the fire is in the upper part of the station. It is also important not to allow passengers already on a train to alight from the train in a station under an emergency evacuation. If passengers are not to be picked up from the station in question, trains should not stop at the station.

- Escalators and elevators as well as stairs are needed for evacuation of underground transit stations. The amount of upward travel from a deep underground station (deeper than 50 feet) is sufficient to tire even able-bodied people. There is also a strong tendency for people to use the exit with which they are most familiar — in most cases the escalator.

- Refuge areas can be provided in deep stations. These are fire-protected, supplied with fresh air, and pressurized in case of a fire. They serve as a safe place to wait out a fire emergency or from which to be rescued by the emergency team.

- One or more emergency evacuation drills from an underground station should be held during the early operation of the system to test procedures and find potential improvements in the procedures.

- Although early underground transit systems often did not include any trackside walkway in the running tunnels, this is a normal design feature of modern systems. Despite the presence of these walkways, however, emergency operation guidelines on many systems have been amended to avoid as far as possible stopping a train in a tunnel and evacuating passengers to safety via the walkway. Fire evacuation tests in Czechoslovakia using able-bodied soldiers in a realistic simulated emergency found that many people refused to exit from the trains into the dark unknown tunnel. In addition, a fire in a tunnel is very difficult for fire fighters to access and fight. On balance, it is usually considered safer
to continue the train (if at all possible) to the nearest station and to evacuate passengers and permit fire fighting to occur there.

- The use of overhead electrical power for the trains removes much of the concern about the danger of electrocution in an emergency tunnel evacuation.

- The use of fire-separated running tunnels for each direction of train operation allows passengers to exit into the other tunnel through periodic cross passageways. The other running tunnel then provides a place of refuge if the ventilation system prevents smoke from entering this tunnel.

- The tunnel ventilation system should be capable of moving smoke from a fire in either direction along the tunnel from the seat of the fire. This allows passengers simultaneously to move to the nearest exit point and away from the smoke and heat. When the fire is on a middle car of a train, however, it is not possible to provide optimal ventilation for people on both sides of a fire in a tunnel.

- Distances between emergency exits from tunnels (other than those at stations) vary considerably in underground transit systems worldwide.

- Exit points from deep underground spaces are limited by the cost of multiple shafts or large open excavations which can provide the necessary escape routes. NFPA-130 (1990) provides criteria for emergency evacuation.

- To maximize safety with a limited number of vertical or inclined shafts, horizontal exit passageways can be used as part of the egress system. When these are fire-separated from the remainder of the space, supplied with fresh air, and pressurized during a fire emergency, they are functionally equivalent to a protected exit stairway and are a point of safety during the transfer to a fully exterior location.

Alarm and Communication

- The existence of a central control station with access to remote camera views of the underground system and the signals from alarm systems, coupled with the ability to centrally operate and control many of the emergency response and evacuation functions, is considered essential to a high level of safety in the underground system. It also has many other
valuable functions for operations and security. In studies of the King’s Cross Station fire on the London Underground and subsequent test evacuations carried on the Tyne and Wear Metro System, local staff at the station were ineffective in assisting evacuation from the station, and in fact contributed to increased problems by directing passengers to evacuate the lowest platform levels by escalators that led into the fire area above. In complex underground stations and networks, the staff cannot have a comprehensive picture of the conditions in all parts of the station and often do not have a clear three-dimensional image of the station. Evacuations directed by specific public address announcements made from the central control station were found to be the most effective in clearing the station in the shortest amount of time in test evacuations. The central control station is in the best situation in most cases to make a rapid assessment of the extent and severity of the fire emergency, contact emergency services, and make specific announcements to system users as to evacuation procedures (Sime et al., 1990; Proulx and Sime, 1991).

- Timely and correct information to system users in an emergency is as important as physical exit distances and capacity requirements (Sime, 1988; Sime, 1990).

- Some research on the behavior of people in emergency evacuations has questioned the traditional weighting of emergency procedures towards avoiding panic among the evacuees. Sime (1990) observes that in many of the major fires he has studied, the initial fire was discovered well before any alarm was sounded (as much as 20 minutes in the Beverly Hills Supper Club, Kentucky fire and the Summerland, Isle of Man fire, in which 164 and 50 people died respectively). By the time the general alarm was sounded, the fire was approaching the flashover point when it rapidly grew in size and intensity. Although evidence of panic was present in these fires, he interpreted that this was more due to the late alarm and rapid spread of fire and smoke than a “panic” response to an emergency.

- It is important to stop new passengers from entering stations from the outside during an emergency. At the King’s Cross fire, passengers were still entering the station when smoke was coming up the stairway even though police were standing by the entrances. Alarms alone may not be a sufficient deterrent — visual signs such as “DO NOT ENTER - EMERGENCY CONDITION IN STATION” may be necessary to help dissuade entering passengers.
• The concept of directed messages from a central control station to guide evacuation requires that areas of the station be easily identified by people in that area. Platform numbers or other unique identifiers simplify the task of directing the occupants of a particular platform to board the next train or to leave by a particular exit.

• Visual and audible alarms should both be used. This allows information to be transmitted to hearing-impaired passengers. The dual use of electronic train information display boards for normal operation and emergency use permits clear information or instructions regarding the emergency to be read rather than deciphered from an audio public address system.

• An in-station public address phone should be located adjacent to the station’s fire enunciator panel. In the emergency evacuation test in the Tyne and Wear Metro, the station attendant was so out of breath after running from the fire panel to the public address location that he could not immediately deliver the message.

Fire Fighting Communications

Conventional walkie-talkie systems do not function through soil and rock, so it is necessary to provide an alternate system to enable emergency communication. These alternatives include the following:

• Repeater stations within the underground structures so that extensive line-of-sight coverage is provided.

• Communication stations distributed throughout the system into which phones can be plugged. These can be integrated with fire extinguishers, hose reels, etc., and can automatically indicate which communication point is in use (example - the Moscone Convention Center).

• Leaky feeder cable systems that allow distributed transmission and reception of signals for portable, cordless units. The position of leaky cable systems should be considered fairly early in the interior design of the underground structures so that good coverage can be obtained. Some problems with the operation of leaky cable systems in actual fire environments have been reported (Swedish Fire Research Board, 1988).
Ventilation Fans and Shafts

As mentioned earlier, ventilation fans for stations and running tunnels should be capable of controlling the direction of smoke movement from a fire in a tunnel and exhausting the smoke from a particular section of an underground station. Reversible fans are typically used to supply air to certain areas of the station or tunnels and remove air and smoke from others. Fans should be capable of remote control from the central control station. Since the fans are large pieces of equipment requiring periodic maintenance, special thought should be given for procedures for maintenance, removal, and replacement without affecting normal system operating schedules.

The shafts required for normal air supply and emergency ventilation are usually combined. Using fire-rated divider walls, these shafts can be combined with other functions such as vertical elevators and emergency stairways. Multiple use shafts will usually be cheaper than several individual shafts (unless the shafts are small enough to be directly drilled — less than approximately 6 feet). The exiting and ventilation requirements usually result in the placement of a shaft at each end of the station to handle emergency ventilation of the tunnels and to provide two separate escape routes from the station. Separate "blast" shafts to limit the pressure buildup ahead of approaching trains are not usually required. This is because the tunnel walkways and the space created in the tunnel to accommodate the overhead power feed for an LRT train limit the pressure buildup. Large station volumes also limit the impact of tunnel air pressure on air velocities in the station.

Normal and Emergency Ventilation Discharge

Under both normal and emergency conditions, ventilation air must be delivered and exhausted from the underground station and/or running tunnels. In downtown areas, the potential exhaust locations are few especially if the station is not being constructed on an open site or as part of a new commercial development. The shaft locations under such circumstances usually are restricted to street right-of-ways and usually will require utility relocation even if the tunnel and station are bored without utility disturbance.

