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Tunnel Boring Machine Performance Study

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16. Abstract

Full face tunnel boring machine "TBM" performance during the excavation of 6 tunnels in sedimentary rock is considered in terms of utilization, penetration rates and cutter wear. The construction records are analyzed and the results are used to investigate 21 downtime classes. Recommendations are made for modifications in excavation system design.

Correlations between rock index properties and penetration rates are achieved when maximum TBM thrust and torque are developed. It is shown that the predicting capabilities of index tests are significantly improved when the penetration rate is normalized with respect to thrust. The interrelationship of penetration thrust and rolling forces is analyzed with a 3-dimensional model which provides a rational basis for explaining variations in cutter forces and penetration rates as a function of rock type. Rock abrasiveness is shown to be a useful parameter to predict rates of cutter abrasion wear. A fracture mechanics approach to the process of the cutting tool-chip formation is proposed as an empirical prediction of TBM performance.

Seismic records of TBM's are presented in terms of peak velocity, frequency and attenuation rates. The technical and non-technical aspects of TBM planning activites are discussed. Use of 4 TBM's on a major transit project is presented as a case history for TBM planning. Recommendations are made for future work and observation records required for future performance evaluations are summarized.

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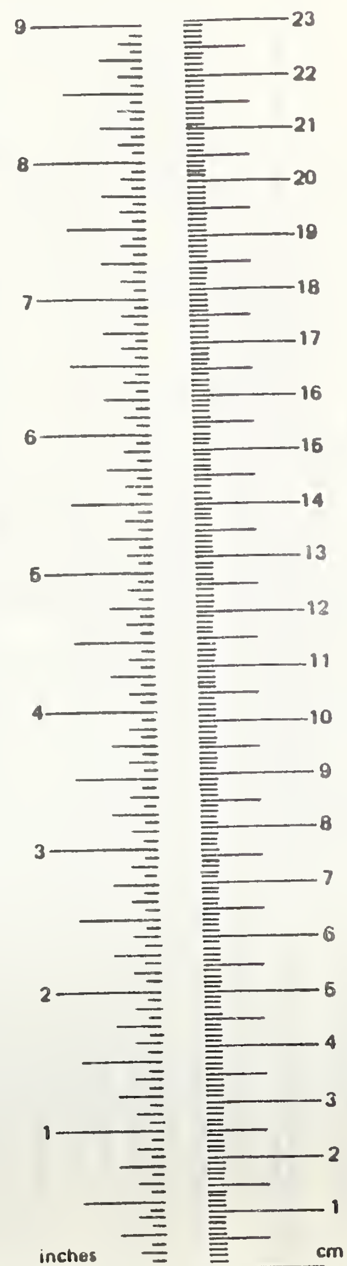
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

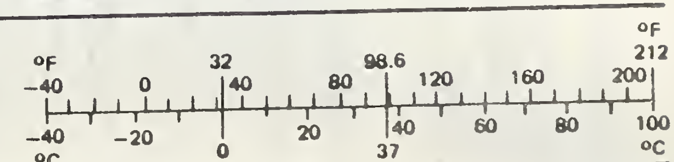
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2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

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



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
he	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

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LIST OF SYMBOLS

A	Trace amplitude
A_R	Rock abrasiveness
D	Distance
d	Diameter of thrust cylinder
d_{50}	Effective muck particle size pertaining to a percentage weight of 50 percent
$E_{t_{50}}$	Tangent modulus at 50 percent uniaxial strength
e	Efficiency
f	Frequency
G_{Ic}	Critical energy release rate
H_A	Abrasion hardness
H_R	Rebound hardness from Schmidt L-Hammer
H_T	Total hardness
I_s	Point load index
K	Intercept of ordinate axis of vibration attenuation plot
K_{Ic}	Fracture toughness
Nm	Number of cutterhead motors
N_t	Number of thrust cylinders
n	Number of cutters
n'	Attenuation rate
υ	Poisson's ratio
P	Power consumed by cutterhead motors
Pc	Total thrust cylinder pressure
Po	Thrust cylinder pressure to advance TBM without face contact

Qu	Uniaxial compressive strength
R	Weighted average cutter distance from the center of the cutterhead face
R_f	Field penetration index
S	Cutterhead rotation rate
S_v	Seismograph gain
σ_t	Brazilian tensile strength
T	Average thrust per cutter
T_o	Maximum torque
T_w	Wave period

EXECUTIVE SUMMARY

S.1 INTRODUCTION

This report represents work conducted by Goldberg-Zoino Associates of New York, P.C. and Cornell University in a broad research program to study full face, tunnel boring machine performance. Funding was provided by the Urban Mass Transportation Administration of the U.S. Department of Transportation by contract DTRS57-80-C-00107 to Goldberg-Zoino Associates. The Niagara Frontier Transportation Authority was a non-funding sponsor.

Richard F. Flanagan of Goldberg-Zoino Associates and Thomas D. O'Rourke of Cornell University were the Principal Investigators for the project. Paul J. Witkiewicz provided technical monitoring and research coordination for the Transportation Systems Center of the U.S. Department of Transportation.

Full face tunnel boring machine (TBM) performance during the excavation of six tunnels have been considered in terms of utilization, penetration rate, and cutter wear. Construction records for over 75,000 ft (22,860 m) of tunnels, in sedimentary rock, have been analyzed and the findings have been used as a data base to investigate the trends and factors influencing performance. The records were obtained from the four tunnels of the Buffalo Light Rail Rapid Transit (LRRT) project, the Culver-Goodman Tunnel (Rochester, NY) and the Chicago TARP Contract 73-287-2H. Seismic records were also reviewed to examine relative magnitudes and characteristics of vibrations from four TBMs.

Conclusions are made regarding estimates of TBM performance, downtime, adverse ground conditions, penetration rates, cutter wear, and muck gradations. The use of fracture mechanics for TBM evaluation and design, and the TBM planning for the Buffalo LRRT are also presented.

Recommendations are made for future research, including further study of cutter wear, the application of fracture mechanics, the interaction among torque, thrust, and penetration rate, and TBM vibration characteristics. Recommendations are also made for observations and record keeping on other TBM projects.

S.2 TBM PLANNING FOR THE BUFFALO LRRT PROJECT

The two tunnel line contracts (twin tubes) required the use of two TBMs per contract in order to meet a five year system wide construction schedule.

Alternate construction schedules, avoiding the two TBM specifications per contract, were considered but led to significant increases in line completion dates and costs.

One contractor ordered two new TBMs which performed better than scheduled. The second contractor reconditioned two used TBMs that performed with excavation rates slightly greater than planned. The time analysis illustrates that either new or used TBMs are effective in a tunneling project, provided proper planning is utilized by both the owner and contractor.

S.3 ESTIMATES OF TBM PERFORMANCE

TBM performance is expressed in terms of utilization, penetration rate, and advance rate. TBM penetration rate is defined as instantaneous penetration per unit time (in distance per unit time) or penetration per cutterhead revolution, utilization is the percentage of available shift time during which excavation occurs, and advance rate is expressed as the product of the penetration rate and machine utilization (in distance per unit time). The average TBM performance parameters for the six tunnels under study showed little variation which was not expected due to the difference in ground conditions, machines, construction planning and contractor practices. No significant difference with respect to machine availability was detected between new and old TBMs. The average values of the performance parameters can provide a general evaluation of TBM use, but cannot supply sufficient detail for many judgments needed on a specific job.

S.4 DOWNTIME

In this work, the total shift time, for each project, was analyzed as the sum of the machine utilization and the downtime percentages caused by: 1) maintenance and repair of the TBM, 2) repair of the backup system including trailing gear, rail, and shaft and surface mucking equipment, 3) ground conditions, and 4) miscellaneous.

The average percentage of all the case studies of the total shift time associated with delay from TBM maintenance and repair, backup system repair, and ground conditions average about 21, 20, and 14 percent, respectively. Delays caused by additional sources accounted for an average 13 percent of the total shift time, while approximately 32 percent of the total shift time was used for TBM excavation. Consideration of average values in each category helps to develop a general picture of the relative importance of each downtime cause, but judgments based soley on averages can be very misleading.

Under the category of TBM maintenance and repair, delays due to cutter changes were significant. The impact of equipment failure was frequently more severe on other aspects of TBM performance than on downtime. For example, cutterhead motors caused only moderate delays, but they affected the penetration rate and may have resulted in a significant increase in construction time. More than 30 percent of the tunneled distance on all the projects was excavated with less than the full complement of functioning motors.

In the backup system delay category, car pass systems required significantly more repair time than tripper systems. Train delays were significant with an average of 42 percent affecting all shifts. Delays caused by installation of utility system components were of moderate importance on projects using reconditioned equipment.

Delays associated with steel sets installed manually, were of significant importance, with the amount of downtime varied and not directly related to the installed number of sets. Delays associated with installation of other support systems (e.g. rock bolts, etc.) were moderate. Reconditioned rock bolt drills required more repair time than for new rock bolt drills. The most common muck jam location was at the hopper between the cutterhead and the TBM conveyor located inside the main beam. Muck jams were most frequent on the reconditioned TBMs. Water inflow was a major source of downtime for three of the tunnels included in this study.

Modifications in the design of several excavation system components and maintenance procedures could help to reduce delays in the following areas; car pass mechanism, muck cars, steel support segment handling and installation, utility line installation, muck accumulations in the invert and redesign of the hopper between the cutterhead and main beam.

Delays associated with mechanical repairs varied and generalizations about the relative efficiency of new and reconditioned equipment cannot be made. It is clear that effective use of a TBM depends closely on the maintenance program and experience of the contractor.

S.5 ADVERSE GROUND CONDITIONS

The six tunnels included in this study were driven through sedimentary rock for which bed thicknesses varied from less than 1.0 in. (25.4 mm) in shale to more than 5 ft (1.5 m) in the more massive sandstone and dolostone units. Bedding planes were the most frequent discontinuities. Much of the initial support installed in these tunnels was used to stabilize rock wedges which were bounded by bedding planes and vertical discontinuities.

Adverse ground conditions were usually associated with closely jointed and/or weathered rock. For the tunnels in this study, however, only about 50 percent of the total downtime associated with ground conditions was required for actual support installation. Additional problems encountered when mining in areas of closely jointed and/or weathered rock included such things as damage from blocky muck, loss of line in areas of springline overbreak, etc. A relationship between joint spacing and penetration rate could not be established. In tunnel sections where discontinuities were closely spaced, penetration rates were often affected by intentional reductions in operating thrust.

S.6 PENETRATION RATE

The average penetration rate for each tunnel was generally within ten percent of the overall average of all the tunnels. However, penetration rates showed much greater variation within each project. Comparisons of machine performance on different projects can best be made if an optimum condition of maximum thrust and torque can be identified. Similarly, TBM performance predictions should take into account the interaction of thrust, torque, rock type, and machine design in the prediction of penetration rates for future projects.

S.6.1 Influence of Machine Operation on Penetration Rate

Penetration rates calculated as overall averages for a given rock unit will be lower than those representing optimum TBM performance at maximum levels of thrust and torque. Thus, it is recommended that correlations between penetration rate and rock index properties be developed for penetration rates under conditions of maximum thrust and torque. In general, penetration rates determined as overall averages for a given rock unit are likely to be 10 to 20 percent less than those corresponding to conditions of maximum torque and thrust.

S.6.2 Influence of Cutter Wear on Penetration Rate

An effect of wear on penetration rate could only be discerned in the Culver-Goodman Tunnel for tunneling in the Grimsby sandstone under conditions of exceptionally high abrasive wear. Measurements showed that penetration rates were not influenced until approximately 1.5 in. (38 mm) of cutter disc diameter had been worn from the gage cutters. In general, cutter wear should not be regarded as a significant influence on penetration rate for the types and spacings of cutters represented in this study.

S.6.3 Correlations Between Penetration Rates and Rock Index Properties

Correlations were investigated between rock index properties and penetration rates. Using the penetration per revolution reduces the influence of cutterhead rotation speed on the results. Statistically, the most significant correlations between penetration rate and rock index properties were found for both abrasion hardness and a linear combination of abrasion and rebound hardness. In contrast, correlations between penetration rate and either uniaxial compressive strength or point load index were poor.

Correlations between rock index properties and penetration rate normalized with respect to thrust show substantial improvements in statistical significance relative to those based solely on penetration rate. A convenient index for relating penetration rate to thrust is the field penetration index, R_f, defined as the ratio of the average thrust per cutter to the penetration rate. Linear regressions of R_f against total hardness or a linear combination of abrasion and rebound hardness indicated the highest degree of statistical significance compared to correlations with many single index properties, including rebound hardness, abrasion hardness, uniaxial compressive strength, point load index, and Brazilian tensile strength.

S.6.4 Relationships Among Penetration Rate, Thrust, and Rolling Force

The relationships among penetration rate, thrust, and rolling force for different rock types may be though of as a critical surface in three dimensions. The cutting process can be analyzed through the use of a combined plot of the penetration rate versus average thrust and rolling force per cutter.

The ratio of the average rolling force to average thrust per cutter, at maximum torque levels varies from approximately 0.15 for high strength rock to 0.25 for low strength rock. These ratios can be used to estimate the average thrust consistent with optimum machine use. The estimated thrust can be used to evaluate the penetration rate by means of the correlations developed for total hardness or linear combinations of abrasions and rebound hardness.

S.7 CUTTER WEAR

A study was made of cutter rolling distances, number of changes and cutter clock life for cutters in the center, face and gage positions for excavation in three different lithologies (shale/limestone, sandstone, dolostone).

Average center cutter rolling distances were similar in the rock units studied. Rolling distances of gage cutters were less than that for face cutters in the abrasive Grimsby Sandstone, and gage and face cutter rolling distances were comparable in the less abrasive shale, limestone, and dolostone units. Face and gage cutter rolling distances were from 5 to 30 times greater than center cutter rolling distances. In the rock units studied, gage cutters were changed more often than face cutters.

Rock abrasiveness, A_R, showed a higher degree of correlation with the rate of cutter disc wear than did uniaxial compressive strength. Little correlation was found between cutter wear and the percent of minerals harder than steel.

S.8 MUCK GRADATION

The particle size distribution of the muck samples collected in this study showed little sensitivity to operating thrust levels and penetration rates. Generally, the gradations were similar, with the exceptions of muck produced by extremely worn cutters and muck produced while mining closely jointed rock.

S.9 FRACTURE MECHANICS APPLICATIONS

A fracture mechanics approach to model the process of chip formation was investigated. Penetration rates and field penetration indices were correlated with the fracture toughness, K_{Ic}, and critical energy release rate, G_{Ic}, for three relatively brittle and high strength rock units. The penetration rate and field penetration index showed a linear variation with respect to G_{Ic}, and no trend between K_{Ic} and performance could be identified. For massive, brittle materials, it appears that G_{Ic}, which includes the effects of rock strength and stiffness, shows potential for use in penetration rate and R_f prediction.

S.10 TBM VIBRATIONS

Particle velocities and frequencies, in three axes, were evaluated from seismograph records from the four Buffalo LRRT tunnels. Generally, more than 90 percent of the peak particle velocities are below 0.1 in./sec (1.54 mm/sec) while the maximum peak particle velocity is 0.3 in./sec (7.6 mm/sec). TBM vibrations are one-half to two orders magnitudes lower than blasting vibrations.

The frequency of public complaints to TBM vibration was less than one per 1000 ft (304.8m) of tunnel. No damage from TBM vibrations were observed during construction. Comparison of the measured vibrations with existing vibration criterion indicates the former are below structural damage levels. The magnitude and frequency characteristics of TBM vibrations are similar to those from moderate to heavy street traffic.

S.11 RECOMMENDATIONS FOR FUTURE RESEARCH

Future research in the following areas is recommended: 1) additional work of correlations of TBM performance with hardness index properties 2) linear cutter tests on additional rock types 3) better cutter replacement records 4) additional muck sample gradation analyses 5) further investigation into the fracture mechanics approach to rock-tool interaction and chip formation 6) fracture material property testing for additional rock types and 7) additional TBM vibration monitoring.

S-12 RECOMMENDATIONS FOR FUTURE OBSERVATIONS AND RECORDS

The following should be included in a shift report, as a minimum; shift identification, tunnel station locations, operating hydraulic pressures, cutter head motor information, fluid and oil temperatures, machine clock times, downtime, cutter wear records, survey location readings, rock support, and number and identification of personnel.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

A full-face tunnel boring machine (TBM) provides simultaneous excavation and mucking with a single, mechanical unit. The machine involves the operation of relatively complex equipment by personnel who are familiar with its function and experienced in underground work. The effective use of the machine and backup equipment depends on the ground conditions and their impact on the support requirements and mucking process. Because TBM construction requires input from many areas of expertise, the engineering associated with machine tunneling is often viewed as the special concern of a single discipline. A machine designer, for example, will emphasize the mechanical components of the system in an effort to provide optimum levels of thrust and torque at the rock face. The contractor will emphasize construction planning and experience. The geotechnical engineer will emphasize the rock properties and in-situ ground conditions as critical for productive machine use and safety of tunneling personnel. Thus, each discipline contributes to the understanding of the TBM and, in aggregate, becomes part of the framework for developing a comprehensive picture of machine performance.

The literature on machine tunneling reflects the multi-disciplinary nature of the subject. For example, there have been many studies of the interaction between the cutting tool and rock. The material in References of Rad (1974), Innaurato, Mancini and Pelizza (1976), Hignett and O'Reilly (1978), Ozdemir, Miller and Wang (1977), and Ozdemir and Wang (1979) indicate how cutter type, cutter spacing, cutterhead geometry and rotation speed affect the levels of thrust and torque associated with various penetration rates. Roxborough and Phillips (1975) and Lindquist (1982) use energy approaches to evaluate disc cutting efficiency. Howarth (1981a, 1981b) reports on the effects of joint characteristics and groove deepening on the rock cutting process. Snowdon, Ryley and Temporal (1982) summarize the results of comprehensive lab experiments to show the relationship among penetration rate, force levels and rock types.

Studies of mucking systems are an important supplement to the research on rock cutting and help in developing a comprehensive understanding of the tunneling process. Morrison (1972), Yu (1972), Faddick and Martin (1974), Duncan, et. al. (1979), and Henneke and Setzepfandt (1981) have reported on various types of mechanical, pneumatic and hydraulic muck disposal systems and discuss the applicability of these systems for different excavation methods and tunnel environments.

There have been several studies of field performance in which detailed observations of TBM construction provide information on major sources of delay. Korbin (1979) discusses the factors affecting TBM performance and describes how cutter servicing, machine bracing, and ground control can have important repercussions on advance rates. Morgan, Barratt and Hudson (1979) provide a detailed breakdown of advance rates, penetration rates, rock support, and cutter replacements for various rock units intercepted during excavation of the Kielder Aqueduct. Studies by Kulhawy and O'Rourke (1981), Ball, et. al. (1981), and Hulshizer, et. al. (1981), provide information on machine advance rates and major causes of delay. Data from twelve different TBM tunnels have been summarized by the U.S. Bureau of Reclamation (1974) with descriptions of the machines and general construction procedures. Robbins (1976) and Rutschmann (1981) discuss factors of special importance for contractors, including versatility of the TBM equipment and continuity of the tunneling operation. Antochow and Sperry (1982) report on the special considerations required for TBM applications in relatively small diameter tunnels.

The geotechnical aspects of TBM construction have been investigated by many researchers. Tarkoy and Hendron (1975), Tarkoy (1981), and McFeat-Smith and Tarkoy (1979) discuss the influence of rock properties on TBM penetration rates and cutter wear. Aeberli and Wanner (1978) show that features such as schistosity can influence penetration rate. Deere (1981), McFeat-Smith (1980), Korbin (1979), Morgan, Barratt and Hudson (1979), and O'Rourke, Priest and New (1979) describe the effects of difficult ground conditions on TBM performance, and Boldt and Henneke (1981) discuss methods used for TBM excavation through fault zones. Modifications in TBM design that can be used when dealing with adverse geologic environments are discussed by Hattrup (1981).

1.2 PURPOSE

Tunneling is a complex process not easily reduced to formulas and rules of thumb. The interrelationship between mechanical wear, continuous mucking, machine operation, and support installation requires a treatment based on understanding the many factors affecting system performance. It is the purpose of this report to investigate TBM construction as an integrated system of rock cutting, mucking, and support. Case history analyses are used as the principal means of accomplishing this goal. The records of actual field performance provide the only true measure of TBM capabilities and the requisite means of verifying any design/analysis methodology.

The principal objectives of the report are:

1) To clarify construction alternatives for the planners and designers of large underground projects. Options avialable with TBM construction are summarized and various design features of the machines are described to provide a comprehensive picture of TBM operation.
2) To develop detailed case histories of TBM construction for rapid transit systems and water conveyance facilities with tunnel dimensions similar to those used for transportation purposes. Special attention in the case histories is directed to establishing clear patterns of tunneling advance rates, machine utilization, penetration rates, and cutter wear. In addition, detailed analyses of tunneling delays are made.
3) To improve the understanding of machine performance and develop predictive capabilities in forecasting penetration rates and causes of delay. Emphasis is place on evaluating the patterns of cutter wear for various tunneling projects and rock types. In addition, several predictive procedures are evaluated to interpret the rock-cutting processes.

1.3 SCOPE

This report is composed of 14 chapters, of which the first covers general background and introductory remarks. The second chapter deals with planning for the effective use of TBMs on a large project. As an example, the strategies for building the Light Rail Rapid Transit (LRRT) system in Buffalo, New York are considered, with emphasis on the construction alternatives offered by TBMs. The third chapter involves a discussion of the design and operation of a TBM. In the fourth through ninth chapters, case histories of TBM construction are presented for tunnels with excavated diameters ranging from 18.5 ft. (5.6m) to 21.2 ft. (6.5m). Each case history provides background on the project, discussion of the geology, description of the machine and a detailed analysis of the tunneling records with emphasis on advance rates, causes of delay, machine penetration rates, and cutter wear. In conjunction with the detailed geologic and downtime information in Appendices A and B, the case histories serve as the data base for investigation of TBM performance.

Chapters 10 through 12 include discussion and interpretation of the case history data with the aim of formulating new concepts for TBM performance and recommendations for improved engineering practices. The 10th chapter summarizes the factors affecting machine utilization and discusses the influence of support requirements on TBM advance rates. The 11th chapter concentrates on machine penetration rate and developes a general relationship between penetration rate and rock index properties. The 12th chapter covers aspects of rock indentation and fracture and includes a detailed discussion of cutter wear. In addition, the results of muck gradation analyses are presented and correlations between penetration rates and properties delineating fracture propagation are developed. The 13th chapter examines the levels of vibration caused by TBM construction. The 14th chapter summarizes the conclusions and recommendations of the study. The relative importance of downtime causes as they affect machine utilization is summarized, and potential sources for improvement in performance and cutter wear predictions are identified.

CHAPTER 2

TBM EVALUATION AND PLANNING

2.1 INTRODUCTION

TBM excavation has become an integral part of U.S. rapid transit tunneling construction, with recent examples such as the Buffalo Light Rail Rapid Transit (LRRT), the Washington, D.C. Metro and additions to the New York City Metropolitan Transit. Where ground conditions allow, the traditional drill-and-blast excavation method is being replaced on larger projects by TBMs, which offer more economical and rapid excavation with environmental advantages.

This chapter presents a comparison of TBM excavation with drill-and-blast excavation, as well as technical and non-technical planning considerations for the use of a TBM. As an example of TBM planning, a case history is presented of the planning aspects for the use of four TBMs on the Buffalo LRRT project.

2.2 TBM AND DRILL-AND-BLAST EXCAVATION

Rock tunnel excavation for civil purposes is done most often by either TBM or drill-and-blast techniques. Some rapid transit tunneling has been performed with partial face excavators, referred to as "roadheaders", but difficulties from pick wear in medium to high strength rock has discouraged their application on other transit projects.

Table 2.1 presents comparisons between TBM and drill-and-blast excavation techniques. In terms of 1983 prices, a new TBM of a size appropriate for rail transportation tunnels may cost 4 to 5 million dollars. Although a contractor will generally amortize the entire machine on a given project, it does have a salvage value and there are now used TBMs that can be obtained and reconditioned for less cost than a new TBM. By comparison, a state-of-the-art drilling jumbo, for transit tunnels, costs only about 11 to 13 percent of that of a new TBM.

The drill-and-blast technique is cyclic and follows three general sequences as opposed to the continuous operation of a TBM. First, drilling the round consists of drilling a pattern of holes in the tunnel face followed by loading the holes with explosives. The second sequence is blasting the round which includes time to ventilate blasting gases. Third, mucking the round consists of removing

TABLE 2.1 COMPARISON OF EXCAVATION METHODS

CONSTRUCTION METHOD	ADVANTAGES	DISADVANTAGES
Tunnel Boring Machine	Continuous operation	High initial capital cost
	Relatively high excavation rates in favorable ground	Poor excavation rates in unfavorable ground
	Relatively low induced ground vibrations	Circular profile,
	Relatively smooth excavated surfaces; minimal overbreak; little disturbance to rock mass; rock support requirements may be reduced in comparison to drill-and-blast excavation	Limited to wide horizontal curves and about ten percent grades
	Tunnel muck easier to handle; may be suitable for road base course	Delivery time of one year or more for new machine
Drill-and-Blast	Relatively low initial capital cost	Cyclic operation with frequent interruptions
	Adaptable to adverse ground conditions	Relatively low excavation rates
	Adaptable to all geometries	Disturbing ground and air vibrations
	Relatively short delivery time for equipment	Disturbance to rock mass; greater support requirements
		Rough tunnel profile with overbreak
		Bulky tunnel muck

the blasted rock and, if needed, adding rock support. Drilling the face has progressed to computer-controlled, mechanized, hydraulic jumbos which can drill several holes simultaneously.

The TBM in favorable ground achieves the highest rates of advance. Average rates of 250 ft/week (76.2 m/week) to 350 ft/week (106.7 m/week) are commonly achieved for transit tunnels. Drill-and-blast, under the same conditions, typically would achieve advance rates of 60 ft/week (18.3 m/week) to 110 ft/week (33.5 m/week). Therefore, for a capital cost from eight to nine times that for a drilling jumbo, a TBM may increase the advance rate by three to four times. Advance rates for a TBM through unfavorable ground, such as faults, shear zones, etc., may be reduced significantly or, in certain cases may be so restricted that drill-and-blast methods are required as a remedial measure for advance. Drill-and-blast excavation through the same ground may also be slow, but will generally be faster than that of a TBM because the exposed rock is accessible for support and stabilization.

TBM ground vibrations are low and usually within tolerable limits for prevention of damage to nearly all structure types. Occasionally, the continuous nature of the vibrations may be annoying to people. Blasting results in both ground and air-overpressure vibrations which are disturbing to the public and may be sufficiently high to cause building damage. Blasting is considered hazardous construction and there are strict limitations on handling and using explosives. Additionally, because of public safety and disturbance factors, operations may be limited to one to two work shifts per day. TBMs are frequently operated two to three shifts per day because of the reduced disturbance and improved safety factors.

Rock support requirements typically are reduced in TBM-mined tunnels, as shown by several studies (Deere, et al., 1969; Wickham, et al., 1974). Blasting tends to disturb, fracture, and loosen the surrounding rock, which leads to increased support requirements. Furthermore, blasting can result in significant overbreak which must be filled during lining installation, resulting in increased cost. Deere, et al. (1969) concluded that for tunnels with a secondary lining, identical rock conditions and support systems, lining costs in a drill-and-blast tunnel is 16 percent to 20 percent more than those in a TBM tunnel excavation. On a typical transit tunnel contract, this increase amounts to costs of significant proportions.

Conversely there are economic advantages when using a TBM, such as described in a recent case history of a large diameter water conveyance tunnel (Zayakov, 1981). Because of the smooth circular bore, a final lining was not required, thereby saving an estimated $2,000,000 to $10,000,000. Although contract specifications allowed either TBM or drill-and-blast excavation, all bids favored the TBM.

Tunnel muck from a TBM is generally smaller and more compact than that from drill-and-blast because of the cutting mechanisms. Therefore, TBM muck requires less hauling and reduced traffic noise. However, with higher advance rates, the amount of hauling traffic may be equal to that of drill-and-blast techniques. In addition, the particle size distribution of TBM muck lends itself to use as a structural fill. For instance, muck from the Buffalo LRRT was used as a base for road pavements.

TBM bores are limited to circular sections, with maximum slopes of 10 degrees and horizontal curves less than about 450 ft (137 m) to 500 ft (152 m). Drill-and-blast techniques are adaptable to all common geometries and shapes. Short tunnel lengths are generally not economical for TBMs since amortization of machine cost is usually done over the tunnel length. However, TBMs have excavated short-length transit tunnels at favorable costs, as evidenced by the use of a TBM for construction of Route 131-A, Section 5B of the New York City Metropolitan Transit (Ziegler and Loshinsky, 1981).

Normal delivery time for a new TBM is generally about 12 months, although delivery of a reconditioned TBM would require several months less. Drill-and-blast equipment can be obtained in a much shorter time; for example, a new drilling jumbo could be delivered in several months.

2.3 GENERAL PLANNING CONSIDERATIONS FOR TBM PROJECTS

Selecting a TBM as the excavation method for a given tunnel is a significant decision for an owner or contractor. It impacts the project not only on the initial cost, but also affects the project completion date. There are several important factors which should be considered during the planning stages, including delivery time, capital cost, and influence of adverse ground.

Delivery time for a new TBM averages about 12 months but may be as much as 15 months from the order date. Used TBMs can be reconditioned for a given project and typical delivery time for such a machine ranges from 4 to 9 months, depending on modifications (Scaravilli, 1981; Ball, et al., 1981). It should be emphasized that the waiting time for TBM delivery is not completely lost. Depending on the nature of the project, the contractor can perform shaft construction, starter tunnels, etc., so that the construction program is coordinated with the TBM delivery.

The capital cost of a new TBM is substantial. Major TBM manufacturers are typically quoting $4,000,000 to $4,700,000 in 1983 prices, for fully equipped machines of rail transportation size diameters. A recent mass transit project case history reports an estimated $3,800,000 initial cost for a TBM (Ziegler and Loshinsky, 1981). Scaravilli (1981) reports that, depending on modifications, reconditioned TBMs may initially cost 25 percent to 50 percent of that of a new machine.

Table 2.2 presents a cost summary for new and reconditioned transit-size diameter TBMs as presented by Scaravilli (1981). The reconditioned TBMs represent both minor and major modifications to two existing TBMs that were eventually used on the Buffalo LRRT and which are discussed in Chapters 6 and 7. Costs exclude those associated with cutter replacements and assume a 7,000 ft (2,134 m) long tunnel. Scaravilli (1981) concluded that it is not readily apparent that a properly reconditioned machine is the most economical choice for a specific project. He did conclude, however, that a minor modification of an existing machine appears to be more economical than a new machine.

Although Table 2.2 indicates that a new TBM would be the most expensive choice, these figures are predicated on a 7000 ft (2,133 m) tunnel length. Greater tunneling distances may disproportionately increase operational costs for reconditioned TBMs, and a new TBM could be more economical than the former.

There are two particular characteristics that influence performance:

(1) Options for support at the cutting face are limited and consequently TBMs are vulnerable to squeezing or collapsing ground.

(2) Rock strength and abrasivity can have substantial repercussions on the advance rate and cutter consumption.

The influence of adverse geological conditions on TBM excavation rates may be very dramatic, and there are cases where the TBM design characteristics were not compatible with ground conditions. For example, poor ground conditions led to a tunnel crown collapse and breaking of the TBM drive shaft during construction on the Washington, D.C. Metro Contract 1K0011 (Garbesi, 1979). Some situations, with major machine design-ground behavior incompatibility, have resulted in the TBM being either abandoned in place or removed.

TABLE 2.2 COST COMPARISON BETWEEN RECONDITIONED AND NEW TUNNEL BORING MACHINES (After Scaravilli, 1981)

ITEM	RECONDITIONED TBM	EXTENSIVELY RECONDITIONED TBM	NEW TBM
Initial Cost	$ 1,500,000	$ 700,000	$ 2,900,000
Operating Expenses and Modifications	625,000	1,090,000	300,000
Gross Project Cost	2,115,000	1,790,000	3,200,000
Salvage Value	750,000	500,000	1,000,000
Net Project Cost	1,365,000	1,290,000	2,200,000

1. All costs subject to the following restrictions: no cutter costs included and cost figures developed for 7,000 ft (2,134 m) long tunnel

2.4 PLANNING DECISIONS FOR TBM USE ON THE LRRT PROJECT

The planning of the Buffalo LRRT system provides an example of the multiple possibilities associated with TBM construction, and the impact of time constraints on the choice and development of the machines. The decision to use four separate TBMs to drive twin tubes on two separate contracts represents a unique approach to rapid transit construction and makes the LRRT noteworthy by virtue of this decision and the resulting savings in time and cost.

The 3.5 mile (5.6 km) long rock tunnel section of the Buffalo LRRT was designed as twin tunnels with a nominal finished 16 ft. (4.9 m) diameter, and five underground stations. Further details on the system geometry are presented in Chapter 4.

The high quality rock along the tunnel alignment was favorable for TBM construction. The design study called for TBMs to be driven through station areas. Subsequent station contracts were planned to enlarge the TBM bores by drill-and-blast methods.

The LRRT was planned for a five year time to completion, which was judged to be the shortest time possible for construction. To achieve this goal, the line contracts had to overlap station construction and release work sites for the latter. The tunnels were divided into a north and south contract covering lengths of 7,600 ft(2,316 m) and 10,640 ft (3,243 m), respectively. Planned TBM excavation lengths were approximately 600 ft (183 m) to 700 ft (213 m) shorter than the total lengths because of shafts, and drill-and-blast and stub tunnels. Time allowances were 31 months (north contract) and 33 months (south contract). To achieve overlapping station and line contracts, it was necessary to specify two TBMs and two muck shafts per line contract. In addition, the line contractors were required to move muck handling equipment once the bores had passed intermediate shaft areas so that concreting could begin and overlap remaining excavation activities.

As an alternative to the selected construction scheme of two TBMs and two muck shafts, the following options were also considered for each contract:

1. Two TBMs and one muck shaft
2. One TBM and two muck shafts
3. One TBM and one muck shaft

All of these alternates led to postponing line tunnel completion dates.

The increased time for the preceding options (2) and (3), which included a single TBM and one or two muck shafts, were not cost-effective. For instance, option (2) added a five-month delay to the revenue date and a $1,300,000 construction cost, assuming a 7 percent inflation rate. The inflation rate has exceeded 7 percent and reinforces the decision for the two TBM concept. More importantly, a single TBM scheme with unanticipated delays would have resulted in further increases to all following contracts.