Inlets for normal ventilation air should be located away from potential contamination by vehicle exhaust fumes. This is not a concern for emergency ventilation. Ventilation exits may be located in sidewalk areas but normal and emergency air velocities at the exit are restricted to avoid discomfort to pedestrians on the surface. They may also be extended above ground adjacent to
Table 5-2: History of transit system fires

<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Location</th>
<th>Probable Cause</th>
<th>Dead/Injured</th>
<th>Vehicle Damage</th>
<th>Approximate Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12/9/1971</td>
<td>Montreal, Canada</td>
<td>Power short-circuit after collision</td>
<td>Train driver died from burns</td>
<td>24 cars burned out</td>
<td>5 million DM</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12 cars damaged</td>
<td>($5 million US)</td>
</tr>
<tr>
<td>2</td>
<td>10/4/1972</td>
<td>Berlin, Germany</td>
<td>Unknown</td>
<td>None</td>
<td>4 cars damaged out</td>
<td>3.5 million DM</td>
</tr>
<tr>
<td>3</td>
<td>1/23/1974</td>
<td>Montreal, Canada</td>
<td>Power short circuit</td>
<td>None</td>
<td>9 cars burned out</td>
<td>&gt; 3.5 million DM</td>
</tr>
<tr>
<td>4</td>
<td>7/2/1975</td>
<td>Boston, USA</td>
<td>Power short circuit</td>
<td>34 injured</td>
<td>Tram burned out</td>
<td>&gt; 1 million DM</td>
</tr>
<tr>
<td>5</td>
<td>5/25/1976</td>
<td>Lisbon, Portugal</td>
<td>Technical defect</td>
<td>None</td>
<td>4 cars burned out</td>
<td>&gt; 3 million DM</td>
</tr>
<tr>
<td>6</td>
<td>10/15/1976</td>
<td>Toronto, Canada</td>
<td>Case of Arson</td>
<td>None</td>
<td>4 cars burned out</td>
<td>5 million DM</td>
</tr>
<tr>
<td>7</td>
<td>10/24/1978</td>
<td>Cologne, Germany</td>
<td>Cigarette stub on bellow frame of the rear bogie</td>
<td>None</td>
<td>Tram burned out</td>
<td>2 million DM</td>
</tr>
<tr>
<td>8</td>
<td>1/17/1979</td>
<td>San Francisco, USA</td>
<td>Broken, lateral current collector</td>
<td>1 dead, 56 injured (smoke)</td>
<td>5 cars burned out</td>
<td>17 million DM</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12 cars damaged</td>
<td>($7 million US)</td>
</tr>
<tr>
<td>9</td>
<td>9/6/1979</td>
<td>Philadelphia, USA</td>
<td>Power short circuit</td>
<td>148 injured</td>
<td>1 car damaged</td>
<td>Unknown</td>
</tr>
<tr>
<td>10</td>
<td>9/8/1979</td>
<td>New York USA</td>
<td>Unknown</td>
<td>4 injured</td>
<td>2 cars damaged</td>
<td>&gt; 1 million</td>
</tr>
<tr>
<td>11</td>
<td>4/8/1980</td>
<td>Hamburg, Germany</td>
<td>Case of arson affecting seat in first-class compartment</td>
<td>4 injured (smoke)</td>
<td>2 cars burned out</td>
<td>10 million DM</td>
</tr>
<tr>
<td>12</td>
<td>6/10/1981</td>
<td>Moscow, USSR</td>
<td>Power short circuit</td>
<td>Unknown</td>
<td>5 cars damaged</td>
<td>&gt; 1 million DM</td>
</tr>
<tr>
<td>13</td>
<td>9/11/1981</td>
<td>Bonn, Germany</td>
<td>Technical defect</td>
<td>None</td>
<td>Tram burned out</td>
<td>2 million DM</td>
</tr>
<tr>
<td>14</td>
<td>3/16/1982</td>
<td>New York, USA</td>
<td>Electrical defect</td>
<td>86 injured</td>
<td>1 car damaged</td>
<td>0.75 million DM</td>
</tr>
<tr>
<td>15</td>
<td>6/2/1982</td>
<td>New York, USA</td>
<td>Unknown</td>
<td>Several injured</td>
<td>4 cars heavily damaged</td>
<td>&gt; 1 million DM</td>
</tr>
<tr>
<td>16</td>
<td>8/11/1982</td>
<td>London, UK</td>
<td>Power short circuit</td>
<td>15 injured</td>
<td>Some cars damaged</td>
<td>0.8 million DM</td>
</tr>
<tr>
<td>17</td>
<td>9/5/1983</td>
<td>Munich, Germany</td>
<td>Electrical defect</td>
<td>7 injured (smoke)</td>
<td>1 car unit burned out</td>
<td>4 million DM</td>
</tr>
<tr>
<td>18</td>
<td>4/30/1984</td>
<td>Hamburg, Germany</td>
<td>Case of arson affecting seat in first-class</td>
<td>1 injured (smoke)</td>
<td>2 cars burned out</td>
<td>&gt; 5 million DM</td>
</tr>
<tr>
<td>19</td>
<td>8/28/1985</td>
<td>New York, USA</td>
<td>Case of arson</td>
<td>About 15 injured (smoke)</td>
<td>16 cars burned out</td>
<td>&gt; 5 million DM</td>
</tr>
<tr>
<td>20</td>
<td>10/27/1985</td>
<td>Mexico City, Mexico</td>
<td>Power short circuit</td>
<td>21 injured</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>21</td>
<td>5/7/1986</td>
<td>Berlin, Germany</td>
<td>Electrical defect</td>
<td>None</td>
<td>Tram burned out</td>
<td>Unknown</td>
</tr>
<tr>
<td>22</td>
<td>11/18/1987</td>
<td>London, UK</td>
<td>Electrical defect of escalator</td>
<td>30 dead, 100 injured</td>
<td>None</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

or within buildings, which removes the velocity restrictions at the exit. Ventilation exits have also been located within the street pavement (recently in the Seattle bus tunnel, for example). This third possibility allows larger ventilation openings located more directly adjacent to the shaft. It is important, however, to provide protection against rainfall and drainage inflows into the main shaft and to provide a capture point for gasoline or chemical spills into the ventilation grating from the roadway.
Chapter 6: Other Station Design Issues

Security

Transit systems (and underground transit systems in particular) suffered from a poor image in the United States prior to the development of safe, new attractive systems over the past two to three decades (the BART and Washington Metro systems, for example). While a public transit system carrying large numbers of people with as little delay as possible cannot be made perfectly safe, many design features can be incorporated to enhance passenger and operating staff safety. Some features must be incorporated into the structure of the stations to be most effective; other features are related to equipment and/or operational procedures.

Most violence to transit passengers occurs during times of low system usage when stations and trains are minimally occupied. However, some types of crimes may increase during periods of heavy usage, such as pickpocketing. In general, passenger safety is increased by design techniques that keep as many people as possible in comfortable proximity and in full view of each other while using the system.

Station Design and Layout

Listed below are recommendations relating to system security that affect the overall design and layout of the station structure.

- Design the station to have a compact, open layout in the public areas with as few columns as possible (SCAG, 1976).
• Maintain clear sight lines for CCTV monitoring (SCAG, 1976).

• Proportion the circulation and waiting areas of the station to provide adequate space for the peak passenger loads without severe overcrowding.

• Reduce the non-paid area of the station to a minimum to discourage non-passengers from loitering in the station (SCAG, 1976). The paid and non-paid areas of the station must be clearly distinguished, especially in a barrier-free system.

• Design stations so that parts may be closed during low use periods of operation (SCAG, 1976). These parts may include secondary entrances and the end portions of platforms. Closing these areas increases the passenger density in the open areas and limits the surveillance area for cameras and station staff.

• Keep passenger circulation routes into and through the station as well coordinated as possible. In particular, vertical elevator access is often remote from the normal circulation patterns both in terms of surface access and location within the station. As a low usage circulation system, remote elevators may be vulnerable to security and vandalism problems.

• Where warranted, use neighborhood crime statistics and local observation to locate entrances away from existing high crime locations and spots where troublesome loitering frequently occurs. It has been noted that station security problems can be related to the specific placement of station entrances near loitering or high crime locations (SCAG, 1976). Even a shift of a relatively short distance for an entrance (such as one block) can affect transit crime statistics significantly.

• Eliminate sharp comers in passageways and areas where people could lurk unobserved to avoid surprise attacks.

Station Equipment and Operation

In addition to station layout issues, there are also a number of issues relating to station equipment and operation. These are discussed below.

• A central control system is necessary in a transit system for many reasons. It is of great value in the provision of security within the system because it
is able to collect operating and visual data from any part of the system at any time and has immediate contact with the city police and emergency services.

- CCTV monitoring visible to the public and viewable by both station staff and the central control station should be used. Additional dummy CCTVs may also be used to act as a further deterrent at a lower incremental cost (SCAG, 1976).

- Fare machines and other vending machines should be kept in view of the guard station if one exists. Otherwise, such machines should be in as visible an area as possible to discourage robbery attempts. Money collection procedures should be evaluated to minimize the security risk (SCAG, 1976).

- The interior of elevators should be as visible as possible prior to entry and during operation.

- Elevators can be locked at night if operation can be initiated remotely following request and verification (Hunter-Zaworski, 1988)

- Statistics on security incidents within the system should be collected with information on the specific location of the incident as well as time of day and other pertinent information. These data can be reviewed to highlight areas that need special security attention or design modifications.

- It is important to establish an image of good safety and security early in system operation to discourage future incidents and to encourage usage even during hours of low patronage, which in turn further discourages problems.

Vandalism

Protection against vandalism is strongly related to the security measures discussed above, all of which can be applied to limit vandalism. The additional concerns for vandalism protection are to avoid damage to station and vehicle equipment and finishes. Such damage is costly to repair and has a further impact on the user's perception of safety and comfort.
• Vandalism-resistant finishes should be specified in vulnerable areas. Vandalism-resistant equipment should be specified whenever available — for example, using two-way speaker grilles instead of standard telephones for emergency purposes (SCAG, 1976).