An overall excavation rate was estimated at 50 ft/day (15.4 m/day) which allowed a slower rate for an initial start-up length of 1,000 ft (308 m) and a faster rate following. This average rate was derived from excavation commencement to completion and accounts for all delays.

Key construction events were identified as TBM deliveries, TBM assembly and excavation, and concreting. At the time of planning, 1977-1978, the TBM manufacturers quoted 15 months delivery time because of a large number of orders. Under normal conditions, delivery time could be as short as 12 months. Used TBMs were not planned for, although their delivery times are shorter. The contract documents allowed tunnel diameter modification, i.e., larger diameters, to increase the range of potential existing TBMs that could be used. Historical records indicate that the used TBMs could be delivered in 8 to 9 months. Therefore, because of uncertainties in TBM delivery times, planning times of 10 and 12 months were used for delivery of the first and second machines for each contract. Two months were allotted for TBM assembly and start-up.

The south contractor, immediately upon bid opening, ordered two new TBMs, several months before Notice to Proceed was given and gained an advantage at his own risk. With this advantage, the contractor requested use of only one muck shaft, which was approved. The successful north contractor bid with two reconditioned TBMs and used two muck shafts. Table 2.3 is a comparison for the planning and actual times for the Buffalo LRRT TBM related construction activities.

Actual total contract completion times essentially were within the planned times as evidenced by Table 2.4. More specific construction details are presented in Chapters 4 and 5 and Chapters 6 and 7, respectively, for the south and north contracts.

2.5 SUMMARY

TBMs are being used frequently, and offer many advantages compared to the traditional drill-and-blast excavation methods. Capital costs range approximately $4,000,000 to $5,000,000 for transit size diameter TBMs. These capital costs are about 8 to 9 times greater than that for drill-and-blast equipment, but the advance rates are 3 to 4 times larger. TBMs offer advantages such as a smooth tunnel bore, reduced rock support requirements and disturbance to surrounding rock, less ground vibration, and more uniform muck size. Some disadvantages are long delivery time, poor excavation rates through unfavorable ground, and geometry limited to circular sections.

On the Buffalo LRRT, different planning schemes for TBM use were examined to achieve the shortest construction time for the two deep tunnel contracts. This was achieved by specifying two TBMs per contract. Other schemes, including the use of one TBM per contract were associated with increased costs because of system opening delays. Contract specifications allowed the use of larger TBM diameters so that contractors could chose from a greater number of used TBMs.

TABLE 2.3 COMPARISON OF ESTIMATED AND ACTUAL TIMES FOR SPECIFIC CONSTRUCTION EVENTS, BUFFALO LRRT

	Delivery (5) (months)	Assembly (months)	TBM Excavation (months) North Contract	TBM Excavation (months) South Contract
Planning Estimate	10.0 12.0	2.0	7.3	9.2
Actual				
South Contract				
Outbound (1)	13.5	1.5	---	8.4
Inbound (2)	15.5	2.0	---	7.4
North Contract				
Outbound (3)	9.0	2.0	6.7	---
Inbound (4)	4.0	2.5	6.7	---

(1) Tunnel length excavated with TBM = 10,208 ft (3,111 m)

(2) Tunnel length excavated with TBM = 10,211 ft (3,112 m)

(3) Tunnel length excavated with TBM = 7,059 ft (2,152 m)

(4) Tunnel length excavated with TBM = 6,813 ft (2,077 m)

(5) Delivery time from order placement to delivery at site.

TABLE 2.4 COMPARISON OF ESTIMATED AND ACTUAL TUNNEL CONSTRUCTION COMPLETION TIMES, BUFFALO LRRT

	Total Completion Times (months) (1)	
Contract	Planned	Actual
South Contract	33	36.2
North Contract	31	31.1

(1) From Notice to Proceed date to completion date

CHAPTER 3

TUNNEL BORING MACHINE DESIGN

3.1 HISTORICAL BACKGROUND

The earliest U.S. design for a tunnel boring machine can be traced to an 1851 patent by C. Wilson. This machine was used to cut a 13-in. (330 mm) wide groove around the 24 ft (7.3 m) tunnel diameter at the east portal of the Hoosac Tunnel, and cutting rates of 10 to 24 in. (254 to 610 mm) per hour were reported (Brunton and Davis, 1922; Brierley, 1976). In 1857, an 8 ft (2.4 m) diameter machine, designed by H. Haupt, was used at the west portal of the Hoosac Tunnel. Neither of these machines was commercially successful, and their lack of success at the Hoosac Tunnel eventually resulted in the development of compressed air drills and nitroglycerine blasting compounds.

At about the same time that the Hoosac Tunnel was completed in 1876, an agreement was reached between the British and French governments for the construction of a tunnel beneath the English Channel. Tunnel boring machines of two different designs were developed for this enterprise. One machine, based on an 1868 patent by J.D. Brunton, cut rock by means of three or more revolving discs, each rotating on its own axis and in aggregate about the central axis of the tunnel (Drinker, 1887; Slater and Barnett, 1957). The other machine, based on an 1864 patent by F. E. B. Beaumont, cut rock by means of pick cutters driven forward on a rotating shaft under the force of compressed air (Brunton and Davis, 1922; Slater and Barnett, 1957). Beaumont's machine was employed by the British, tunneling east from Dover, and the French, tunneling west from Sangatte. At both sides of the Channel, the machines drove 7 ft (2.1 m) diameter tunnels in chalk approximately 1.2 mi. (1.9 km) long. On the English side, a maximum advance rate of 81 ft (24.7 m) per day was attained, and an average of 50.5 ft (15.4 m) per day was sustained for 53 consecutive days (Brunton and Davis, 1922). In 1882, work on the Channel Tunnel was stopped because of political opposition from the British military and Parliament.

Although Beaumont's machine used the same basic mechanisms for thrust and torque as those of modern machines, over 70 years elapsed.

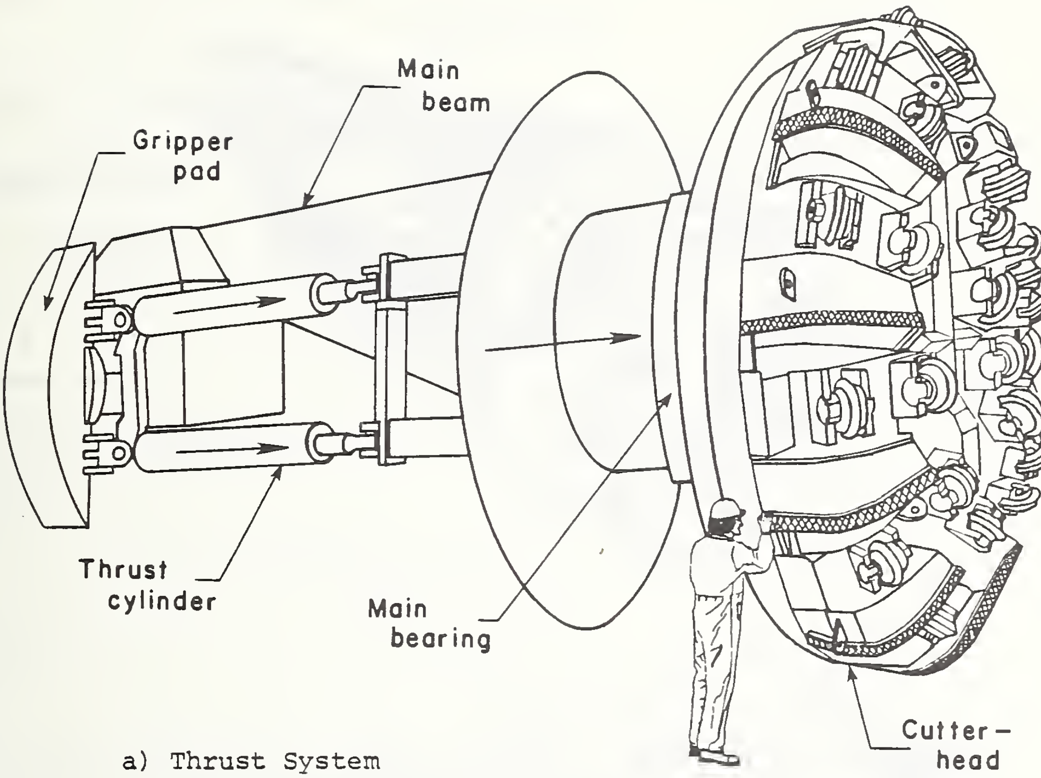
before a TBM was successfully employed by J.S. Robbins at the Oahe Dam in South Dakota. This machine and a similar one supplied in 1955 drove a combined 4.3 mi. (6.9 km) of 26.2 ft (8.0 m) diameter tunnel through shale. Robbins experimented with different cutters and combinations of cutters, and achieved notable success in 1956 on the Humber River Sewer Tunnel in Toronto, Ontario. The 10.8 ft (3.3 m) diameter machine used on this job was the first to be completely equipped with circular disc cutters (Thon, 1982).

Experience over the past 30 years has resulted in the consolidation of different ideas regarding machine performance to yield a basic pattern of design that is remarkably consistent among different manufacturers. Although important differences between individual manufacturers do exist, this chapter emphasizes machine design from a general, conceptual viewpoint. It describes the basic mechanical components of full-face machines with illustrations from major American manufacturers to show how the mechanical systems operate. Methods for estimating machine performance and determining various operational parameters are discussed to provide an understanding of the machine systems and develop a baseline from which to approach the case histories presented in later chapters.

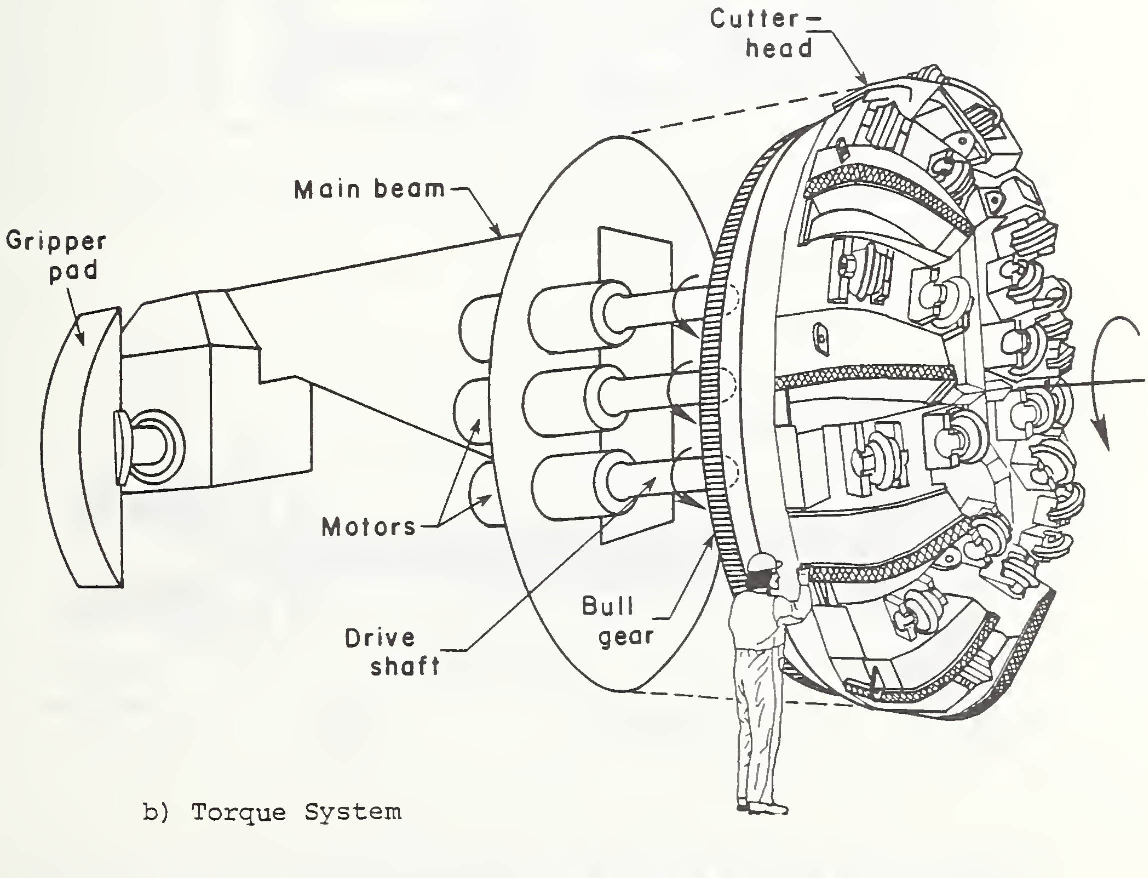
3.2 THRUST AND TORQUE SYSTEMS

Rock cutting involves the indentation of a rock surface by a cutting tool as it is driven forward, leaving a groove, fractured and crushed rock behind. Indentation requires a normal force or thrust delivered to the rock surface. The rolling force, needed to drive the tool forward, requires torque to turn the cutterhead supporting the tool. A TBM may be thought of as a device that simultaneously generates thrust to push the cutterhead forward and torque to turn the cutterhead against the tangentail forces resisting the cutting tools.

Figures 3.1 and 3.2 show the thrust and torque mechanisms associated with TBMs manufactured by The Robbins Company of Seattle, Washington, and Atlas Copco Jarva, Inc., of Solon, Ohio, respectively. Figure 3.1 provides three-dimensional views of a Robbins machine having dimensions similar to those included in this study. Figure 3.2 provides both three- and two-dimensional views of an Atlas Copco Jarva machine, in which the details of the thrust and torque systems are shown in profile.



a) Thrust System



b) Torque System

FIGURE 3.1 THRUST AND TORQUE SYSTEMS OF ROBBINS TBM

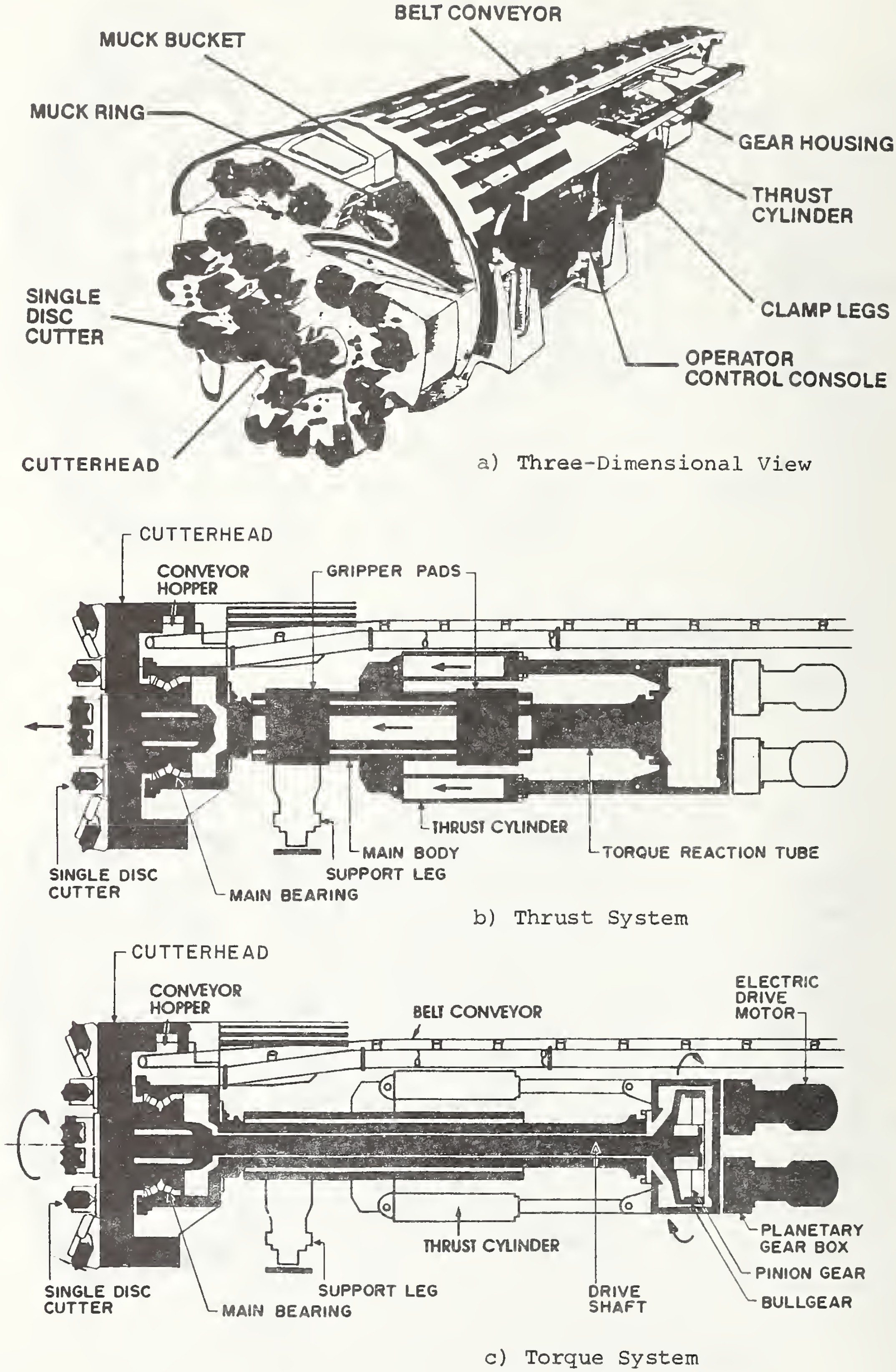


FIGURE 3.2 THRUST AND TORQUE SYSTEMS OF ATLAS COPCO JARVA TBM

The thrust and torque systems associated with each machine are discussed under the headings that follow.