• Vandalism damage should be repaired as quickly as possible to discourage other vandalism (SCAG, 1976).

• Repeated vandalism in particular locations should be investigated to assess whether access or operational changes could be made to discourage the vandalism. In order to do this, it will be necessary to record the date, location, and nature of vandalism attempts.

Station Environment

The major decisions relating to transit system interior environment are whether to condition the transit vehicle, the station interior, or both, and whether the spaces chosen will be heated, air-conditioned, or both. Transit systems in moderate climates may not need full conditioning since ventilation can provide reasonable comfort throughout the year.

Transit systems consume a large amount of energy for train propulsion and release much of this energy as heat when trains brake for station stops. Ventilation can be used to remove this heat from the station and the running tunnels if the temperature and amounts of ventilation air are suitable. Problems occur if the exterior air is too hot to be used to cool the tunnels and stations or if the exterior air is so cold that icy drafts are created in the station area.

Minnesota has a climate in which heating and air-conditioning for both the transit vehicles and the stations is indicated. It may be possible to use natural and train-induced ventilation for removal of some of the heat from the train operation but there will be times of the year when both heating or air-conditioning will be mandatory if reasonable comfort is to be provided.

To separate the station environment from the tunnel environment, it is possible to install a partition and set of sliding doors along the platform edges. The trains are then stopped opposite these locations and both sets of sliding doors must be opened before train boarding can occur. The use of this second set of doors has several other impacts on station design, but control of the station environment usually is the primary motivation. The other impacts are as follows:
• A second set of sliding doors is usually considered a precondition for a fully automatic, driverless train operation system (e.g., Atlanta and Seattle airports). If future automatic operation is contemplated, such a feature should be considered.

• The partition wall is most easily installed in a single-level platform area, i.e., a station without a two-story mezzanine layout in the immediate platform space.

• Safety of passengers waiting for the train is enhanced and it is not possible for blind passengers to fall inadvertently onto the tracks (a major concern for blind passengers using a rail transit system). It is also not possible for suicide attempts to be made by jumping in front of trains as they enter the station.

• The interior volume of the passenger waiting area is reduced by the partition walls. This is beneficial for reducing the cost of heating, cooling, and providing air changes within the station but will reduce the feeling of spaciousness in the station.

• The partition walls isolate the station from the effects of train-induced air velocities.

• The extra set of sliding doors doubles the mechanical operations involved in loading and unloading passengers. They also tend to preclude passenger-initiated door operations, which are valuable in reducing vehicle air-conditioning costs and door maintenance (especially for low passenger usage conditions).

• It appears as if the second set of doors would help reduce train delays due to passengers interfering with the closing of train doors. It also appears that the station doors would take some of the abuse normally taken by train doors and would be able to be repaired more easily. Neither of these hypotheses has been confirmed by contacting system operators for the appropriate data.

• The partitions reduce the impact of train noise on the station environment. This improves the acoustic environment for clear public address messages.

Assuming no platform-edge partitions are used, the station environment is controlled to limit train-induced air velocity, to maintain a comfortable
temperature and humidity environment, and to control noise levels and acoustics due to the large number of hard surfaces usually present.

**Operating Costs**

The total operating costs of the system are dependent on a wide range of factors outside the scope of this study. Only a few of the operating costs that are most related to underground tunnel and station design are mentioned here.

- The smaller the station volumes, the less energy will have to be consumed for heating and air-conditioning. Usage of under-platform exhaust (from heat produced by vehicle braking) and platform edge partitions can further reduce these energy requirements.

- Some systems use a roller coaster tunnel alignment with stations at the high points. This allows gravity to assist in braking and accelerating. However, the potential impact of this is reduced because much of the acceleration and braking occurs within the station length, which is essentially flat. For tunnelling in the saturated St. Peter Sandstone, it is not considered advantageous to make the tunnels deeper between the stations to accommodate this arrangement.

- The widely varying climate of the Twin Cities area and the heat capacity of the rock surrounding the running tunnels may provide some possibilities for diurnal or annual thermal storage to reduce overall energy consumption and/or to reduce peak usage.

- Purchasing district heating and cooling from a local source can eliminate the need for expensive underground space in the ancillary areas of the downtown, University, or airport stations. The purchased conditioning capability may also be cheaper than site-produced conditioning.
Part B: Development and Analysis of Conceptual Designs

In Part B of this report, the conceptual alternatives for station design that meet operational and geological constraints are explored. Part B is divided into the following chapters:

Chapter 7: LRT System Characteristics
Chapter 8: Downtown Minneapolis Stations
Chapter 9: University of Minnesota East Bank Station
Chapter 10: Airport Station

The intent of this work is to lay out the principal station design alternatives in the major geologic conditions present in the Twin Cities area. This has been done for the airport settings, where very little system design development had been completed. However, for the downtown Minneapolis location, the Hennepin County consultant team had reached a more advanced stage of development of system design, which made a comparison of design concepts desirable. This led to a more detailed look at the IDS station to resolve whether some station layouts were precluded by local foundation conditions. At the University of Minnesota, the only feasible alternative for an underground LRT station is in a cut-and-cover configuration beneath Washington Avenue. In this case, the problem was not evaluating geologic constraints but exploring the surface development constraints of this difficult site. As with the airport, very little design development has been done to visualize feasible underground alternatives at the University.

The LRT alignment in downtown St. Paul as recommended by the consultant
(BRW, Sept. 20, 1990) will be a surface option located along Cedar and Fourth Street. Because of this recommendation and because of confirmation from Ramsey County that a surface alignment would be chosen in the downtown area, an analysis of an underground station in the geology of the downtown St. Paul area (including the State Capitol area) was not included in this study. The thickness of the limestone and its proximity to the surface, however, make the geology of the downtown location similar to the airport site. One major difference, aside from the existing surface land utilization, is that St. Paul has many utility tunnels in the St. Peter Sandstone located beneath the street right-of-way.

As site and system constraints are further explored, some of the conceptual designs presented may prove infeasible in specific locations. It has often been observed that the potential for major impact on system cost is principally in the early stages of design when alternative concepts are formulated. This is particularly true in underground construction and also for complex systems such as transit, which must balance community, system, and political constraints.
Chapter 7:
LRT System Characteristics

In developing the current level of planning and design for the LRT system, many system-wide design decisions already have been made. The following discussion is taken from the LRT Transit Coordination Plan (RTB, 1990). Only those aspects of the design guidelines that are pertinent to the issues discussed in this report are included here.

The proposed LRT system is conceptually a high speed, high capacity, moderate cost, commuter service radiating out from the two metro centers. The system will utilize high-platform level boarding, exclusive (but not necessarily grade-separated) rights-of-way, and stations spaced approximately one mile apart. The system will be fully accessible to mobility-impaired people. Vehicles will be operated singly or in trains of up to three vehicles, dependent on ridership demand. LRT will serve as the backbone of the regional transit system, supported by a bus system which will be reconfigured to feed the LRT lines.

The LRT system will be designed as far as possible around proven "off-the-shelf" technology. Grade separations and tunnels will be provided only where it can be shown that they are needed to address topographic or operational concerns.

A preliminary study of the assumed ultimate patronage of the stations on the underground portion of the system through downtown Minneapolis resulted in the assumed passenger volumes shown in Table 7-1 for morning rush period at the two busiest stations — the 7th Street Station and the Convention Center Station (Kennedy, 1990).

The minimum design headway for the tunnel is 2 minutes and the maximum train interval is 30 minutes during off-peak hours. Station dwell times are estimated at 20 seconds. The system is planned to be operational between 5:00 a.m. and 1:00 a.m. Each vehicle will have 76 seats and adequate floor space for
Table 7-1: Assumed passenger volumes at two busiest downtown Minneapolis stations

<table>
<thead>
<tr>
<th>Activity</th>
<th>Average Flow (people/hr)</th>
<th>15-Minute Peak Flow (people/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entering</td>
<td>360</td>
<td>468</td>
</tr>
<tr>
<td>Exiting</td>
<td>6840</td>
<td>8892</td>
</tr>
<tr>
<td>Crossing over</td>
<td>360</td>
<td>468</td>
</tr>
</tbody>
</table>

90 standees based upon 2.6 to 2.7 square feet per standee. Thus the total design capacity for each car is 166 passengers and for the maximum three-car train is 498 passengers.

Stations

The overall design goals for LRT stations in the Twin Cities will be as follows:

- Meet safety and functional requirements without compromise.
- Provide facilities that are accessible to the elderly and the disabled.
- Provide movement patterns for patrons that are easy to understand.
- Establish the system's image through simple, logical, and strong designs.
- Accommodate maintenance and replacement issues.
- Be cost-effective.

Most stations on the system will be at-grade stations with center or side platforms. Stations that are not at-grade will be two-level stations with access to the track level from a mezzanine level. All stations in the system will be similar functionally. Each station will be made compatible with its surrounding environment through variations in design details and finishing materials.

Platforms

All stations will be high platform stations (39 inches above the top of rail) to accommodate level boarding. Platforms will be 300 feet long to accommodate three-vehicle trains. The absolute minimum platform width will be 10 feet for a side platform and 20 feet for a center platform. The preferred minimum will be 12 feet for a side platform and 24 feet for a center platform.
Platforms will be designed to provide shelters for weather protection in above grade settings, limited bench seating, wheelchair and standee space, tactile warning strips along the perimeter edge of the platform, and minimum design clearances.

Vertical Circulation

A minimum of one ramp will be provided at all at-grade stations to provide access from the ground level to the raised platform. These ramps will be covered for weather protection. Escalators will be provided in both directions when the vertical rise exceeds 12 feet. Elevators will be provided where ramps are impractical and at all stations with escalators. Elevators will be sized to accommodate a wheelchair.

Fare Collection

The system is being designed as a no-barrier fare system with roving inspectors to check whether passengers have the correct, validated tickets in their possession. A minimum of two self-service ticket and validation machines will be provided at all stations. The total number of machines at each station will depend on predicted patronage.

Communications

Public address systems will be provided at all stations. Closed-circuit television monitoring will be provided at all subway and open two-level stations and at selected at-grade stations. Public telephones will be provided at all stations. Emergency phones will be provided at all subway stations.

Restrooms

Public restrooms will not be provided at stations. Operator layover rooms and restrooms will be provided at selected station locations.

Lighting

Lighting in station areas and park-and-ride lots will be designed to reinforce patron circulation and security while minimizing impact on nearby neighborhoods.

Heating and ventilation will be provided as required in subway stations.
Heating will be provided within the shelter areas on the platform at at-grade and open two-level stations.

**Acoustics**

Stations will be designed to keep noise levels at the stations below guidelines established by the American Public Transit Association (APTA). Stations will be designed to buffer surrounding neighborhoods from rail, bus, and auto noise.

**Materials, Finishes, and Landscaping**

Finishing and landscaping materials will be selected to provide an attractive but safe, durable, easily maintained environment. Modular furniture will be utilized. A landscape buffer will be constructed between LRT stations and sensitive visual receptors.

**Signs, Graphics, and Artwork**

A uniform system of graphic design and signage will be utilized throughout the system to create a regional system identification and to contribute to a system that is easy to understand and use. Signs will be simply designed and easy to read. The extent and appropriate locations for artwork will be determined for each station in conjunction with the local community.

**Advertising and Concessions**

Advertising will be allowed at LRT stations but will be carefully controlled to maintain a pleasant environment for patrons, to prevent interference with passenger circulation, and to limit impacts to neighborhoods. Concessions will not be provided at stations either by shops or vending machines.

**Safety and Security**

Fire/life safety criteria will be based upon national standards. A local fire/life safety committee, consisting of representatives of all emergency services of state, county and affected cities, will be formed to comment on and approve proposed safety standards. Station attendants will not be provided. Subway and two-level stations will have the capability to be secured during non-operating periods. Subway, two-level stations, and selected at-grade stations will be monitored by central security personnel via closed-circuit television.
Accessibility for Seniors and the Disabled

Design criteria will be developed to achieve the highest quality, safest, and most accessible system possible. The Regional Transit Board and the county regional railroad authorities will work with the disabled and elderly community to achieve this objective.

Stations will be provided with ticket vending, emergency, and communication equipment that will be accessible to the disabled community. Identification of essential facilities will be by raised letters or numbers. Vending and validation equipment will be designed to facilitate “touch” operation. Warning signals will be both visual and audible. Lettering for all warning and emergency facilities will be a minimum of 4 inches high.

Walkways will be at least 48 inches wide with gradients not greater than 5 percent. Walks will have a continuous surface. When walks cross other walks or driveways, they will blend to a common grade. Additional accessibility features relevant to the design of the underground stations are described elsewhere in this chapter.

Vehicles

- The proposed vehicles are single articulated, six axled, 90 feet long, 12 feet 9 inches high, and 8 feet 9 inches wide, dual directional, and capable of being coupled up to a maximum of three vehicles. They will have eight doors, four on each side; will be accessible; and will be designed for high platform loading. Seating for a minimum of 76 passengers will be provided in each vehicle. Doors will be sliding doors equipped for either passenger or operator activation. Vehicles will have heating and air conditioning. Electrical power (750 volts DC) will be supplied to the vehicles through an overhead catenary system.

- Boarding from high platforms will be provided by ramps for at-grade stations and by elevators for subway or two-level stations. All vehicle doorways will be equally accessible. The vehicle/platform gap will be 2.5 +/- 0.5 inches horizontally and 1.0 +/- 0.25 inches vertically. Door openings will be 48 inches. Aisle width will be a minimum of 24 inches.

- Passenger activation buttons on doors will be located and marked for easy access by the physically and visually handicapped. Those passengers
unable to activate the door button will be required to use the lead vehicle to ensure that the operator can see the passenger.

- Two manually operated wheelchair tiedown devices will be provided at each door vestibule (eight per car). A voice intercom system will be easily accessible at each wheelchair tiedown location to provide direct communication to the train operator. Passengers needing assistance will be required to enter the lead vehicle directly behind the operator.

- Seating capacity will be maximized in light rail vehicles and continuous handhold capabilities will be provided.

- Vehicles will be equipped with an on-board public address system to allow the train operator to make both internal and external announcements. In addition, each vehicle will be equipped with route/destination signs above the front windshield and along the side.
Chapter 8:
Downtown Minneapolis Stations

The current plan for the central corridor of the LRT system in Minneapolis includes a tunnel extending from 29th Street and Nicollet Avenue northward to a location near the Mississippi River (see Figure 8-1). Along this tunnel five underground stations have been proposed: Art Institute, Convention Center, IDS (7th Street and Marquette), Public Library, and Warehouse District.

Currently, the Art Institute Station has been proposed at a level above the limestone in the soil. A deeper station is also feasible here although cavern spans may be limited due to weak rock, thus requiring a two-cavern design.

The library and warehouse district stations occur in weaker rock conditions or must be at a level closer to grade and thus may resemble deep cut-and-cover as opposed to mined stations. The two remaining stations, the IDS and Convention Center sites, are deep mined stations. They are located beneath the limestone in the sandstone layer at a depth of approximately 80 to 100 feet. Because of this unique geologic setting, and the importance of these two central stations to the overall system, the focus of this analysis is on deep mined stations appropriate for these sites. Many of the design schemes and principles can be adapted to the other sites as well.

Alternative Station Configurations

A three-stage process was used to identify and evaluate station design options for the IDS site. First, a wide range of possible configurations were identified. These are shown in a series of three-dimensional drawings in Figures 8-2 through 8-13. The preliminary design by the consulting team was a two-level single cavern similar to Figure 8-2. In the second stage, a few schemes were...
Figure 8-2: Two-level station under Marquette Avenue at the IDS site. One escalator bank extends toward Nicollet on 7th Street. A ventilation shaft is shown at each end of the station, and a single elevator shaft is shown alongside the escalator at one end.

Figure 8-3: Two-level station under Marquette Avenue at the IDS site. One escalator bank extends toward Nicollet on 7th Street. A second bank can be added which extends on 8th Street. A ventilation shaft is shown at each end of the station, and a single elevator shaft is shown alongside the escalator at one end.

Figure 8-4: Two-bay, one-level station under Marquette Avenue at the IDS site. One escalator bank extends to the north beneath Marquette. The escalators enter the station in the central space connecting the two platforms. Smaller ventilation shafts are located at each end of the station.

Figure 8-5: One-level station under Marquette Avenue at the IDS site. Escalators and elevators are located in a large open cut atrium that extends over the entire length of the station platform. This large atrium contains all ventilation and other shafts.

Figure 8-6: One-level station under Marquette Avenue at the IDS site. Escalators and elevators are located in a 120-foot-long open cut atrium over the center of the station. A ventilation shaft is shown at each end of the station.

Figure 8-7: One-level station under Marquette Avenue at the IDS site. Switchback escalators, an elevator, and major ventilation ducts are located in an open cut atrium at one end of the station. This minimizes the size of the cut through the limestone. A ventilation shaft is shown at the other end of the station.
Figure 8-8: One-level station under Marquette Avenue at the IDS site. One escalator bank extends toward Nicollet on 7th Street. A large square shaft at one end of the station contains an elevator, ventilation ducts, and a landing at the base of the escalators. A smaller ventilation shaft is located at the other end of the station.

Figure 8-9: One-level station under Marquette Avenue at the IDS site. One escalator bank extends toward Nicollet on 7th Street. A large cylindrical shaft at one end of the station contains an elevator, ventilation ducts, and a landing at the base of the escalators. A smaller ventilation shaft is located at the other end of the station.