Thrust System

In the Robbins machine, the cutterhead is driven forward by hydraulic cylinders, located adjacent and parallel to the main beam. The cylinders are connected to a structural frame that transfers force to the face of the machine through the main bearing. The main bearing is a sealed system of tapered roller bearings that allows for the simultaneous application of thrust to and rotation of the cutterhead. The thrust reaction comes from a structural frame and cradle assembly connected to the gripper pads. The main beam is supported by the cradle assembly, which incorporates a sliding mechanism so the main beam and cutterhead can move relative to the gripper pads. The main beam houses a conveyor belt, through which excavated rock is transferred from the TBM face to a trailing floor assembly at the rear of the machine.

In the Atlas Copco Jarva machine, the cutterhead is similarly driven forward by hydraulic cylinders, located peripherally around a central main body and drive shaft. The main body is clamped to the tunnel wall by gripper pads, and the thrust is delivered through the torque reaction tube, which slides forward within the main body. The torque reaction tube transfers force to the face of the machine through a main bearing, which is a sealed system of tapered roller bearings. Rock excavated at the face is collected on an overhead conveyor and transferred to a trailing floor assembly at the rear of the machine.

A single cycle of forward thrust generally involves between 4 and 5 ft (1.2 and 1.5 m) of movement. The manner in which this boring cycle is accomplished is similar for most full face machines. A typical thrust cycle is illustrated in Figure 3.3 by reference to a Jarva machine with an "X" type clamping system composed of eight gripper pads. At the beginning of the cycle, the main body is clamped to the tunnel wall by extending the gripper pads. With the gripper pads clamped in place, the central drive shaft is driven forward until the thrust cylinders have been extended through their entire stroke length. The support leg is then lowered and the gripper pads retracted. The main body is pushed forward into position for the next cycle of thrust. Finally, the gripper pads are extended and the support leg is retracted to set up for the next cycle of thrust.

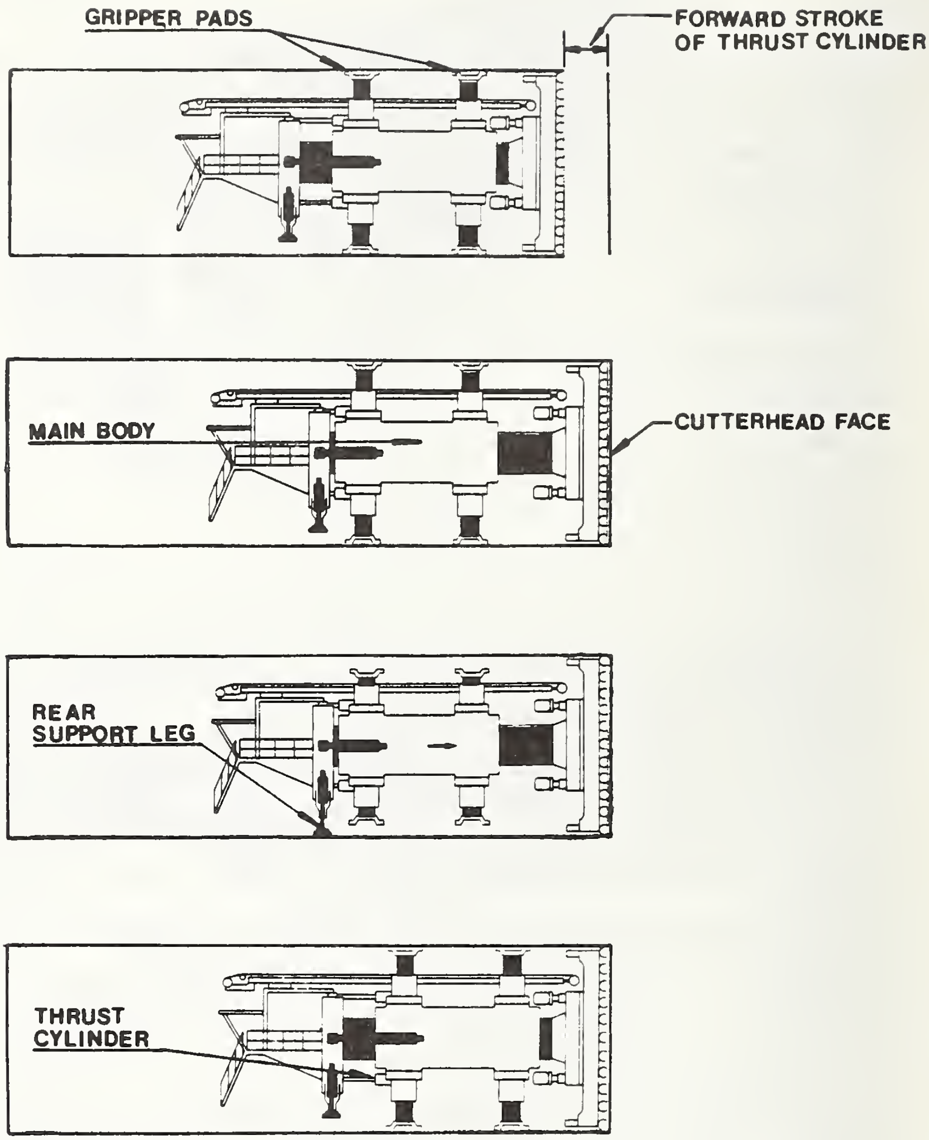


FIGURE 3.3 PROFILE VIEWS ILLUSTRATING FORWARD THRUST CYCLE OF TBM

It should be noted that, during a cycle of forward thrust, the thrust cylinders are used to push most of the TBM forward as well as the trailing gear assembly connected to the rear of the machine. Hence, the thrust actually transmitted to the rock face equals the force generated by the cylinders minus the sliding resistance of the machine and trailing gear.

From the TBM operating records, the average thrust per cutter, T, can be determined by:

$$T = \frac{N_t (p_c - p_o) \pi d^2}{4\, n} \tag{3.1}$$

where N_t is the number of thrust cylinders in use, d is the cylinder diameter, n is the total number of cutters, p_c is the total cylinder pressure recorded for a given forward stroke, and p_o is the cylinder pressure required to advance the TBM and trailing gear without face contact. The value of p_o can be recorded by means of a special set-up and series of measurements at the start of tunneling. This pressure is generally 10 to 15 percent of the total pressure recorded at a given location. Although it may vary depending on alignment, tunneling through curves, and the use of side supports, the variations are not likely to represent a significant percentage of the calculated net thrust under most circumstances.

Torque System

In the Robbins machine, the face of the cutterhead is rotated by motors anchored to the back panel of the cutterhead. The reaction for torque is obtained through the main beam, which is linked to the cradle assembly and gripper pads. Torque is transmitted through pinion gears that connect with a relatively large diameter bull gear, causing rotation of the cutterhead around the main bearing.

In the Atlas Copco Jarva machine, the cutterhead is similarly rotated by motors, anchored to a frame at the rear of the central drive shaft. The reaction for torque is obtained through the gripper cylinders, which are attached to the main body and gripper pads. Torque is transmitted through the pinion gears to the bull gear, all of which are at the rear of the drive shaft. The torque is transferred through the drive shaft to the cutterhead face, which rotates on the main bearing.

The most critical aspect of the torque system is the power consumed by the motors, generally rated in terms of amperage. If the motors draw too much amperage, they will overheat and lead to internal damage. The machine operator controls the TBM by controlling the amperage consumed by the motors. Each motor is rated by its manufacturer to operate at a maximum level. For example, motors are commonly rated to provide 200 HP (149 kW) of power at a maximum amperage of 216 amps. Because each motor is connected to an ammeter, the operator can evaluate how much amperage is drawn by the motors and make adjustments in the thrust to keep the amperage near the maximum rating.

The maximum torque, T_o, transmitted to the face can be determined from:

$$T_o = \frac{N_m Pe}{2\pi s} \tag{3.2}$$

where N_m is the number of motors in use, s is the rotational speed of the cutterhead expressed as revolutions per unit time, P is the power consumed by each motor per unit time (often expressed in terms of horsepower, HP) and e is the efficiency of the motor and drive train assembly. The power consumed by each motor can be estimated from the operating records of average amperage for a given shift. The relationship between power per unit time and amperage is nearly linear for values ranging 20 percent above and below the maximum rating. Under most conditions, the power consumed at amperages other than the maximum rating can be determined by linear extrapolation. For example, a motor rated at 200 HP (149 kW) and 216 amps would deliver 222 HP (165 kW) at 240 amps. The combined efficiency of the motor and drive train is often estimated at approximately 85 percent.

The average rolling force per cutter, t, may be estimated by equating the torque, T_o, with the product of t and the weighted average cutter distance from the center of the face, R, to obtain:

$$t = \frac{N_m Pe}{n 2 \pi s R} \qquad (3.3)$$

Expressions similar to this have been used by Hamilton and Dollinger (1979) and Ozdemir and Wang (1979) to interpret the operating records at selected locations on several projects in which boring machines were used. This latter expression should be used cautiously because it does not account for the resistance to rotation from a variety of sources including the weight of muck-filled buckets, frictional forces along the periphery of the machine, resistance to rotation at the individual disc cutters, and obstructions caused by muck accumulations at the face.

3.3 CUTTERS

The most common cutting tool used on full-face TBMs is the single disc cutter. This cutter is composed essentially of a ring or disc on a hub connected to a central shaft protruding on either side of the unit. The cutter is mounted so it can rotate about its longitudinal axis on a steel saddle, which is bolted to the cutterhead face. Most single disc cutters are 15.5 in. (394 mm) in diameter and are capable of transmitting up to 45 kips (200 kN) of thrust.

Figure 3.4 shows a three-dimensional, cut-away view of a single disc cutter, typical of those manufactured by The Robbins Company. The cutter ring is composed of a high alloy, heat treated steel and is attached to the hub by means of heat shrinking the ring and locking it in position with a welded split ring. The hub rotates on tapered roller bearings that are insulated within the hub by metal-to-metal face seals, known as Caterpillar seals. The inside of the hub is filled with oil to protect and lubricate the moving parts.

Cutters should be distinguished on the basis of where they are located on the cutterhead face. Figure 3.5 shows a profile view of a typical Robbins cutterhead, on which the locations of center, face, and

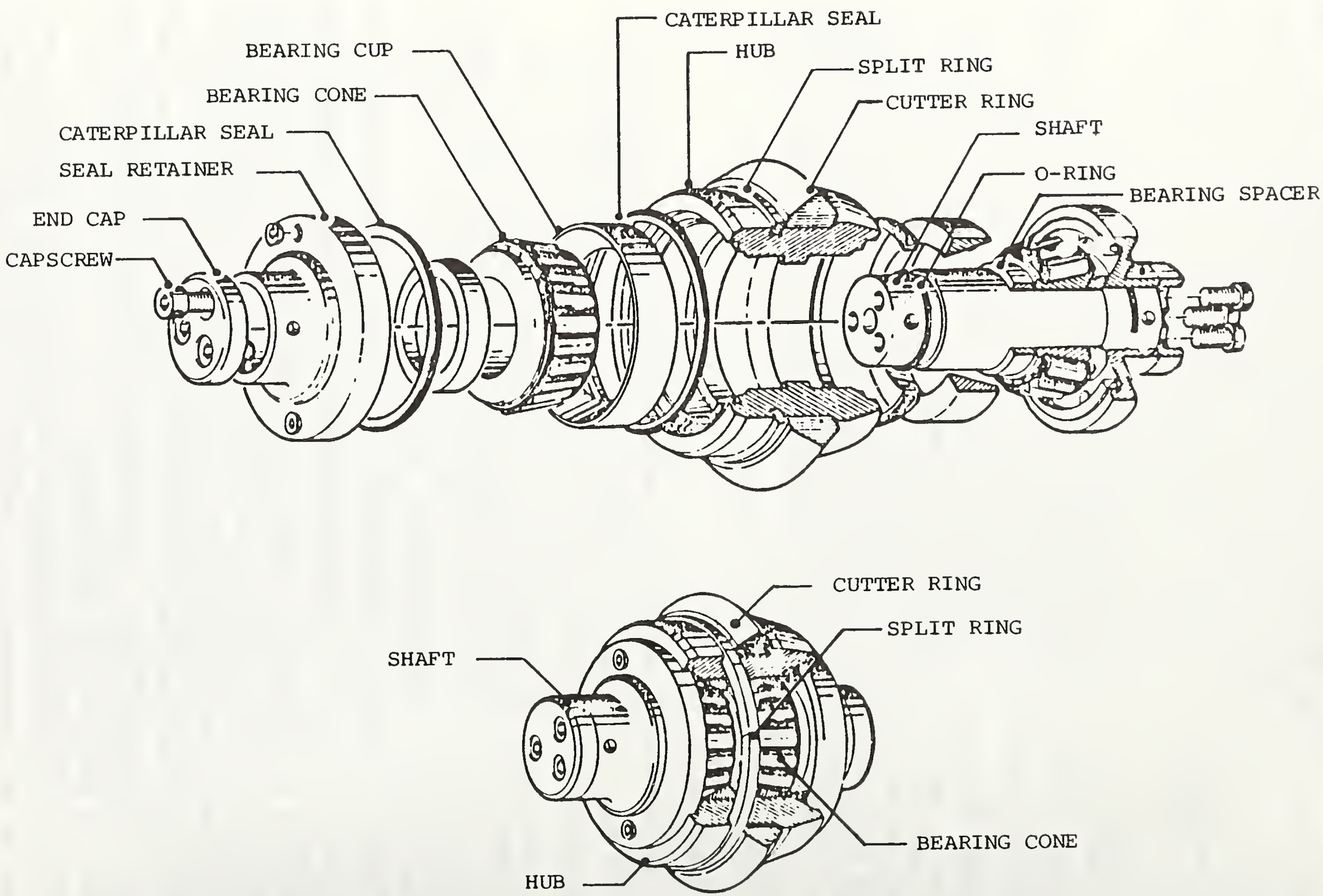


FIGURE 3.4 THREE-DIMENSIONAL, CUT-AWAY VIEW OF DISC CUTTER

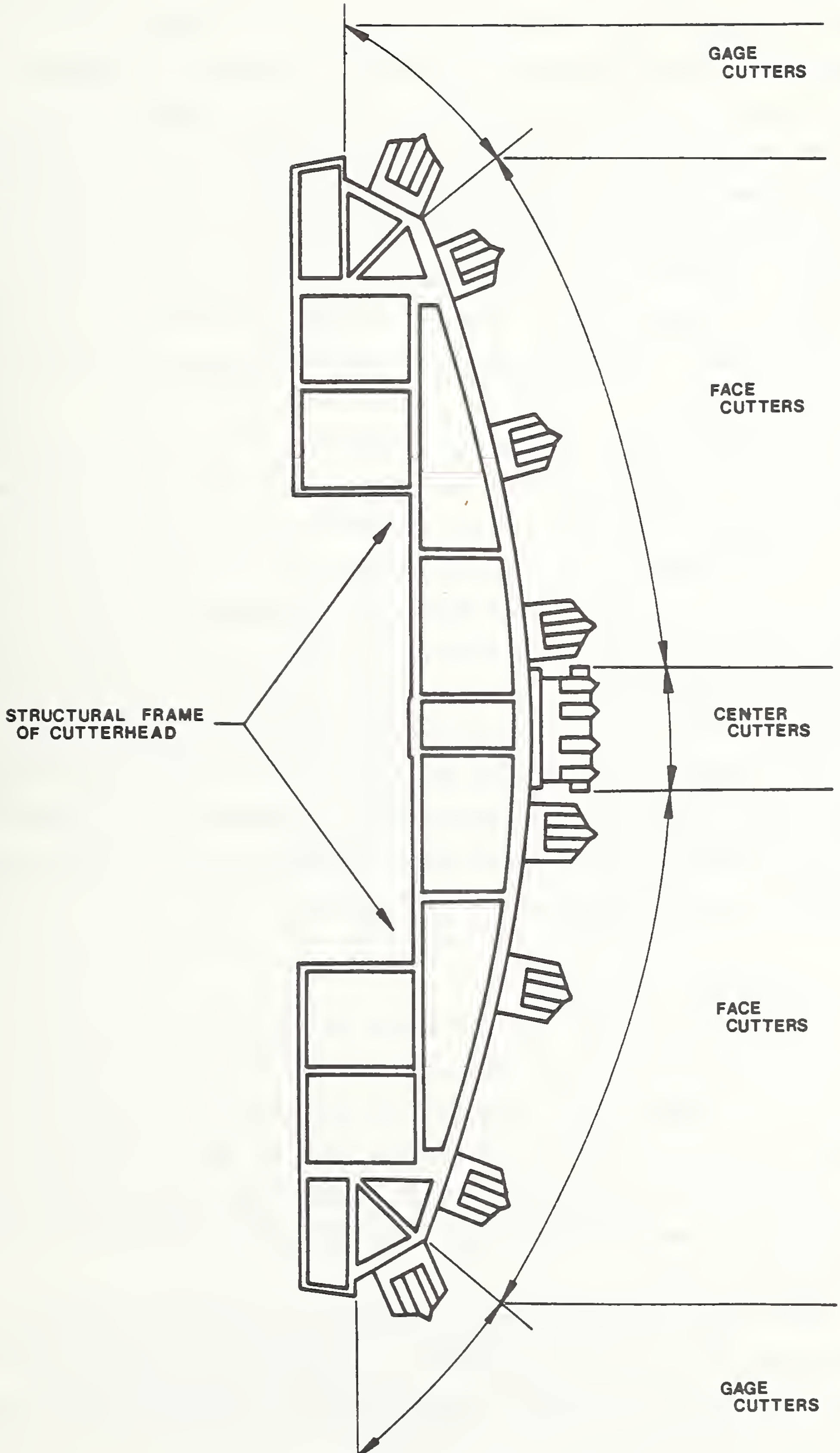


FIGURE 3.5 PROFILE VIEW OF TYPICAL ROBBINS CUTTERHEAD

gage cutters are shown. The four center cutters are normally 12 in. (305 mm) in diameter and are mounted on two twin disc assemblies. The center cutters rotate within the central 12 in. (305 mm) radius of the cutterhead and are, therefore, subject to significant scuffing. The face cutters are generally 15.5 in. (394 mm) in diameter and are located between the center cutters and outer periphery of the face. Robbins machines are typically constructed with a domed cutterhead, and the face cutters tend to be located across the face profile on a line with a constant radius of curvature. The gage cutters are generally 15.5 in. (394 mm) in diameter and are located at the outer portions of the cutterhead where it curves rapidly to form the boundaries of a three-dimensional bore.