Figure 8-10: One-level station under Marquette Avenue at the IDS site. One escalator bank extends toward Nicollet on 7th Street. A large cylindrical shaft in the center of the station contains an elevator, and a landing at the base of the escalators. A smaller ventilation shaft is located at each end of the station.

Figure 8-11: One-level station under Marquette Avenue at the IDS site. One escalator bank extends beneath 7th Street. A second bank can be added as shown which extends beneath 8th Street. A large shaft at each end of the station contains an elevator, ventilation ducts, and a landing at the base of the escalators.

Figure 8-12: One-level station under Marquette Avenue at the IDS site. One escalator bank extends to the north beneath Marquette. A large shaft at one end of the station contains an elevator, ventilation ducts, and a landing at the base of the escalators. A smaller ventilation shaft is located at the other end of the station.

Figure 8-13: One-level station under Marquette Avenue at the IDS site. One escalator bank extends to the north beneath Marquette. A second bank can be added as shown which extends to the south beneath Marquette. A large shaft at each end of the station contains an elevator, ventilation ducts, and a landing at the base of the escalators.
selected for further development to determine whether they were feasible alternatives to the two-level design. These are shown in five sets of drawings illustrating these concepts:

A. A one-level station with two bays (a binocular scheme).
B. A one-level station with a large open cut at one end containing switch-back escalators.
C. A one-level station with a large square shaft at one end.
D. A one-level station with a large circular shaft at one end.
E. A variation on scheme D where the large circular shaft is placed in the center of the station.

Two-Bay Station (Binocular)

As the initial layouts were reviewed, some of the alternatives were found to have drawbacks for the downtown Minneapolis alignment. The short spans provided by the two-bay station (Scheme A) are not necessary because poor rock conditions do not exist. Moreover, because of the width of a binocular station, easements would have to be acquired from adjacent property owners. Based on a preliminary estimate of raw structural costs, the two-span layout cost slightly more than the single-span cavern.

Open Cut Station

The large open-cut station design consolidates a number of separate shafts into one large atrium-like opening (Scheme B). This approach is considered most suitable if the open cut can be located beneath a pedestrian plaza to allow natural light to penetrate to the station below. Unfortunately, in the central downtown area the station must be beneath the street right-of-way. The large open-cut design is arranged so that a switchback escalator system placed in the atrium collects and delivers passengers to/from the street directly above the station. In the Marquette Avenue alignment in downtown Minneapolis this may not be desirable, since the preferred collection/delivery point is closer to the pedestrian mall (Nicollet Avenue) parallel to and one block away from the transit alignment. Because of this, designs with an inclined escalator cut perpendicular to the station alignment are preferred. Despite the large excavation volumes, the raw structural costs for a large center open-cut design are only slightly more than
for the other single-level cavern designs (in part because no separate escalator cut is used).

Large Shaft Station

The remaining three schemes (C, D, and E) are all variations on the same basic concept — the station is one-level with most services and vertical circulation consolidated into a single shaft. This approach is considered most promising as an alternative to the standard two-level design.

The one-story design attempts to minimize the size of the station cavern in the sandstone, which means that excavation quantities as well as the amount of concrete used for structural support are substantially reduced, especially for those stations where the sandstone is fully saturated. Other advantages are that the depth of the single-story caverns is approximately 22 feet below the limestone compared with 42 feet for the two-story cavern; the depth of the escalator cut is reduced one level; and escalator travel times are reduced. Further, to distribute passengers to the center platform requires a landing within the shaft at the level of the limestone. By utilizing a moderately large shaft at this location, this landing can be provided together with vent shafts, emergency stairs, and ancillary spaces. Placing some of the ancillary spaces within the large shaft and part of the escalator cut also reduces the required extra length of the station cavern (beyond that required for train loading). In order to minimize the amount of concrete used to resist water pressure, a curved shell structure is used for the station cavern as shown for Schemes C, D, and E.

During development and review of the conceptual designs and associated cost estimates by the review panel for the project, it was noted that the deep basements in downtown Minneapolis may preclude the large shaft concept. The one-level design with a square shaft was modified by adjusting the station alignment and shaft cross section to avoid any interference with existing basements. In addition another variation of the large shaft concept utilizing a 75-foot-diameter circular shaft was developed (Scheme D). The escalator cut was aligned to take advantage of the deep basement wall of the adjacent building in the soil. The circular shaft has some structural advantages and the shape is suited to avoiding interference with existing deep basements. A final variation (Scheme E) was developed to illustrate that the large circular shaft could be placed over the middle of the station making it more adaptable to the constraints of the Convention Center site.
Two-Level Station

The two-story station cavern design is similar to that used on several U.S. metro systems and the new Seattle bus tunnel. It creates large, impressive interior volumes and has clear open spaces, except under the mezzanine floor areas. Since the long escalators can be routed to this mezzanine level via a one-story inclined tunnel, no large excavations are needed in the Platteville Limestone. Roof spans are similar to the single-level one-span station but the volume of the station is much greater. When circulation areas are provided under the street level, this type of station actually has two mezzanine-type levels (one under the street and one within the station).

During development of this scheme the consultants reduced the cost estimates by utilizing a curved shell structure. The revised two-level design used in the cost analysis reflected the consultant's plans at that stage of the project (see Scheme F).

Cost Comparison of One- and Two-Level Design

Tables 8-1 and 8-2 indicate the approximate raw structural costs for Scheme D (one level with large circular shaft) and Scheme F (two level). Both shell structures for the station cavern have a minimum thickness of 18 inches—the one-story cavern has a lower water pressure but a larger radius than the two-story design. The costs include preliminary estimates for soil, limestone, and sandstone excavation, backfilling, temporary retaining walls, rockbolting, shotcreting, waterproofing, and final structure. Utility relocation costs, street interfaces for station services, mechanical equipment, station finishes, etc., are not included. The costs of interior structure are only included as an allowance for the mezzanine floor level in the two-story design and the interior structure for the large shaft. The costs are by no means complete or accurate but were intended to gain a sense of whether the potential cost differences merited a closer examination of the one-story cavern option.

As can be seen from Tables 8-1 and 8-2, the one-story station cavern has a preliminary cost savings for the basic structural shell of approximately $5,800,000 per station. The total cost of the two-story cavern station has been estimated at approximately $30,000,000 per station. Three mined stations and two cut-and-cover underground stations are currently planned.
Discussion

The savings in station cost must be weighed against station performance and impact on total system cost. Is a large station volume desirable for system image and passenger comfort? Should the centerpiece stations of the system have a grand design which adds a relatively small increment to a total system cost?

Much of this decision revolves around how much of the system is built initially. If the full-stage system is built at one time the tunnel and its large stations are fully functional initially. If only a portion of the system is built initially, the tunnel designed to serve the full system becomes a larger proportion of the initial cost. To reduce station costs, the platform length has been set for a maximum train length of three cars, and a close look at smaller station designs may be warranted for this preliminary LRT system.

One proposal reevaluated during the study period was to change the Minneapolis tunnel alignment to a tunnel in soil with cut-and-cover stations. This option had been discarded earlier because of the length of tunnels and low cost of station and tunnel construction in initial estimates. Changes in station locations and horizontal alignment during design and the community consensus process gradually altered these parameters to the point where an external review panel recommended a fresh look at the soil alignment. A soil alignment with fully cut-and-cover stations offers the advantage of not requiring the long transition to deeper sandstone tunnels but does mean more disturbance to the downtown area during construction. Since less expensive deep stations appear feasible, a comparison of the soil tunnel alignment with the sandstone tunnel alignment might also revisit the station configurations and overall sandstone tunnel length since many assumptions continue to be modified during the evolution of the LRT system.
Table 8-1: Approximate raw structure costs for two-level mined station (Scheme F).

<table>
<thead>
<tr>
<th>Structure of station cavern: Shell</th>
<th>Number of shafts: Six plus escalator cut</th>
<th>Type of shafts: Rectangular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone/Shale</td>
<td>52956</td>
<td>10</td>
</tr>
<tr>
<td>Limestone &gt;1500 cy</td>
<td>7033</td>
<td>21</td>
</tr>
<tr>
<td>Limestone &lt;1500 cy</td>
<td>2519</td>
<td>27</td>
</tr>
<tr>
<td>Soil</td>
<td>11055</td>
<td>5</td>
</tr>
<tr>
<td>Subtotal - Excav.</td>
<td>73563</td>
<td></td>
</tr>
<tr>
<td>Backfill</td>
<td>6249</td>
<td>10</td>
</tr>
<tr>
<td>Subtotal - Structure</td>
<td>177339</td>
<td>14966</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: These cost estimates are for the basic station structure only. They do not include the costs for construction dewatering and they assume the station structure will be designed to resist the external water pressure. Unit cost data were developed from data supplied by CNA Engineers and from Means Cost Data (1990). The costs per square foot of structure are based on the following individual costs (see table for correct reference).

(a) Waterproofing only at $4 per sq ft.
(b) Rock bolting ($8) + shotcrete ($6) + waterproofing ($6) = total of $20 per sq ft.
(c) Rock bolting ($5) + shotcrete ($3) + waterproofing ($6) = total of $14 per sq ft.
(d) Rock bolting ($5) + shotcrete ($3) = total of $8 per sq ft.
(e) Temporary retaining wall ($24) + waterproofing ($4) = total of $28 per sq ft.
(f) Temporary retaining only at $24 per sq ft.
(g) Rock bolting ($7) + shotcrete ($3) + waterproofing ($6) = total of $16 per sq ft.
(h) Rock bolting ($3) + shotcrete ($2) + waterproofing ($6) = total of $11 per sq ft.
Table 8-2: Approximate raw structure costs for one-level mined station (Scheme D).

<table>
<thead>
<tr>
<th>Number of levels in Sandstone: One</th>
<th>Structure of Station Cavern: Shell</th>
<th>Number of shafts: Two plus escalator cut</th>
<th>Type of shaft: Circular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone/Shale</td>
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<td>10</td>
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<tr>
<td>Limestone &gt;1500 cy</td>
<td>5236</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>Limestone &lt;1500 cy</td>
<td>1931</td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>Soil</td>
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<tr>
<td>Subtotal - Excav.</td>
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</tr>
<tr>
<td>Backfill</td>
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<td></td>
<td>10</td>
</tr>
<tr>
<td>Subtotal - Backfill</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Station box shell (g)</td>
<td>63338</td>
<td>1.5</td>
<td>3519</td>
</tr>
<tr>
<td>Sta. ovrbk. + fill</td>
<td></td>
<td>729</td>
<td>100</td>
</tr>
<tr>
<td>Ls Walls (c)</td>
<td>12451</td>
<td>1.0</td>
<td>461</td>
</tr>
<tr>
<td>Soil Walls (d)</td>
<td>19546</td>
<td>1.5</td>
<td>1086</td>
</tr>
<tr>
<td>Soil Walls (abut IDS) (a)</td>
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<td>165</td>
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<tr>
<td>Soil roof - Shallow (a)</td>
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<td>1.5</td>
<td>462</td>
</tr>
<tr>
<td>Escalator Floor (a)</td>
<td>3102</td>
<td>1.0</td>
<td>115</td>
</tr>
<tr>
<td>Interior Structure</td>
<td>18520</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtotal - Structure</td>
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<td>6537</td>
</tr>
<tr>
<td>Total</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Plus Contingency 20%</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Plus Project Overhead 20%</td>
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<td></td>
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</tr>
</tbody>
</table>

Notes: These cost estimates are for the basic station structure only. They do not include the costs for construction dewatering and they assume the station structure will be designed to resist the external water pressure. Unit cost data were developed from data supplied by CNA Engineers and from Means Cost Data (1990). The costs per square foot of structure are based on the following individual costs (see table for correct reference).

(a) Waterproofing only at $4 per sq ft.
(b) Rock bolting ($8) + shotcrete ($6) + waterproofing ($6) = total of $20 per sq ft.
(c) Rock bolting ($5) + shotcrete ($3) + waterproofing ($6) = total of $14 per sq ft.
(d) Rock bolting ($5) + shotcrete ($3) = total of $8 per sq ft.
(e) Temporary retaining wall ($24) + waterproofing ($4) = total of $28 per sq ft.
(f) Temporary retaining only at $24 per sq ft.
(g) Rock bolting ($7) + shotcrete ($3) + waterproofing ($6) = total of $16 per sq ft.
(h) Rock bolting ($3) + shotcrete ($2) + waterproofing ($6) = total of $11 per sq ft.
DEEP MINED STATION A:
ONE LEVEL WITH TWO BAYS

This one-level station is shown under Marquette Avenue at the IDS site. Tracks and platforms are in two separate bays with intervening sandstone pillars. Various shafts contain escalators to the surface, an elevator, ventilation ducts, and emergency stairways. Connections to the above-grade buildings and ventilation outlets at the surface are not shown in these drawings.

In the drawings that follow, it is assumed that the station section through the platform bays is 25 feet across and 20 feet high. The intervening sandstone pillars are 60 feet wide. Openings cut between the pillars are 40 feet wide.

Ancillary space is located at each end of the station for ventilation equipment and other functions. The total area of ancillary space at platform level is 15,500 square feet.

At each end of the station a 6-foot-wide stairway provides emergency egress. Three 4-foot-wide escalators from the platform to the surface also provide egress.

Figure 8-14: Diagram of one-level mined station with two bays.
DEEP MINED STATION A:
ONE LEVEL WITH TWO BAYS

Figure 8-15: Longitudinal section.

Figure 8-16: Section through station platforms at pillar.

Figure 8-17: Section through station platforms at escalator base.
DEEP MINED STATION A:
ONE LEVEL WITH TWO BAYS

Figure 8-18: Plan at platform level.

Figure 8-19: Plan at platform level with alternative shaft locations (5 smaller shafts are replaced by 2 larger shafts).
This one-level station is shown under Marquette Avenue at the IDS site. A large shaft at one end of the station contains escalators to the surface and can be designed as a high space that resembles an atrium extending from the surface down to the platform level. In addition the large shaft contains an elevator, ventilation ducts, emergency stairway, and a mezzanine area at the base of the escalators. A smaller shaft containing an emergency stairway and ventilation ducts is located at the other end of the station. Connections to the above-grade buildings and ventilation outlets at the surface are not shown in these drawings.

In the drawings that follow, it is assumed that the basic station section is 60 feet across and 20 feet high. Even though the water pressure is reduced compared to a two-level design and dewatering is possible, an 18-inch-thick concrete shell is still assumed. This leaves up to 34 feet for the platform width.

Two types of ancillary space are shown in this layout. There is space at each end of the platform for ventilation equipment. In the larger shaft/atrium area, there is space on several levels above the platform. The total area of ancillary space at platform level is 3600 square feet and the ancillary spaces in the shaft/atrium are 11,250 square feet for a grand total of 14,850 square feet. Obviously the ends of the station can be extended and additional ancillary space can be placed in the volume of the shaft.

At each end of the station a 6-foot-wide stairway provides emergency egress. Three 4-foot-wide escalators to the surface from the mezzanine also provide egress. Two escalators and stairs provide egress from the platform to the mezzanine.
DEEP MINED STATION B:
ONE LEVEL WITH ATRIUM/SHAFT AT ONE END (VERSION 1)

Figure 8-21: Longitudinal section.

Figure 8-22: Section through large shaft/atrium.

Figure 8-23: Section through atrium landing.

Figure 8-24: Section through station center.
Figure 8-25: Plan of platform level.

Figure 8-26: Plan of mezzanine level (within shaft through limestone).

Figure 8-27: Plan of escalator landing level in soil above the limestone (at approximately 30 feet below the surface).
DEEP MINED STATION C:
ONE LEVEL WITH LARGE SHAFT AT ONE END

This one-level station is shown under Marquette Avenue at the IDS site. One escalator bank extends toward Nicollet on 7th Street. A large shaft at one end of the station contains an elevator, ventilation ducts, emergency stairway, and a mezzanine area at the base of the escalators. A smaller shaft containing an emergency stairway and ventilation ducts is located at the other end of the station. Connections to the above-grade buildings and ventilation outlets at the surface are not shown in these drawings.

In the drawings that follow, it is assumed that the basic station section is a thin shell structure approximately 60 feet across and 22 feet high. Even though the water pressure is reduced compared to a two-level design and dewatering is possible, an 18-inch-thick concrete shell is still assumed. This leaves up to 34 feet for the platform width.

Two types of ancillary space are shown in this layout. There is space at each end of the platform for ventilation equipment. In the larger shaft, there is space on three levels above the mezzanine. It is assumed that the level just beneath the street is devoted to utilities and is not counted as ancillary space.

At each end of the station a 6-foot-wide stairway provides emergency egress. Three 4-foot-wide escalators to the surface from the mezzanine also provide egress. Two escalators and stairs provide egress from the platform to the mezzanine. An elevator to the surface is located adjacent to the main escalators.
DEEP MINED STATION C:
ONE LEVEL WITH LARGE SHAFT AT ONE END

Figure 8-29: Longitudinal section.

Figure 8-30: Cross section through large shaft and escalators to the surface.

Figure 8-31: Cross section through station center.
DEEP MINED STATION C:
ONE LEVEL WITH LARGE SHAFT AT ONE END

Figure 8-32: Plan of platform level.

Figure 8-33: Plan of mezzanine level (within shaft through limestone level).
DEEP MINED STATION C:
ONE LEVEL WITH LARGE SHAFT AT ONE END

Figure 8-34: Plan of levels above mezzanine within big shaft containing ancillary spaces.