The gage cutters derive their name from a term used in the drilling industry to describe drilling tools as setting the "gage" or diameter of a borehole. The gage cutters excavate rock along the tunnel diameter. They are set at increasingly greater angles to the direction of thrust as the transition from face to side excavation occurs. Accordingly, the gage cutters are subject to significant tangential forces acting perpendicular to the rolling direction, and the cutters tend to sustain relatively high levels of wear both from abrasion of the disc ring and damage to the rolling bearings. In contrast to face cutter paths, which are typically separated by a constant 3 in. (76 mm), the distance separating gage cutter paths decreases rapidly with radial distance from the center of the cutterhead.

3.4 PERFORMANCE PARAMETERS

Tunnel boring machine performance is generally measured in terms of progress or advance rate. The major factors contributing to the advance rate are the rate at which the TBM can excavate and the amount of time available for excavation. The advance rate is equal to the product of the penetration rate and the machine utilization. The utilization is the percentage of available shift time during which excavation or rock penetration occurs.

Both the penetration rate and machine utilization depend on the measurement of time. Most TBMs are equipped with a machine clock that records the time during which the machine was actually used to cut, or excavate rock. The machine clock can be activated in several ways that include: 1) exceeding a minimal pressure of 1000 psi (6.9 MPa) in the thrust cylinders, 2) engaging the clutch between the drive trains and motors, and 3) introducing current in the cross-line starting mechanism of the motors. The first two methods were used in the machines studied as part of this work. Although both methods result in a measured time which is longer than the time taken up by boring at full operating capacity, the resulting errors are not likely to be significant. With clutch activation, in which the greatest inaccuracies are possible, the time registered before and after boring at full capacity is generally one to two minutes. This accounts for less than five percent of the time typically required for one forward stroke of the thrust cylinder.

Machine availability represents the percentage of the shift time during which the machine was ready or available for excavation. In this study, the availability is calculated on the basis of time losses incurred through difficulties with the hydraulic equipment, motors and other electrical devices, and general mechanical repair of the machine. The time required to replace cutters or repair minor damage resulting from blocky ground at the face was not included in this determination.

In the case history summaries that follow, TBM performance is investigated by evaluating the penetration rates, machine utilization, machine availability, and advance rates for each tunnel drive on a shift-by-shift and overall average basis. In addition, the causes of downtime are analyzed and the cutter wear is summarized for each position on the cutterhead.

CHAPTER 4

C11 OUTBOUND TUNNEL

4.1 PROJECT OVERVIEW

The Buffalo Light Rail Rapid Transit (LRRT) System is part of a regional scheme to provide transportation and stimulate development in the central business district and adjacent environs of Buffalo, New York. The system is owned and operated by the Niagara Frontier Transportation Authority. Funding for the project is provided by a grant from the Urban Mass Transportation Administration of the U.S. Department of Transportation and by the New York State Department of Transportation. The system will be the first predominantly underground light rail system in North America (Ball, et al., 1981).

As shown in Figure 4.1, development of the 6.4 mile (10.3 km) long system consists of three principal operations. The southernmost 1.2 miles (1.9 km) of the system involves surface construction in the central business district of Buffalo. To the north, the alignment follows Main Street through a 1.7 mile (2.7 km) long section of cut-and-cover construction. The final 3.5 mile (5.6 km) long section continues beneath Main Street as twin tube rock tunnels. The project includes 15 stations. The southernmost six stations are at the surface. Delavan, Humboldt, La Salle, and South Campus Stations are cavern-type excavations developed from rock tunnels driven in advance of station construction. All other stations are built in cut-and-cover excavations.

The principal design consultant and construction manager for the tunnels and stations in rock is Transit and Tunnel Consultants, Inc. and Goldberg-Zoino Associates of New York, P.C., is the general geotechnical consultant for the project. The rock tunnel section was divided into two contracts, the southern C11 Contract and the northern C31 Contract. Construction of the C11 Contract was performed by Fruin-Colnon Corporation of St. Louis, Missouri, as part of the joint venture of Fruin-Colnon, Traylor Brothers and Onyx, Inc.

The C11 Contract involved the construction of two 16.0 ft (4.9 m) internal diameter tunnels, each 10,603 ft (3,232 m) in length. The excavated diameter of the tunnels was 18.5 ft (5.6 m). Figure 4.2 shows a plan view of the contract work that emphasized the outbound tunnel.

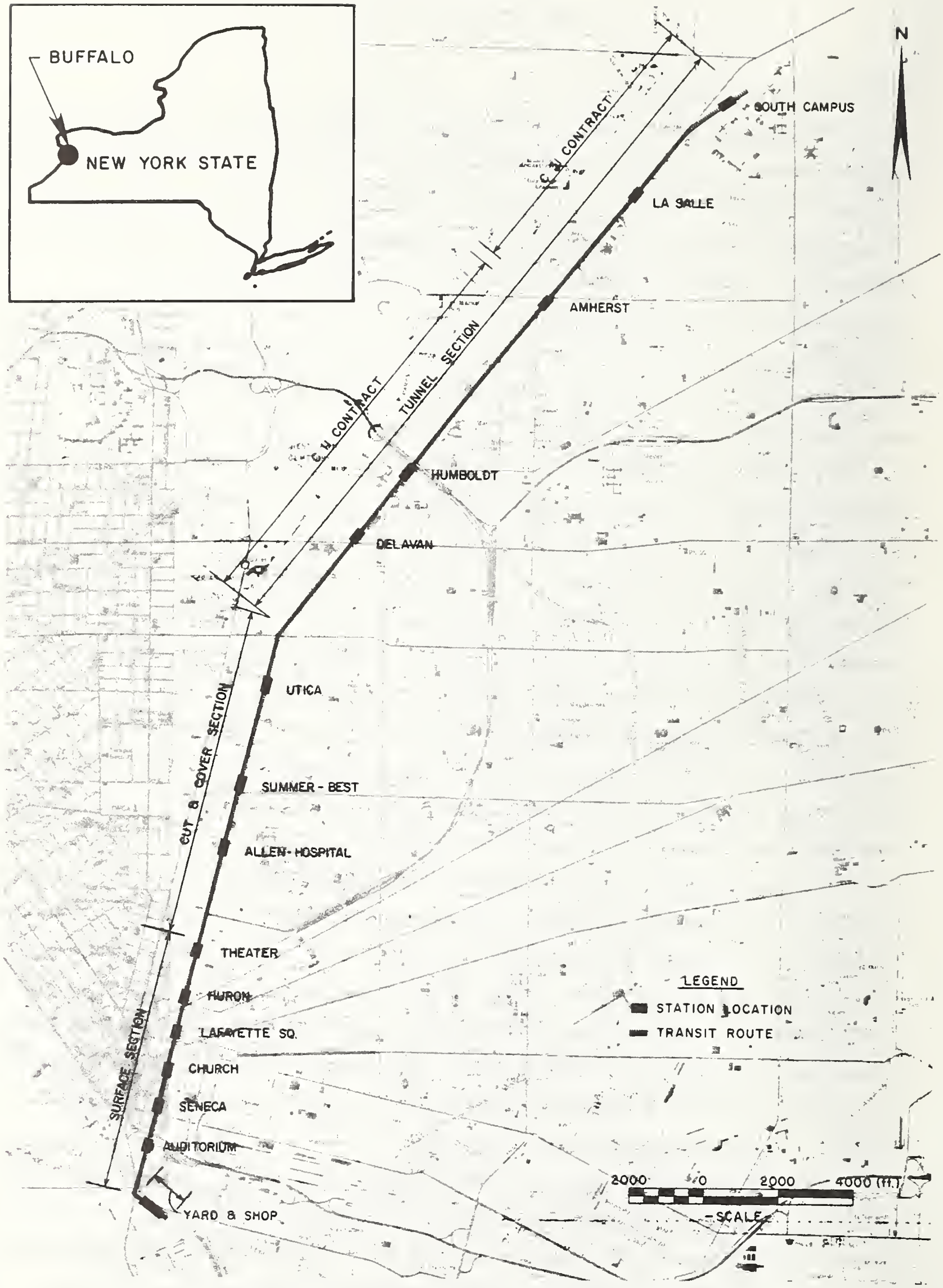


FIGURE 4.1 PLAN VIEW OF THE BUFFALO LRRT

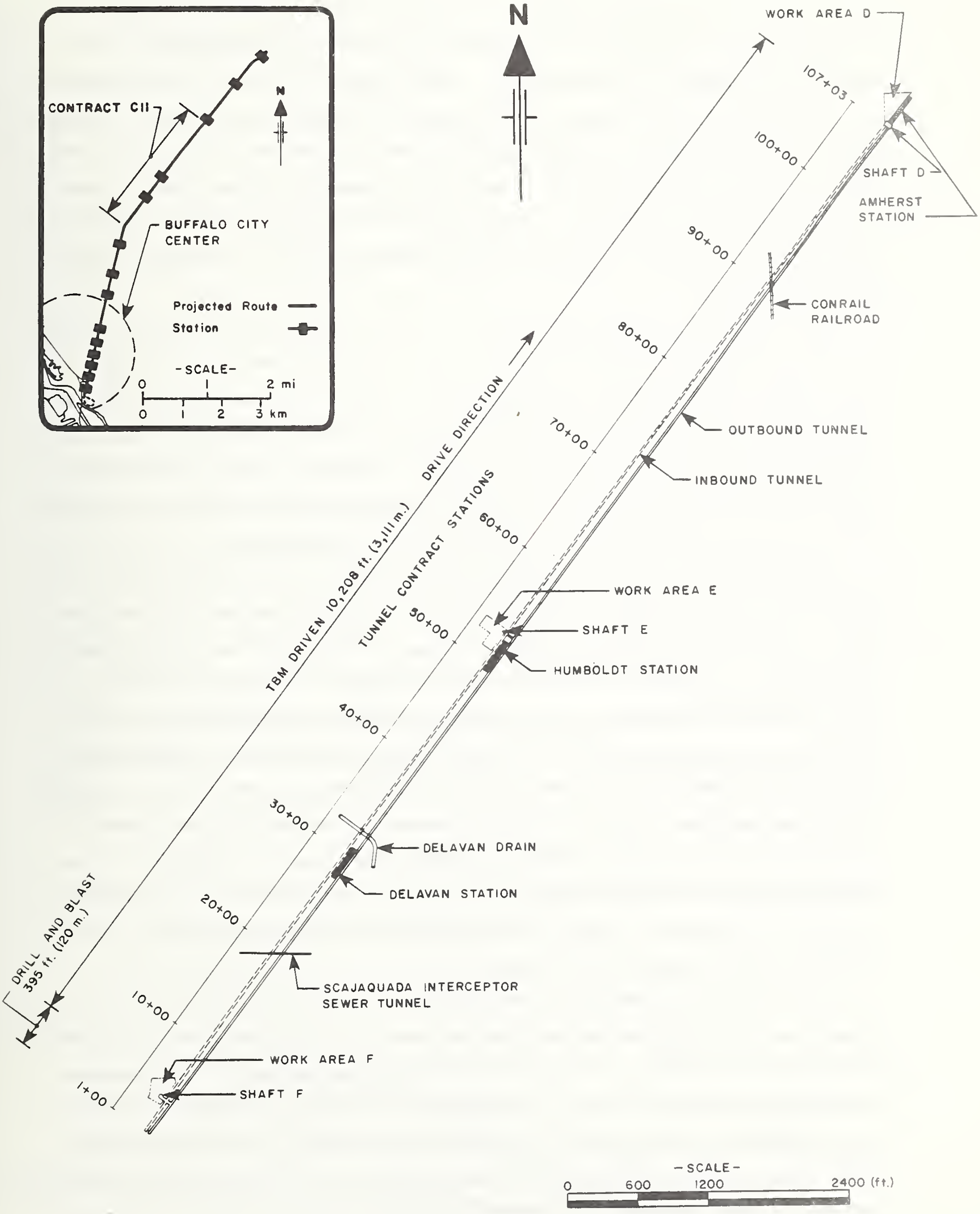


FIGURE 4.2 PLAN VIEW OF CONTRACT C11, BUFFALO LRRT

construction. The inset diagram shows the relationship of the C11 Contract to the entire system. The tunnel stations are drawn to scale along the alignment of the tunnel. Tunnel stations used in this report are in units of feet, conforming with conventional U.S. practice. Work areas, access shafts, and other facilities crossing over the tunnel are shown at their true locations along the alignment and are drawn at an expanded scale for emphasis. The contract work extended from approximately 2800 ft (853 m) south of Delavan Station to the southern end of Amherst Station.

The contractor began at the south end of the contract, at Work Area F, and excavated an access shaft 33 ft (10 m) in diameter to a depth of 82 ft (25 m). The shaft was offset 67 ft (20 m) to the west of the inbound tunnel centerline. An adit from the shaft to the tunnel locations was excavated by drill-and-blast methods. Starter tunnels for the tunnel boring machines and tail tunnels to the southern cut-and-cover section were also excavated by drill-and-blast techniques.

The contract included a shaft at Work Area E, at approximately the midpoint of the contract. The contractor was required to transfer the spoil removal operations to Shaft E after the tunnels were driven past this point. Instead, the contractor installed a rollover-conveyor-bucket elevator system at Work Area F, and Shaft E was used only for maintenance and entry access. Shaft E was 20 ft (6 m) in diameter and 66 ft (20 m) deep. It was offset 29 ft (9 m) to the west of the inbound tunnel centerline. The shaft and a crossover heading to the tunnel alignment were excavated before the TBMs reached this location. A recovery shaft at the future Amherst Station, Work Area D, was excavated with plan dimensions of 35 ft (11 m) by 57 ft (17 m) and used to remove the TBMs after completion of each drive.

Horizontal alignment for most of the contract was set with the tunnels on 75 ft (23 m) centers to maximize rock pillar sizes at Delavan and Humboldt Stations. At the south end of the contract, this spacing was decreased to 30 ft (9 m) to minimize the volume of open cut excavation required in the adjoining cut-and-cover section. At the northern end of the contract, the spacing was reduced to 33 ft (10 m) by moving the outbound tunnel towards the inbound tunnel.

This was done to keep construction for Amherst Station on the west side of Main Street, away from business properties on the east side.

Toward the north end of the contract, the C11 tunnels pass beneath a railroad cut which is part of the Conrail system. The alignment at this location was selected to allow 11 ft (3.4 m) minimum rock cover between the tunnel crowns and base of the concrete abutments for the Main Street bridge over the cut. Rock covers of 7 ft (2.1 m) and 12 to 15 ft (3.7 to 4.6 m), respectively, were provided between the contract tunnels and the Scajaquada Interceptor Sewer and the Delavan Drain Tunnels. Figure 4.2 shows the location of the Conrail cut, and Scajaquada and Delavan Drain Tunnels.

4.2 GEOLOGIC SETTING

The subjurface geology in the Buffalo area consists cf a sequence of glacial deposits of varying thickness overlying a sequence of Lower Paleozoic sedimentary rocks. The rock beds strike approximately east-west and dip southward at about 40 ft/mile (7.6 m/km).

Glaciation of the area was extensive. During the Pleistocene epoch, continental ice sheets advanced from the north, and modified the surface topography. Most of the glacially derived deposits in the Buffalo area are associated with the last ice advance (12,000 to 13,000 years ago), referred to as the Port Huron substage. There were a wide variety of depositional environments near the ice front, and landforms currently found in the area include till sheets, lake and beach deposits, moraines, drumlins, and meltwater channels. The deposits include gravel, sand, silt, and clay and vary from well to poorly graded. Both varved and uniform clays are present. Thicknesses of the deposits often vary with the contours of the bedrock surface topography.