Figure 8-35: Plan at surface level showing location of big shaft station on IDS site.
DEEP MINED STATION D: 
ONE LEVEL WITH LARGE CYLINDRICAL SHAFT AT ONE END

This one-level station is shown under Marquette Avenue at the IDS site. One escalator bank extends toward Nicollet on 7th Street. A large cylindrical shaft at one end of the station contains an elevator, ventilation ducts, emergency stairway, and a mezzanine area at the base of the escalators. A smaller shaft containing an emergency stairway and ventilation ducts is located at the other end of the station. Connections to the above-grade buildings and ventilation outlets at the surface are not shown in these drawings.

In the drawings that follow, it is assumed that the basic station section is a thin shell structure approximately 60 feet across and 22 feet high. Even though the water pressure is reduced compared to a two-level design and dewatering is possible, an 18-inch-thick concrete shell is still assumed. This leaves up to 34 feet for the platform width.

Two types of ancillary space are shown in this layout. There is space at each end of the platform for ventilation equipment. In the larger shaft, there is space on three levels above the mezzanine. It is assumed that the level just beneath the street is devoted to utilities and is not counted as ancillary space.

At each end of the station a 6-foot-wide stairway provides emergency egress. Three 4-foot-wide escalators to the surface from the mezzanine also provide egress. Two escalators and stairs provide egress from the platform to the mezzanine. An elevator to the surface is located adjacent to the main escalators.

Figure 8-36: Diagram of one-level mined station with a large cylindrical shaft at one end.
DEEP MINED STATION D:
ONE LEVEL WITH LARGE CYLINDRICAL SHAFT AT ONE END

Figure 8-37: Longitudinal section.

Figure 8-38: Cross section through large shaft and escalators to the surface.

Figure 8-39: Cross section through station center.
DEEP MINED STATION D:
ONE LEVEL WITH LARGE CYLINDRICAL SHAFT AT ONE END

Figure 8-40: Plan of platform level.

Figure 8-41: Plan of mezzanine level (within shaft through limestone level).
Figure 8-42: Plan at surface level showing location of big shaft station on IDS site.

Figure 8-43: Plan of levels above mezzanine within big shaft containing ancillary spaces.
This one-level station is shown under Marquette Avenue at the IDS site. One escalator bank extends toward Nicollet on 7th Street. A large cylindrical shaft in the center of the station contains a mezzanine area at the base of the escalators. Two smaller shafts containing an emergency stairway and ventilation ducts are located at the ends of the station. Connections to the above-grade buildings and ventilation outlets at the surface are not shown in these drawings.

In the drawings that follow, it is assumed that the basic station section is a thin shell structure approximately 60 feet across and 22 feet high. Even though the water pressure is reduced compared to a two-level design and dewatering is possible, an 18-inch-thick concrete shell is still assumed. This leaves up to 34 feet for the platform width.

Two types of ancillary space are shown in this layout. There is space at each end of the platform for ventilation equipment. In the larger shaft, there is space on three levels above the mezzanine. It is assumed that the level just beneath the street is devoted to utilities and is not counted as ancillary space.

At each end of the station a 6-foot-wide stairway provides emergency egress. Three 4-foot-wide escalators to the surface from the mezzanine also provide egress. Two sets of escalators and stairs provide egress from the platform to the mezzanine. An elevator to the surface is located adjacent to the main escalators.
DEEP MINED STATION E:
ONE LEVEL WITH LARGE CYLINDRICAL SHAFT IN CENTER

Figure 8-45: Plan of mezzanine mevel (through shafts within limestone).

Figure 8-46: Longitudinal section.

Underground Station Design Issues for Light Rail Transit in the Twin Cities Geology
DEEP MINED STATION F:
TWO LEVEL WITH MEZZANINE AND SINGLE ESCALATOR SHAFT

This two-level station is shown under Marquette Avenue at the IDS site. One escalator bank extends toward Nicollet on 7th Street. There is a mezzanine within the station. Ancillary space is located at each end of the station and occupies some of the upper level.

Figure 8-47 is a schematic representation of a two-level station design concept. A two-level station design has been developed by the consulting team for Hennepin County and was used as the basis for cost estimates. On the following page, an isometric drawing of that design and two cross sections are shown. Initially the design was rectangular but was modified to a curved shell structure to reduce the concrete thickness. The basic station section is approximately 60 feet across and 42 feet high. The curved shell structure with a thickness of 18 inches was used in the cost estimate that appears in Table 8-1.

Figure 8-47: Diagram of two-level mined station with one escalator shaft.
Figure 8-48: Cross section of the two-level station with a rectilinear shape. The relatively thick concrete walls reflect the structure necessary to resist water pressure.

Figure 8-49: Cross section of the two-level station with a curved shell structure. The concrete floor remains thick to resist water pressure, but the rest of the structural concrete is reduced. This design was used in the cost estimate in Table 8-1.

Figure 8-50: Isometric drawing showing the two-level station beneath Marquette Avenue near the IDS site.
Chapter 9: University of Minnesota East Bank Station

In the current plan for the LRT system, the corridor connecting downtown Minneapolis and St. Paul passes through the University of Minnesota. As shown in Figure 9-1, this alignment runs on Washington Avenue with a station on the West Bank and on the East Bank. The line runs above grade on the West Bank, crosses the Mississippi River Bridge at the level of the roadway, and then continues as an above-grade line to the east of the campus. Both an above-grade and below-grade alignment have been suggested for this East Bank section of the corridor. The narrow right-of-way on Washington Avenue, combined with the need for some level of vehicular and bus traffic, makes an underground tunnel beneath the street the most desirable alternative. In this case, the running tunnel would be cut-and-cover construction. Unless longer sections of the alignment are placed in a deep tunnel, a deeper station is not a practical alternative.

This chapter explores the urban design alternatives related to the underground alignment from the Mississippi River to Union Street on the East Bank. The purpose of this chapter is not to present a detailed proposal, but to illustrate design concepts that may assist in evaluating and further developing alternatives.

In the first part of the chapter, background information related to the setting is presented. This is followed by a presentation of two basic concepts for the underground alignment and East Bank Station.

Background of University Transit Development

The University of Minnesota has been actively concerned about finding a solution to transit and congestion issues at and between the Minneapolis and St. Paul campuses for more than two decades. The problems were analyzed in the
long-range development plans for the St. Paul campus (1972) and the Minneapolis campus (1976).

A University Area Transit Study conducted in 1973 (MTC, 1974) recommended a 5.6-mile two-fixed guideway for an Activity Center Transit (ACT) system serving the Cedar Riverside area, the West Bank and East Bank of the Minneapolis campus, and the St. Paul campus. This was intended to complement a larger regional transit system also serving the University. The system had eight stations, with two located on the East Bank campus — one adjacent to Jones Hall and one located on Washington Avenue adjacent to Church Street. Both the East Bank stations were to be located underground utilizing two-level mezzanine stations in a rectangular cut-and-cover structure.
The stations were to be designed to handle 6000 persons per hour and 600 boarding passengers per peak five minutes. The system was to be capable of moving 660 persons per five minutes between two stations.

The cut-and-cover underground stations were estimated to have a construction cost of $2,115,000 each, and the cut-and-cover guideway was estimated to cost $3525 per foot (both in 1973 dollars including design, administration and contingencies).

Because the automated fixed-guideway system proposed above did not proceed, the University prepared a new study in 1978, the University Area Short Range Transportation Program (BRW, July 1978). The principal recommendation of the study was the creation of a busway connecting the Minneapolis and St. Paul campuses, with consideration of a later upgrade to a higher level transit system.

Automobile and Bus Traffic

Washington Avenue presently carries 16,000 vehicular trips per day, or almost twice the volume of an average city street. Only an estimated 7500 of these trips have either their origin or destination at the University; of this number, about 5000 are “drop off” trips to the Health Science area on Church Street. By the year 2010, it is projected that the volume of trips on Washington Avenue will exceed 20,000 per day. Washington Avenue is presently a two-way, four-lane city street. The pavement is 52 feet wide, the right-of-way is 90 feet wide, and there is 120 feet between Amundson Hall and Lyon Lab (UM Physical Planning, Feb. 1989).

Washington Avenue is also a very important bus route. The MTC Route 16-A, University Route 52 Express bus service, and the Route 13 Intercampus bus service all use Washington Avenue.

A study of University Connector Light Rail Transit Alternatives (BRW, Oct. 1989 for the HCRRA) concluded that if LRT were located at grade on Washington Avenue, the street must be closed to general automobile traffic between Cedar Avenue and Church Street in order to accommodate the LRT and bus service in the area.

Special Concerns of the University

The East Bank LRT stop must be integrated with the pedestrian circulation system so that LRT riders can be distributed to the Health Sciences buildings, Coffman Memorial Union, Institute of Technology buildings, and others.
Figure 9-2: Map indicating the location of two underground station design alternatives for the Washington Avenue alignment. Site A is the Mall Station located in the depressed roadway in front of Coffman Union. Site B is the Church Street Station which is completely underground extending from Church Street to Union Street.