The bedrock in the Buffalo area consists of limestones, dolostones, and shales deposited during the Silurian and Devonian periods. A stratigraphic column of near surface bedrock in the Buffalo area is shown in Figure 4.3. The Onondaga Limestone Formation is often at the top of rock in the Buffalo area. Only the lower member, the Edgecliff, is present in the immediate area of the transit project. The Edgecliff Member varies in thickness from 8 to 20 ft (2.4 to 6.1 m) and is a hard, light gray, coarsely crystalline dolomitic limestone with chert nodules

SYSTEM	SERIES	GROUP	FORMATION	MEMBER	LITHOLOGIC DESCRIPTION*
DEVONIAN			ONONDAGA	EDGECLIFF	8-20 ft (2.4-6.1 m) thick, light gray, coarse texture, slightly fossiliferous LIMESTONE, occasional shale partings, gray CHERT nodules in lower section.
			UNCONFORMABLE CONTACT		
SILURIAN	CAYUGAN		AKRON		6-8 ft (1.8-2.4 m) thick, gray to tan fine-grained DOLOSTONE, medium to massive bedded.
			BERTIE	WILLIAMS-VILLE	5-8 ft (1.5-2.4 m) thick, brown, gray, fine-grained DOLOSTONE, thin to medium bedded.
				SCAJAQUADA	3-10 ft (0.9-3.0 m) thick, gray, medium-grained argillaceous DOLOSTONE, thin to medium bedded.
				FALKIRK	18-25 ft (5.5-7.6 m) thick, dark gray to brown, medium- to coarse-grained DOLOSTONE, massive with thinly bedded, undulating shale partings.
				OATKA	5-8 ft (1.5-2.4 m) thick, dark gray, medium-grained dolomitic SHALE, medium to thinly bedded. May be fissile
		SALINA	CAMILLUS		≃ 400 ft (122 m) thick, gray-green to gray-brown dolomitic SHALE, thin-bedded shale to massive mudstone, layered seams of gypsum and anhydrite.

*Units shown at maximum thickness

FIGURE 4.3 STRATIGRAPHIC COLUMN - BUFFALO LRRT irregularly spaced in the lower section. The rock is slightly fossiliferous and massively bedded. A major unconformity exists between the Onondaga and the older Akron Formation. The Akron is a 6 to 8 ft (1.8 to 2.4 m) thick dolostone that is greenish gray to tan in color. Typically, the unit is massive and fine-grained, with occasional small solution cavities and some secondary mineralization of pyrite and dolomite.

Beneath the Akron Formation is the Bertie Formation. In the Buffalo area, this unit consists of dolostone, dolomitic limestone and dolomitic shale. The total thickness of the Bertie Formation is 35 to 60 ft (10.7 to 18.3 m). Four members have been identified within it. The youngest member, the Williamsville, is 5 to 8 ft (1.5 to 2.4 m) thick and generally appears as a hard, massive, fine-grained dolostone with occasional thin beds of shale separating the massive beds. The next lower unit, the Scajaquada Member, varies from 3 to 10 ft (0.9 to 3.0 m) in thickness and is thin to medium bedded, dark gray, dolomitic shale and argillaceous dolostone. This member is often laminated with thinly spaced bands of dark shale and traces of pyrite. The underlying Falkirk Member, approximately 18 to 25 ft (5.5 to 7.6 m) thick, is a massive, hard, grayish brown to tan, medium to coarse-grained dolostone. Occasionally 3 to 4 in. (76 to 102 mm) thick beds of shale separate the dolostone beds of the Falkirk. The Oatka Member is the oldest of the Bertie Formation. This member has been identified as being 5 to 8 ft (1.5 to 2.4 m) thick, but the lithology is very similar to the underlying Camillus Shale so that the lower contact of the Bertie Formation is difficult to define. The Oatka Member generally consists of medium bedded, moderately hard, dark bluish-gray dolomitic shale and shaley dolostone.

The Camillus Formation underlies the Bertie and was formed during late Silurian time when the northeastern United States was an evaporite basin. In the Buffalo area, the Camillus Formation is a gray green to gray brown, thinly bedded, dolomitic shale to massive mudstone. The unit is approximately 400 ft (122 m) thick and contains occasional zones and pockets of severely weathered and solutioned rock. It also contains thin beds of gypsum and anhydrite.

In places, small terraces and low folds account for variations in the rock dip from as much as 60 ft/mile (11.4 m/km) to as little as 17 ft/mile (3.2 m/km) (Buehler and Tesmer, 1963). Only minor folds and faults are found in this area of western New York. High horizontal in-situ stresses have been measured in the bedrock of the Niagara Frontier area (Palmer and Lo, 1976; Lo, 1978; Kulhawy and O'Rourke, 1981). These high stresses were found in rocks lower in the stratigraphic section than the transit tunnels. Joints are found in all rock units, and are best developed in the shales. Three joint sets, striking at N 75° E, N 40° W and N 5° E, have been identified from outcrop exposures. Most of these joints are vertical, tight with wavy surfaces, slightly weathered with an average spacing of 5 to 18 ft (1.5 to 5.5 m). Occasionally, open joints with rough weathered surfaces have been noted. These are often filled with broken shale and clay.

The site exploration program covering the length of the C11 Contract included 49 NX, 2.13 in. (54 mm) diameter borings on approximately 200 ft (61 m) centers. The percentage of core recovery and Rock Quality Designation (RQD) were determined at the time of exploration. The cores were described, stratigraphic contacts were identified, and laboratory tests were performed by the geotechnical consultants. Average values of the RQD, core recovery, and unconfined compressive strength for each formation are listed in Table 4.1.

The subsurface geology, as interpreted from the site exploration borings, is shown in Figure 4.4. The tunnel alignment has been superimposed on the cross-section. The tunnel is well below the potentially abrasive chert at the base of the Onondaga Formation. In many core borings, the top of the Camillus was gypsiferous or heavily pitted by solution removal of the gypsum. Piezometers and pumping tests showed these zones to be major aquifers (Guertin and Flanagan, 1982). The invert of the tunnel was positioned to avoid the top of the Camillus Shale because of potential water inflow and possible difficulties in maintaining TBM grade in lower strength and fractured rock. The contractor was required to install a deep well dewatering system to maintain the water level at least 2 ft (0.6 m) below the tunnel invert.

Detailed mapping of the tunnel wall geology and of installed sup-

TABLE 4.1 SUMMARY OF AVERAGE PERCENT RECOVERY, RQD, AND UNCONFINED COMPRESSIVE STRENGTH FOR ROCK FORMATIONS IN THE BUFFALO AREA (after Goldberg-Zoino Associates, 1978)

FORMATION	RQD (%)	CORE RECOVERY (%)	UNCONFINED COMPRESSIVE STRENGTH
Onondaga	64	96	25.6 ksi (176 MPa)
Akron	67	95	12.3 ksi (85 MPa)
Bertie	79	98	24.0 ksi (166 MPa)
Camillus	59	84	8.0 ksi (55 MPa)

port was performed as the tunnels were excavated. Maps and support descriptions are included in Appendix A.

4.3 DESCRIPTION OF MACHINE AND MUCKING SYSTEM

The TBM used in the C11 outbound tunnel was manufactured by The Robbins Company of Seattle, Washington, and was designated as Model 186-207. The machine was part of a dual order by the contractor and was identical in design to the TBM used in the C11 inbound tunnel. Figure 4.5 shows a profile and two cross-sectional views of the machine. The figure is drawn to scale and prominent components are labeled.

The machine was 52 ft (15.9 m) long with thrust cylinders retracted, as measured from the front of the cutterhead to the rear of the conveyor assembly. The maximum cylinder pressure was 3,500 psi (24.1 MPa) for a maximum forward thrust of 1,860 kips (8,280 kN). During tunneling the thrust cylinders were operated at an average 2,650 psi (18.3 MPa) pressure, which is consistent with the operating pressure recommended by the manufacturer. Two cutterhead speeds were available at 5.87 and 2.93 rpm. The slower speed was intended for use in difficult ground conditions. The higher speed was used during most of the tunneling. The cutterhead was equipped with 12 muck buckets spaced on equal

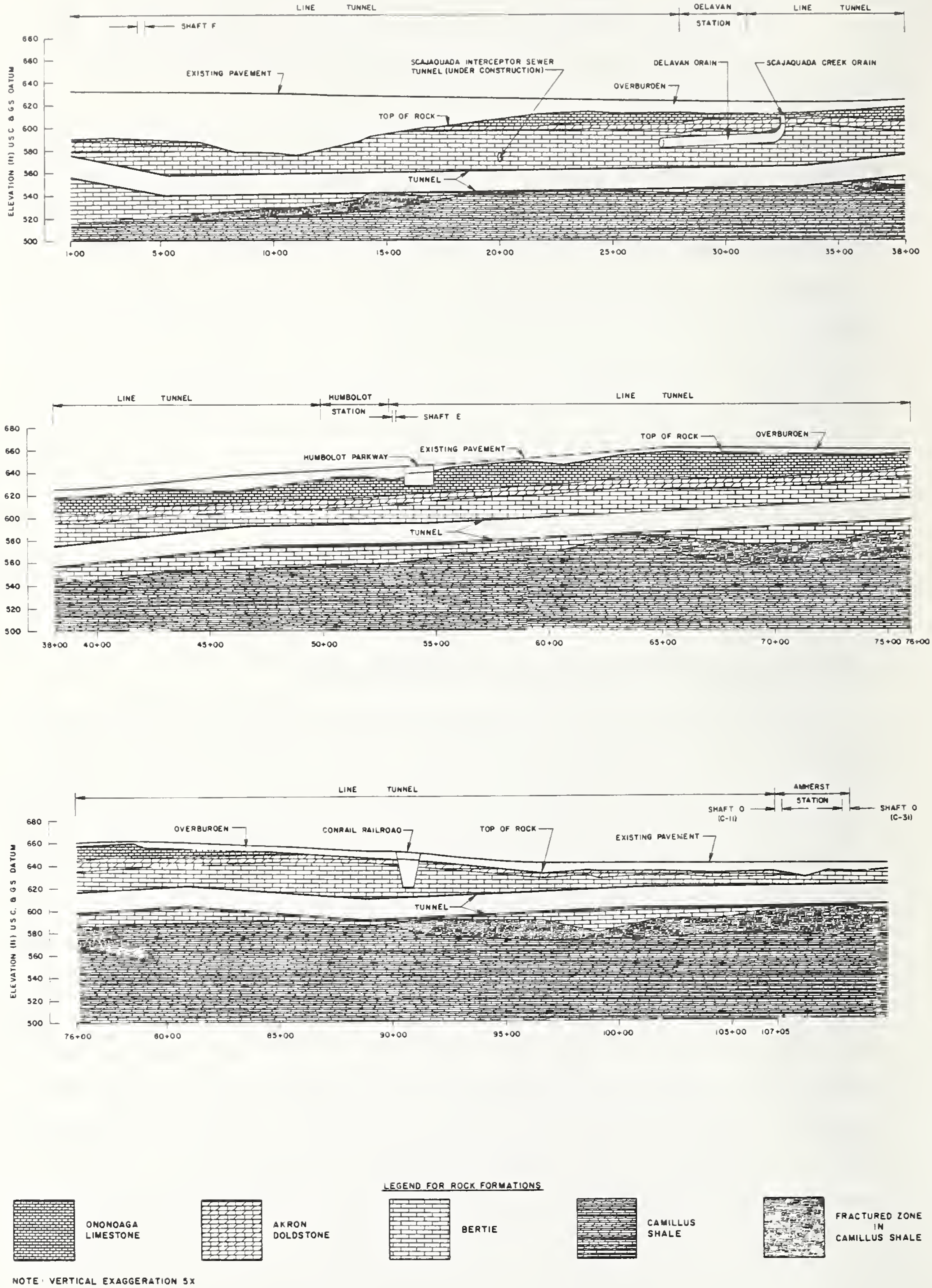


FIGURE 4.4 GEOLOGIC PROFILE FOR CONTRACT C11

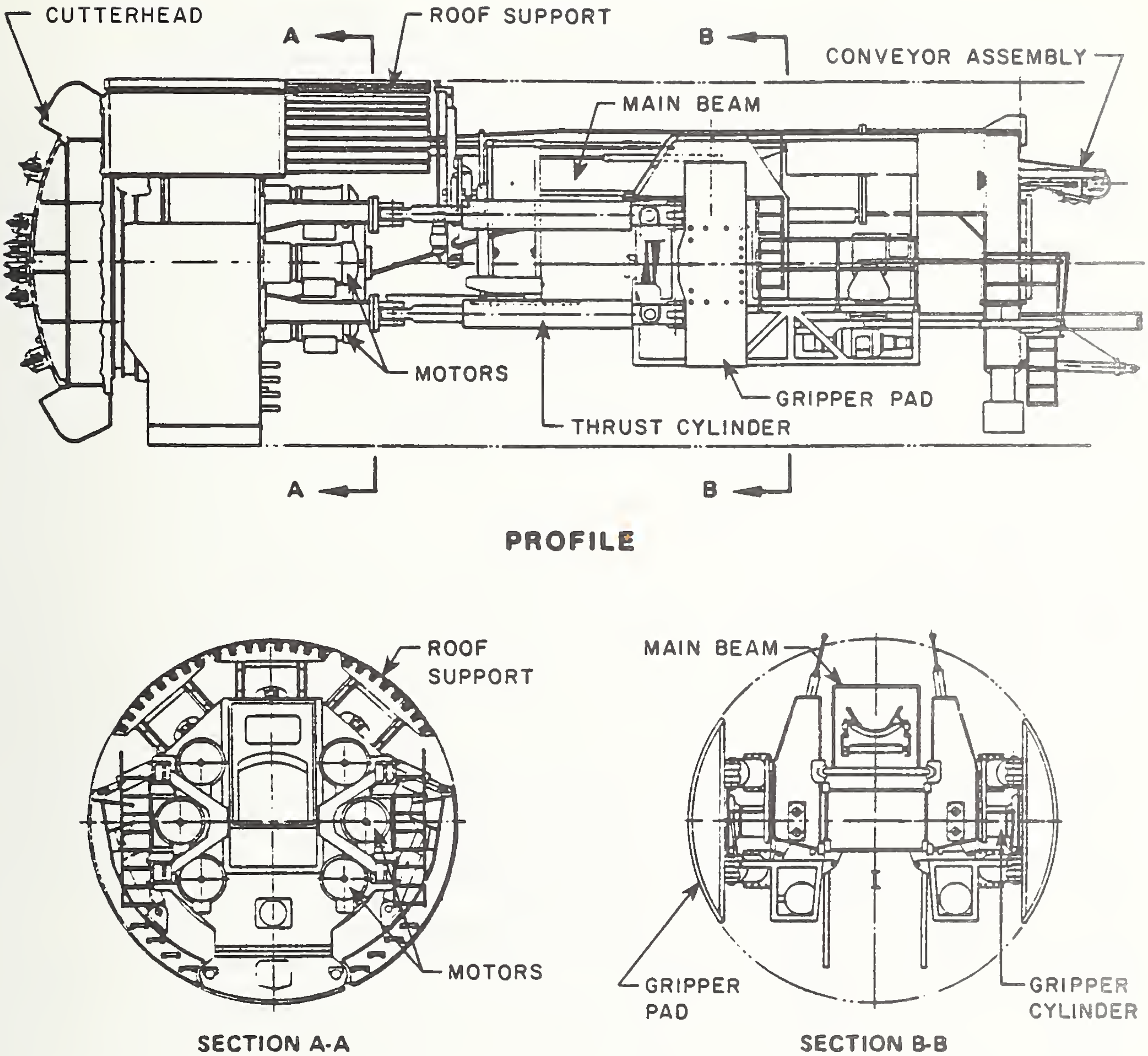


FIGURE 4.5 PROFILE AND CROSS-SECTIONAL VIEWS OF THE C11 OUTBOUND AND INBOUND TBMs

circumferential distances. The muck buckets were designed with scalloped heads to minimize rock jams at the muck intake areas.

Table 4.2 summarizes machine dimensions, components, and operating characteristics. As indicated in the table, the thrust cylinder pressure required to advance the TBM without face contact was measured as

TABLE 4.2 SUMMARY OF DIMENSIONS, COMPONENTS, AND OPERATING CHARACTERISTICS OF THE C11 OUTBOUND TBM

Manufacturer	The Robbins Company, Seattle, Washington
Model Number	186-207
Diameter	18.5 ft (5.6 m)
Length	52.0 ft (15.9 m)
Weight	630 kips (2.80 MN)
Drive Motors	6
Drive Motor Rating	200 hp (149 kW) at 216 amps
Average Operating Amps	not available
Cutterhead Speeds	5.87, 2.93 rpm
Thrust Cylinders	4
Cylinder Diameter	13.0 in. (330 mm)
Stroke Length	5.0 ft (1.5 m)
Maximum Cylinder Pressure	3,500 psi (24.1 MPa)
Average Operating Pressure	2,650 psi (18.3 MPa)
Cylinder Pressure to Move TBM without Face Contact[a]	600 psi (4.1 MPa)
Number and Types of Cutters	38 single disc cutters, 15.5 in. (394 mm) diameter 2 twin disc center cutters, 12.0 in. (305 mm) diameter
Conveyor Belt Width	30.0 in. (762 mm)
Conveyor Belt Speed	374 ft/min (114 m/min)
Conveyor Capacity[b]	560 yd^3/hr (413 m^3/hr)

[b] based on troughing angle of 25 degrees, surcharge angle of 25 degrees, and muck unit weight of 100 lbs/ft^3 (15.7 kN/m^3)

[a] measured with trailing gear in tow.

600 psi (4.1 MPa). This value was determined during tests near the beginning of the drive when the trailing gear was connected to the TBM.

The trailing gear was composed of a series of balanced sleds pulled forward on a track laid directly behind the TBM. The sleds carried the trailing conveyor, fan line, high voltage transformer, and a variety of other mechanical and electrical equipment. The full trailing gear system extended approximately 285 ft (87 m) behind the TBM face where a ramp for train access from the main line track was located. The trailing conveyor was equipped with a deflector arrangement to load trains on either side of the tunnel at a distance of approximately 150 ft (46 m) behind the TBM face. The trailing floor components were manufactured by the Moran Engineering Sales Company of Montebello, California.