Clustered around the Mall. Providing access for LRT riders to this area should not interfere with the access needs of riders on other forms of transit. The East Bank Station also needs to convey a character and a quality commensurate with the state's most prestigious institution of higher education. The overall quality of the campus environment must be at least maintained and preferably enhanced.

A long-standing urban design issue for the East Bank campus has been the desire to extend the mall across Washington Avenue to create a continuous pedestrian level. This would require lowering Washington Avenue in the vicinity of the Mall. The two-level bridge across the Mississippi River was originally designed to facilitate this concept.
Design Alternatives

On the following pages, two schematic designs are presented for the underground alignment and station on the East Bank campus. In the first case, the LRT station occurs in the roadbed in front of Coffman Union. The tracks and road are depressed so that the pedestrian plaza extends over the top of the station platform level. This station is not a completely enclosed underground facility. In the second case, the station is located beneath Washington Avenue extending from Church Street to Union Street. This is a completely enclosed two level cut-and-cover station. In the drawings that follow, the two schemes are referred to as the Mall Station and the Church Street Station. On the site plan shown in Figure 9-2, the Mall Station is Site A and the Church Street Station is Site B.
Figure 9-3: Aerial view of the Mall Station scheme.
Figure 9-4: Cutaway view of the Mall Station scheme showing the station platform and running tunnel.
Figure 9-5: View of the pedestrian plaza in front of Coffman Union with the Mall Station scheme. The roadway and tracks are depressed so that the pedestrian level can extend over the station platform below. Access to the central platform occurs through escalators and elevator shafts at each end.

Figure 9-6: Cutaway view of the Mall Station in front of Coffman Union with the pedestrian plaza removed. The roads must be separated to accommodate the full width of the center platform and tracks. A bus drop-off area is shown on each side of the roadway.
Figure 9-7: View of Washington Avenue between Church and Union Streets with the Mall Station scheme. The running tunnel stays depressed and the roadway slopes up to grade.

Figure 9-8: Cutaway view with Washington Avenue removed over the train running tunnel.
Figure 9-9: Aerial view of the Church Street Station scheme.
Figure 9-10: Cutaway view of the Church Street Station scheme showing station platforms and mezzanines extending from Church Street to Union Street beneath Washington Avenue.
Figure 9-11: View of the pedestrian plaza in front of Coffman Union with the Church Street Station scheme. The roadway and track are depressed so that the pedestrian level can extend across Washington Avenue.

Figure 9-12: Cutaway view of Church Street Station scheme with pedestrian plaza and station cover removed. A bus drop-off area is shown on each side of the roadway. The width of the cut in front of Coffman Union is minimized with this scheme.
Figure 9-13: View of Washington Avenue between Church and Union Streets with the Church Street Station scheme.

Figure 9-14: Cutaway view with Washington Avenue removed over the Church Street Station. Mezzanine levels are beneath both the Church Street and Union Street intersections. The platforms and tracks are two levels below the street. The station can be entered through stairs or escalators on the ends. The mezzanine areas also provide understreet walkways connecting buildings on either side of Washington Avenue.
Figure 9-15: View of Washington Avenue looking west at the Union Street intersection.

Figure 9-16: Cutaway view with Washington Avenue removed over Church Street Station. Similar to the mezzanine at Church Street, the mezzanine at the Union Street end of the station provides a pedestrian connection between buildings on either side of Washington Avenue.
Chapter 10: Airport Station

The current LRT plan includes a corridor extending from downtown Minneapolis along Hiawatha Avenue to the vicinity of the Minneapolis/St. Paul International Airport. The central portion of the airport property is underlain by Platteville limestone and St. Peter sandstone. Similar to downtown Minneapolis, a tunnel and station cavern can be constructed in the sandstone with the limestone acting as the roof. This permits the LRT station to be located directly in front of or even beneath the main terminal building, and the tunneling can occur with little surface disruption. Figure 10-1 illustrates one proposed alignment for the airport LRT tunnel and station.

While the general station design concepts at the airport site are similar to those in downtown Minneapolis, some conditions make the airport site quite different. First, the water table in the sandstone is approximately 100 feet below the bottom of the limestone. Thus, there is no need to design tunnels or stations to resist water pressure (and costs will be reduced). Consequently, with respect to water pressure, there is no penalty associated with a two-level versus one-level station.

Another characteristic of the airport site is that the limestone appears thinner (16 to 18 feet in most places) compared with a 30-foot-thickness in the downtown sites. Information is not extensive concerning the thickness and quality of the limestone at the airport site. It is possible that the thinner limestone will reduce maximum spans, resulting in a two-cavern station design (binocular scheme). Until further site investigations are completed, this possible limitation is uncertain. In the design schemes that follow, the two-cavern station is shown along with some one-cavern schemes that may be feasible if the rock is sufficiently thick.

Finally, there is relatively little overburden above the limestone.

Figure 10-1: Site plan of the Minneapolis-St. Paul International Airport. The LRT tunnel alignment runs beneath the limestone at a depth of approximately 40 to 50 feet below grade. The underground station is shown in front of the main terminal, however it is possible to place the station directly beneath the terminal.
(approximately 10 feet). This means the distance from the station roof to grade is approximately 30 feet compared to 80 feet in downtown Minneapolis. In addition, the distance from the station roof to the basement floor of the terminal may be as little as 15 feet. Vertical circulation costs are reduced, and multiple points of access to the station platforms may be feasible. One consideration in this setting is whether a two-level station with a mezzanine is necessary beneath the limestone. While a mezzanine is an effective way of distributing people within a deep station, the lower level of the terminal building could, in effect, act as a mezzanine. This would permit the construction of a one-level mined station and the running tunnels could remain just beneath the limestone where they are likely to be more economical.

On the following pages, four basic schemes are illustrated that could be constructed beneath the airport terminal. They are: (A) the two-cavern design (binocular), (B) the one-level, single cavern design, (C) the two-level, single cavern design, and (D) the one-level design with a large open cut shaft over the center third of the station.

Figure 10-2: This cutaway view illustrates a typical two-bay configuration (the binocular scheme). Large sandstone pillars are left between the two platform tunnels. Interconnecting corridors provide access to both sides of the station. Although the escalator is shown in the center of the station here, additional access points elsewhere in the station are possible.
AIRPORT STATION A: TWO BAY CONFIGURATION WITH SHORT SPANS

The two-cavern station may be the only feasible configuration if the rock thickness and quality place span limitations on the structure. This is a relatively common station in subways throughout the world, and usually is a relatively economical approach. Because escalators and elevators are located along the interconnecting corridors, access and egress can be handled relatively efficiently. Sight lines for security and orientation are not as clear in a binocular configuration. The platform areas themselves are more confined than in single-cavern and two-level stations, although interior design techniques can offset this concern.

Figure 10-3: Section of one-level station with two bays.

Figure 10-4: Section of one-level station with two bays.
The one-cavern station may be feasible only if the rock thickness and quality are sufficient to permit a span of approximately 60 feet. Either a center platform or side platform arrangement is possible depending on the design of the running tunnels. With the center platform design, a maximum feeling of openness is created by providing access to the ends of the platform. Separate vertical access must be provided to each of the side platforms from the airport terminal above. With this approach, the lower level of the airport serves like a mezzanine in a two-level station. Generally, a single-cavern station will appear more spacious than a two-cavern (binocular) approach.
If it is feasible to span 60 feet and create a single-cavern station at the airport, then a two-level station design can be considered. Like traditional deep stations, passengers descend to a mezzanine level and then down again to center or side platforms below. Since the water table is lower than the floor level of the station, there is no additional cost in resisting water pressure with the two-level design on this site. Two-level stations are more spacious and open than one-level designs; however, there still may be confined areas and poor sight lines in places beneath the mezzanines.

Figure 10-8: Section of two-level station with center platform.

Figure 10-9: Section of two-level station with side platform.

Figure 10-10: Plan of two-level station with center platform.
AIRPORT STATION D: MULTI-LEVEL CONFIGURATION WITH LARGE SHAFT OVER THE CENTER

This station design is similar to Station B—a one-level single-cavern station. The primary difference is that a large opening is cut through the limestone over the center of the platform. This creates a 30 to 50 foot high atrium space extending from the airport terminal down to the platform level below. Vertical circulation can occur in this open cut. Such a large open space can create a great sense of orientation by visually connecting the station and the terminal. In addition, there is a sense of openness and potentially a strong, positive image. Like the other single-cavern stations, this approach requires limestone of sufficient thickness and quality to permit spaces up to 60 feet.

Figure 10-11: Section of multilevel station with large central shaft and side platforms.

Figure 10-12: Section of one-level portion of multilevel station with side platforms.

Figure 10-13: Plan of multilevel station with large central shaft and side platforms.
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