Muck was transferred from the trailing conveyor to muck cars by means of a car pass system. The car pass was composed of a pulling and pushing mechanism on opposite sides of the tunnel. Empty muck cars on one side of the trailing gear were automatically pulled forward, disengaged from the train and transferred by means of a sliding track to the opposite side of the tunnel where they were filled. Cars were moved forward successively by the full car pusher to make up a loaded train. The train was taken to the muck shaft by means of a locomotive.

Figure 4.6 shows a three-dimensional view of the shaft mucking equipment. Cars were moved to a rollover bin at Shaft F where the muck was dumped into a 65 yd^3 (50 m^3) hopper. The muck was transferred from the hopper on two vibrating conveyors to a grizzly, which removed rock fragments larger than 6 in. (152 mm) in diameter. Muck from the grizzly was transported by conveyor to a transfer chute and deposited in elevator buckets. The elevator lifted the muck 110 ft (34 m) to ground surface, where it was discharged into a 25 ft (7.6 m) high bin. The design capacity of the shaft mucking system was 415 yd^3/hr (317 m^3/hr), assuming a muck unit weight of 100 lbs/ft^3 (15.7 kN/m^3).

4.4 CONSTRUCTION EVENTS

Figure 4.7 shows a plot of the tunneled distance versus the total project hours for the tunnel crew on the C11 outbound TBM. The figure also shows a simplified tunnel profile and summarizes information on the machine, project, and lithologies encountered in the bore. The format

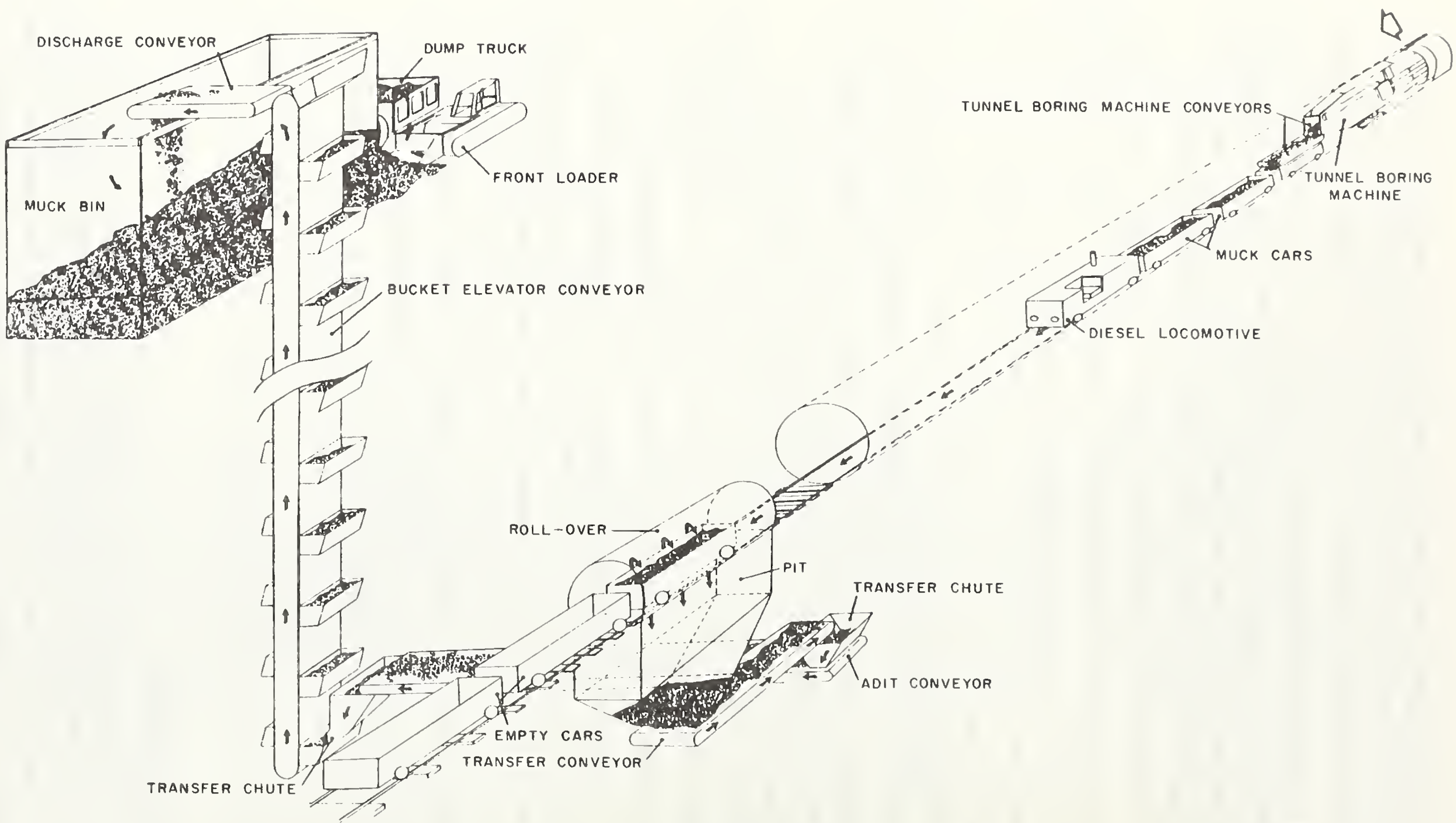
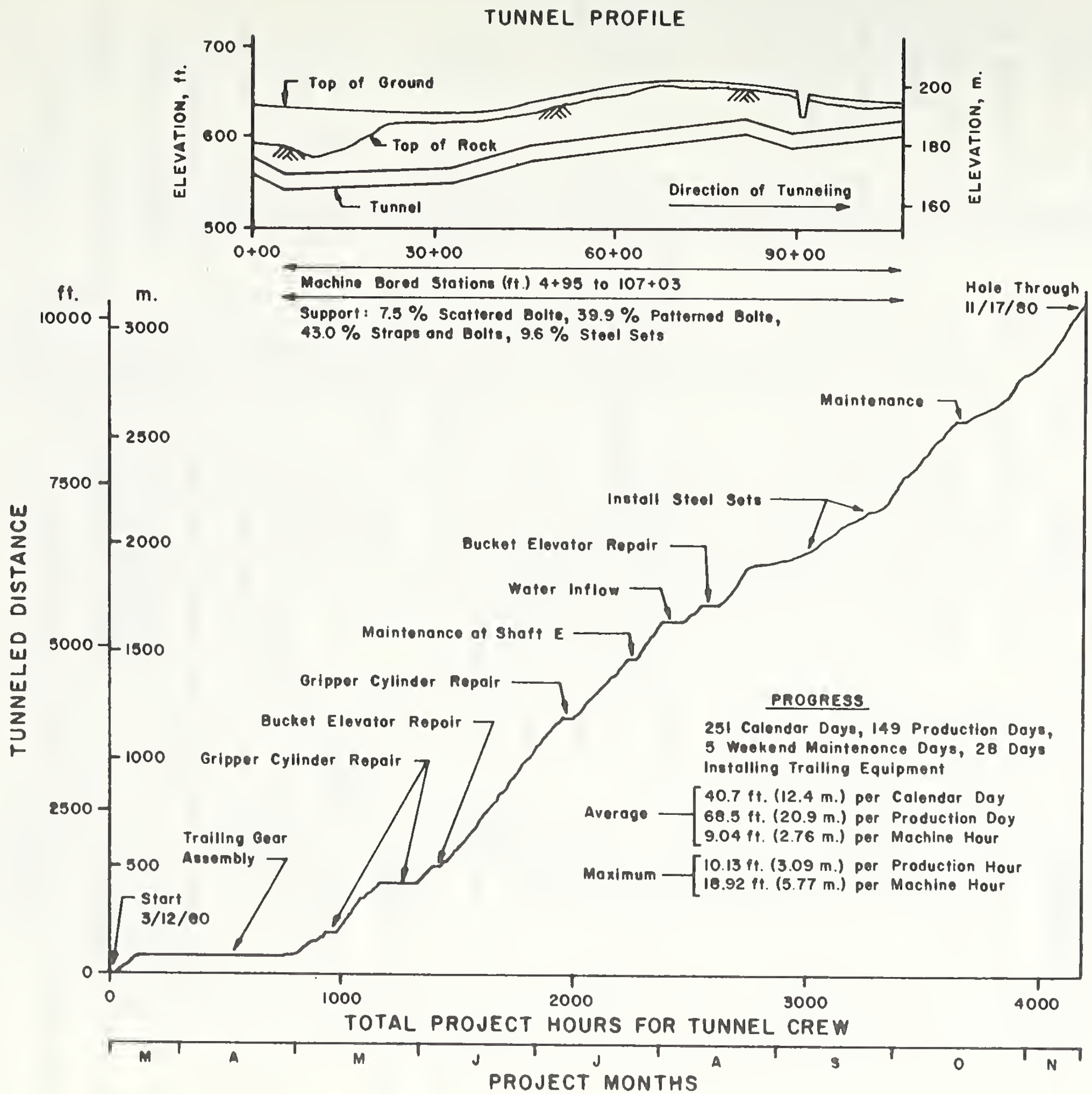


FIGURE 4.6 SHAFT MUCKING SYSTEM FOR CONTRACT C11



MACHINE DATA

Robbins Model 186-207

Diameter 18.5 ft. (5.64 m.)

Length 52 ft. (15.9m.)

Weight 315 tons (2.80 MN)

Max. Thrust 1858 kips (8.27 MN)

Recycle Stroke 60 in. (1.5 m.)

Cutterhead Rotation 5.87 rpm and 2.93 rpm

Cutters 38 15.5 in. (394 mm.) Single Disc

4 12 in. (305 mm.) Single Disc Center

Motors 6 200 hp

PROJECT INFORMATION

10208 ft. (3111 m.) Total Length

Variable Grade: Uphill Max. 1.91 %
Downhill Max. 1.56 %

Muck Loading by Car Pass

Muck Disposal through Shaft by Rollover, Conveyors and Bucket Elevator

Contractor: Fruin-Colnon Corporation

Owner: Niagara Frontier Transportation Authority, Buffalo, New York

LITHOLOGY

Dolostone and Dolomitic Shale, Unconfined Compressive Strengths from 6 ksi (42 MPa) to 47 ksi (320 MPa)

FIGURE 4.7 TUNNELED DISTANCE VERSUS CUMULATIVE PROJECT HOURS AND PROJECT INFORMATION FOR THE C11 OUTBOUND TUNNEL of this figure is similar to that used by the U.S. Bureau of Reclamation, which serves as a standard reference base for TBM-driven tunnels owned by that agency (U. S. Bureau of Reclamation, 1974).

Figure 4.8 summarizes the advance rate, utilization, availability, and penetration rate as a function of tunnel station in histogram form. Each horizontal line segment of the histogram plots corresponds to one shift. The length of the line segment is proportional to the distance tunneled during the shift. Each line segment is plotted above the graph abscissa at a distance proportional to the value of the performance parameter calculated for the shift. The utilization and penetration rates were calculated on the basis of machine boring time determined from the resident engineer shift reports. If tunneling delays at a given station were longer than the duration of a shift, the performance parameters at that station are equal to zero, and the plot appears as a vertical line intersecting the horizontal axis. The causes and durations of major delays are listed at the stations where they occurred in the plot of penetration rate versus distance. Figure 4.8 also shows a simplified illustration of the geologic profile as mapped in the excavated tunnel and the types of initial support used at various locations in the tunnel. A detailed record of the geology with stratigraphic identifications, joint planes, overbreak and support is given in Appendix A.

In combination, Figures 4.7 and 4.8 provide a summary of the tunneling events and TBM performance referenced by the cumulative hours and distance tunneled. They index shift time and tunnel station for the discussion of construction events that follows.

The work schedule consisted of a five day week. Initially, the shifts were of 8.0, 7.5, and 7.0 hour durations but, beginning 12 May 1980, the contractor ran 8.5, 8.0, and 7.5 hour shifts.

The TBM was assembled in Work Shaft F at the south end of the contract and was advanced through a drill-and-blast tunnel to Station 4+95. Starting on 12 March, the TBM excavated 274 ft (84 m) to Station 7+69, where production was halted on 20 March 1980 to allow erection of the trailing sleds and muck handling equipment. While the mucking gear was being assembled, all six TBM cutterhead motors were returned to the manufacturer, repaired, and reinstalled. In addition, the rollover,

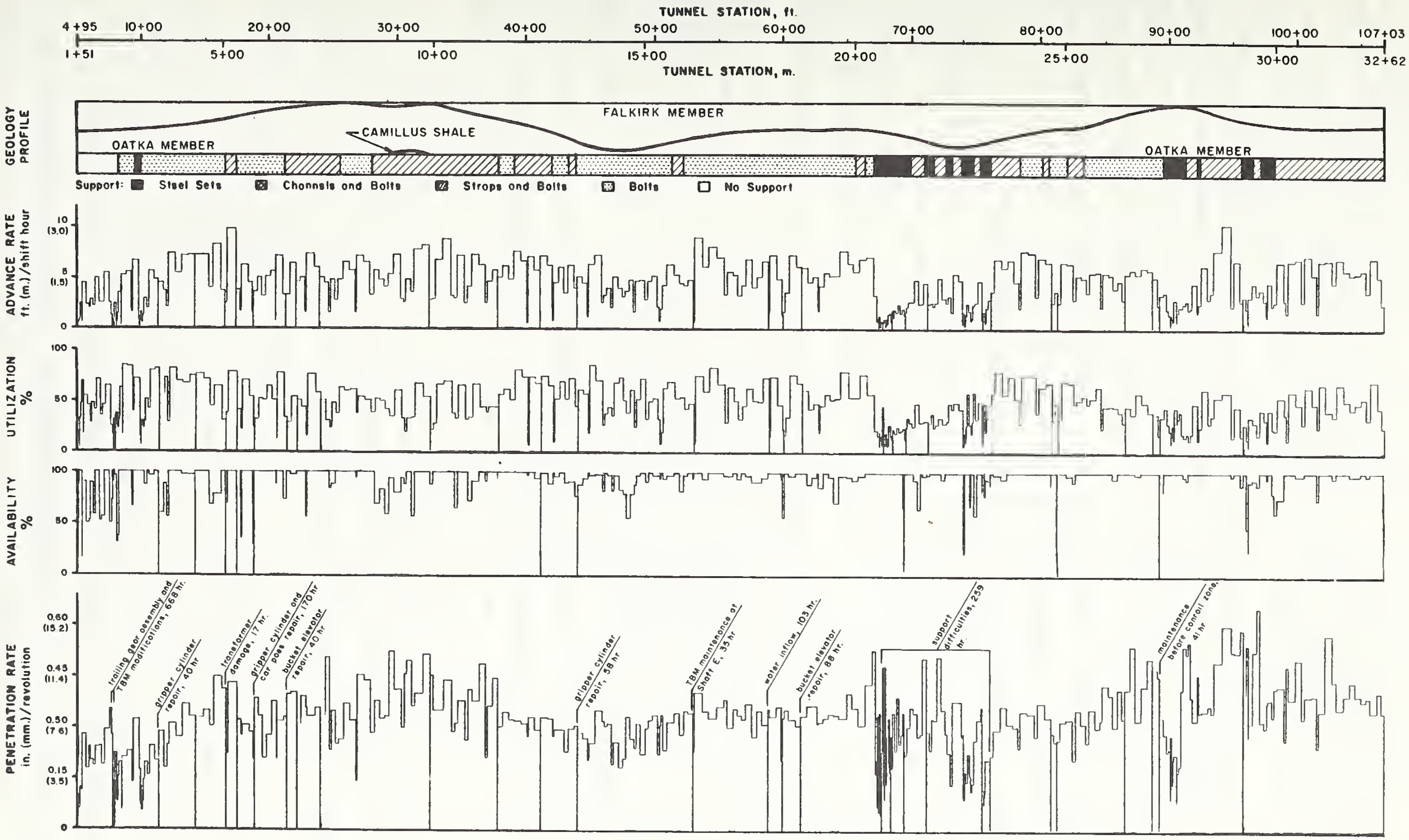


FIGURE 4.8 TBM PERFORMANCE RECORD, TUNNEL GEOLOGY, AND SUPPORT FOR THE C11 OUTBOUND TUNNEL

conveyors, and bucket elevator at Shaft F were installed, and assembly of the inbound TBM was started. In total, 28 working days were spent on these activities, and this delay is labelled on Figures 4.7 and 4.8.

On 23 April 1980, boring was started again. The next 16 shifts were used for trial runs and final adjustments of the mucking equipment. On 30 April 1980 at Station 7+84, shakedown of the equipment was finished and tunneling with the complete excavation system was begun. Most of the downtime from Stations 7+84 to 53+03 was associated with gripper repair, car pass system repair, and cutter changes. The right gripper cylinder developed leaks three times at Stations 11+13, 18+81, and 44+11. Each of these appear as horizontal portions of the plot in Figure 4.7. Car pass problems were sporadic and mainly associated with the full car pusher. At Station 21+39, production was stopped for five shifts to repair the bucket elevator. In addition to mechanical downtime, progress was halted for one shift at Station 24+00 because of water inflow from the tunnel invert. Water depth at the heading reached a maximum of 18 in. (0.46 m) before it was controlled.

At Shaft E, Station 53+03, tunneling was stopped for five shifts. During this time, 24 cutters were changed and maintenance was performed on the TBM and mucking equipment. During the last week in July, heavy inflows of groundwater were encountered in the inbound tunnel. Over the first weekend in August, the deep well dewatering system and pumps failed, resulting in flooding of both tunnels and the mucking area at Shaft F. At this time, the outbound tunnel heading was at Station 58+85. Water reached a maximum depth of 8 ft (2.4 m) at the lowest point in both tunnels. The outbound tunnel heading was not flooded since the TBM was located upgrade. Further details on the effects of the flooding are included in the discussion of inbound tunnel construction events in Chapter 5. Excavation in the outbound tunnel was stopped for 13 shifts to remove the water and lower the groundwater table with a deep well system. The TBM crew performed various maintenance tasks including car pass system repair, cutter changes, and rerouting the ventilation line to Shaft E. After an additional 17 ft (5 m) of excavation to Station 60+02, a 12 hour loss of electrical power caused Shaft F to be flooded again. The contractor stopped all tunneling operations on 13 August 1980 at Station 61+46 to repair the shaft mucking equipment which was damaged by the flooding. Rollover and conveyor motors had to be replaced, conveyor bearings were changed, and belt splices were required. The elevator buckets and chain guides had also been damaged and required repair or replacement.

Between Stations 67+33 and 76+21, many areas were encountered in which steel sets were used for initial support. Of the total 888 ft (271 m) in this section, 510 ft (155 m) were supported by full circumferential steel sets (WF 6x25) on 4 to 5 ft (1.2 to 1.5 m) centers. When mining these areas, the TBM was operated at a reduced thrust pressure and often at the slower cutterhead rotation rate of 2.93 rpm. The reduced advance rate shows up both in Figure 4.7, as an area of diminished slope, and in Figure 4.8, as groups of short, narrow histogram cells. In addition to time losses caused by steel support installation, the excavation system was also down for car pass system repair and repair of the Shaft F and TBM conveyors.

Tunneling was stopped at Station 89+47 on 15 October 1980, before excavation beneath the Conrail tracks and the Main Street bridge abutments. During the next seven shifts, the heading was stocked with rock support materials and maintenance was performed on the TBM. At this time, repairs were also made on the car pass system and the bucket elevator guiderails. To protect the surface structures, the contractor was required to mine continuously between Stations 89+52 and 91+37 and install bolts, straps and steel sets. Fourteen shifts were required to mine through this section.

Between Stations 95+71 and 98+25, steel sets were used in two areas for a combined distance of 190 ft (58 m). Muck jams occurred in the TBM main beam at these locations and the TBM conveyor was replaced. Over the last 1,500 ft (457 m), car pass difficulties and train delays were the principal causes of downtime.

In summary, tunneling for the C11 outbound tunnel commenced on 12 March 1980 and ended on 17 November 1980. The tunneling required 251 calendar days, of which 149 were production week days. A distance of 274 ft (84 m) was mined before trailing gear was installed, and 9,934 ft (3028 m) were mined with the trailing gear was installed, and 9,934 quired to drive the tunnel was 3,516 hours (441 shifts), of which 122 hours (16 shifts) were worked before trailing gear installation. An additional 668 hours (89 shifts) were required for trailing gear and shaft mucking equipment assembly.

4.5 TUNNELING PERFORMANCE

Table 4.3 summarizes the average advance rate, utilization, availability, and penetration rate for the outbound tunnel of Contract C11. The average advance rate and utilization were calculated on the basis of the cumulative project hours from Station 7+84 to holing through of the TBM at Station 107+03. The time before and during mucking equipment assembly and the time used to perform trial runs were not included in the calculations. These averages include the time devoted to maintenance and preparation at both Shaft E and before tunneling beneath the Conrail tracks and Main Street bridge abutments. The average penetration rate and utilization were calculated in the same manner as the individual shift penetration rates and utilizations by using the boring time from the resident engineer shift reports.

In general, utilization was low in sections where steel supports were installed. Sustained high values of utilization generally correlated with sections where the mucking system was in good working order and the rock was unweathered and contained few fractures.

The penetration rate was influenced primarily by two factors: 1) the relative amounts of the Falkirk and Oatka Members at the face, and 2) the degree of jointing and weathering of the rock, particularly in areas requiring steel sets for support. Highest penetration rates were achieved when the face was mostly in the Oatka Member. This unit is more thinly bedded with higher joint frequency than the Falkirk Member. The contrast in penetration rate associated with each member is shown in Figure 4.8, where the average penetration rate through a nearly full face of the Oatka Member between Stations 27+00 and 37+00 is approximately 33 percent greater than the average penetration rate through a nearly full face of the Falkirk Member between Stations 42+00 and 52+00. After Station 65+00, comparisons of penetration rate solely on the basis of rock unit become increasingly more difficult because of variations in the degree of weathering, joint frequency, and type of support. The penetration rate was highly variable at many locations where steel sets

TABLE 4.3 AVERAGE ADVANCE RATE, UTILIZATION, AVAILABILITY, AND PENETRATION RATE FOR THE C11 OUTBOUND TUNNEL

PARAMETER	AVERAGE VALUE
Advance Rate	2.9 ft/hr (0.88 m/hr)
Utilization	32.0 percent
Availability	84.9 percent
Penetration Rate	9.2 ft/hr (2.8 m/hr) 0.31 in./revolution (7.9 mm/revolution)

were installed. In particular, this variation is shown by the sharp fluctuations in rate between Stations 66+90 and 76+12.

Availability of the TBM was limited principally by two factors: 1) repairs on the right gripper cylinder, and 2) repair of the TBM conveyor. Availability was low at the start of the tunnel, primarily because of clogged water nozzles on the cutterhead and break-in maintenance of the new machine.

4.6 DOWNTIME ANALYSIS

Table 4.4 summarizes the delay, or downtime, associated with various components of the C11 outbound tunneling. Four general categories have been used to group the individual causes of delay. These categories include: 1) repairs and maintenance of the TBM, 2) repairs and interrupted operation of the backup equipment, 3) delays from ground conditions requiring special support or interfering with the normal use of the machine, and 4) delays from causes that were not recorded on a consistent basis for all jobs or could not be distinguished as belonging to a specific part of the tunneling system. A discussion of downtime categories and a detailed description of tunneling delays is given in

TABLE 4.4 TABULATION OF DOWNTIME AS A PERCENTAGE OF TOTAL SHIFT HOURS FOR THE C11 OUTBOUND TUNNEL

TBM Maintenance and Repair	Percentage Downtime	Backup System	Percentage Downtime	Ground Conditions	Percentage Downtime	Additional Items	Percentage Downtime
Cutter Change	2.6	Power Supply	0.3	Water Inflow	3.4	Stroke Recycle	3.9
General Maintenance and Inspection	4.2	Cable Utilities Fanline	1.5	Steel Sets	11.3	Shaft Downtime	1.0
Lube Oil	0.9	Survey	0.1	Bolts/Straps	1.7	Methane Probe	not used
Hydraulics	8.2	Car Pass	3.5	Bolt Drill Repair	0.6	Other (Shift changes, Supplies, Blasting, Special Delays, etc.)	4.7
Motors	0.3	Tripper	not used	Scaling/ Rock Jam	1.1		
TBM Conveyor	1.5	Trailing Gear Conveyor	0.5	Gripper Difficulty	0.2		
Electrical	1.6	Train Delay	5.4	Clearance	0.1		
		Shaft Operations	6.7				
		Laying Rails	0.8				
		Derailment	1.9				
Subtotal	19.3	Subtotal	20.7	Subtotal	18.4	Subtotal	9.6

TOTAL PERCENTAGE DOWNTIME 68.0

Appendix B. The downtime percentages were calculated on the basis of the project hours, excluding time before and during the assembly of the trailing gear.

Figure 4.9 shows the downtime percentages in the form of a pie chart. Approximately 68 percent of the shift hours was spent on delays resulting in an average machine utilization of 32 percent.

The major cause of downtime under the general category of TBM maintenance and repair was related to the hydraulic system. A total of 8.2 percent of the shift time was spent on hydraulic repairs, of which 7.5 percent was devoted to the repair of leaks in the right gripper cylinder.

Shaft operations and car pass difficulties were principal causes of downtime under the general category of backup systems. Repairs of the shaft mucking system led to a loss of 6.7 percent of the shift time,

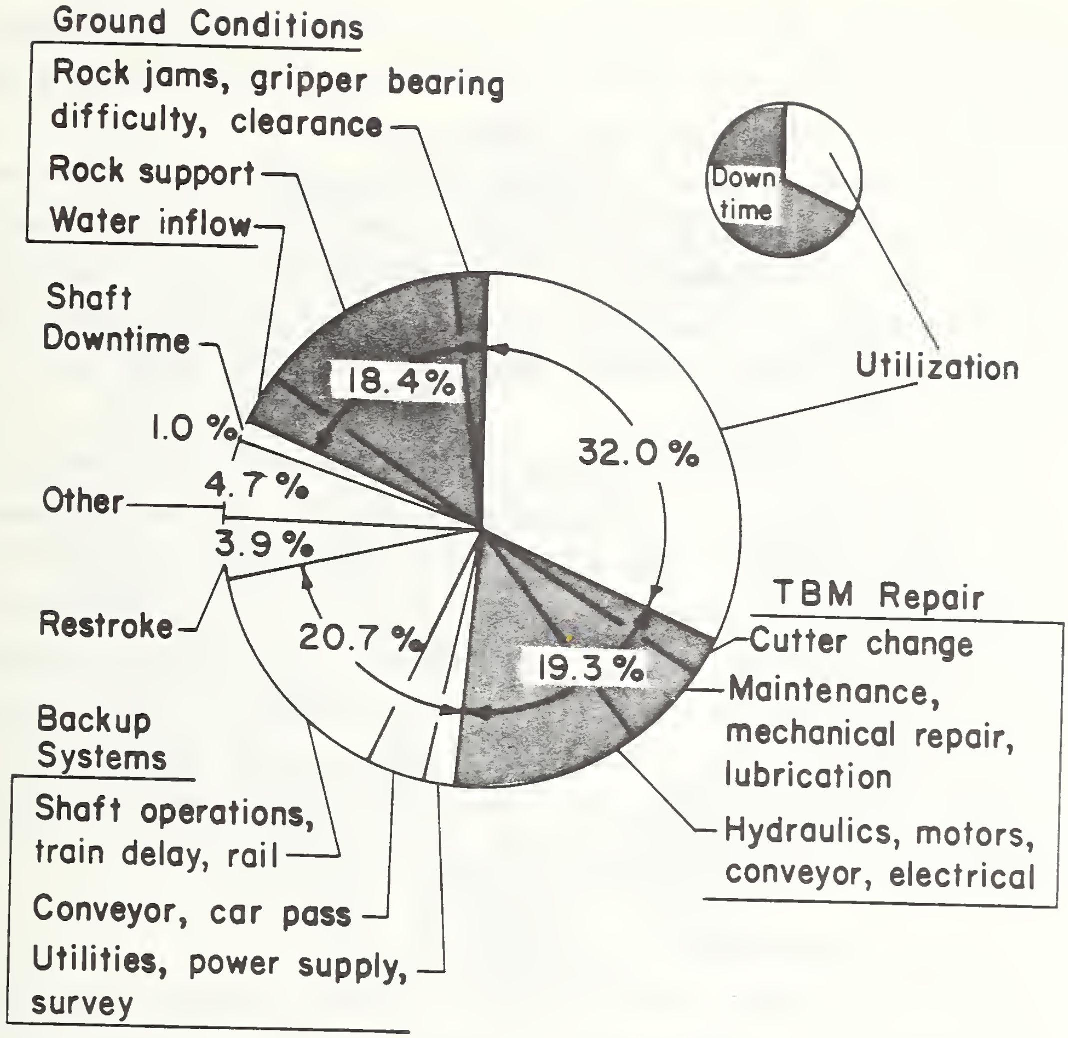


FIGURE 4.9 SUMMARY OF DOWNTIME AS A PERCENTAGE OF TOTAL SHIFT HOURS FOR THE C11 OUTBOUND TUNNEL

with most of the delay caused by the bucket elevator. Car pass problems required 3.5 percent of the shift time, the greatest part of which was spent on repairs of the full car pusher and sliding track mechanism.

The downtime associated with ground conditions was principally related to the installation of steel sets, which accounted for 11.3 percent of the shift hours. In some sections where steel sets were installed, rock jams at muck intake areas of the cutterhead and the scaling of loose rock along portions of the crown caused additional delays. Adequate gripper reaction was difficult to achieve at locations of significant springline overbreak. In total, the percentage downtime related to steel sets, rock jams, scaling, gripper difficulties and clearance of trailing gear components was 12.7 percent.

The category of "shaft downtime" includes scheduled downtime at Shaft E. The category of "other" covers downtime for shift changes, waiting for dust to clear so the laser could be read, and bringing supplies such as utility line segments, rock bolts, and steel sets to the heading. Shift changes were the principal cause of delay in this category.

Causes of downtime frequently were interrelated. For example, water inflow had indirect consequences, particularly on the rollover conveyors and the lower part of the bucket elevator in Shaft F. The relatively high percentage downtime for shaft operations includes repairs partially caused by damage from flooding. In a similar fashion, mechanical difficulties with the car pass system led to difficulties in the coordination of muck trains traveling to and from the heading. Accordingly, problems with the car pass equipment contributed indirectly to downtime associated with train delays.

4.7 CUTTER CONSUMPTION

Figure 4.10 shows a front view of the TBM cutterhead on which each cutter position is designated by a number. Numbers 32 through 42 refer to gage cutters and 1 through 31 refer to face cutters. Single disc, 15.5 in. (394 mm) diameter cutters were used at the positions shown by numbers 5 through 42 and twin disc, 12 in. (305 mm) diameter cutters were used at the center positions.

A total of 63 cutters were changed over the 10,208 ft (3,111 m) of tunnel bore. Cutters needing repair were transported to a shop located on site, where rings were replaced and hubs reconstructed. No records were available on the type of repairs made.

Figure 4.11 summarizes information regarding the number and location of replaced cutters. Cutter changes are referenced according to tunnel station. The replacements are shown in histogram form for all but six cutters. Twenty-four cutters were changed at Shaft E during scheduled maintenance. The remaining 39 cutters were changed in the tunnel. The contractor changed cutters at a rate of one cutter per 1613

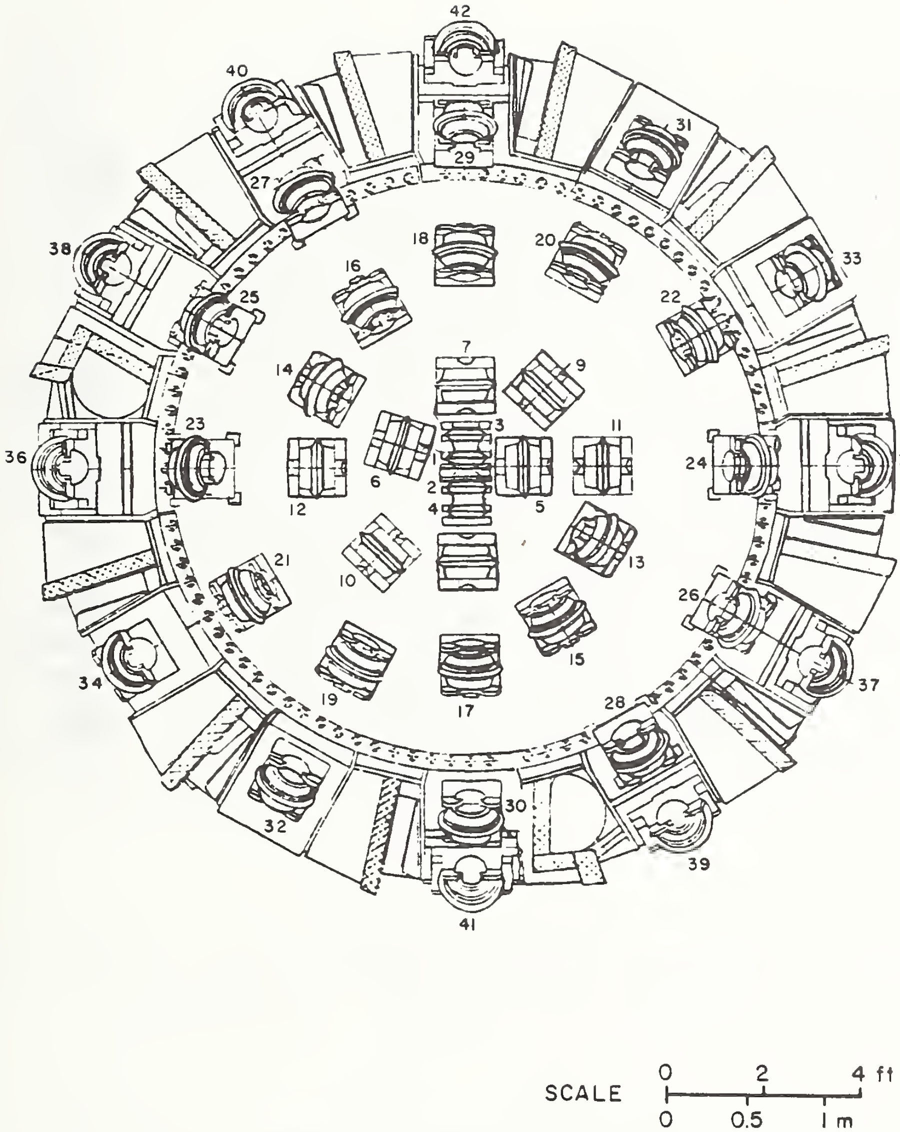


FIGURE 4.10 VIEW OF CUTTERHEAD FACE OF THE C11 OUTBOUND AND INBOUND TBM

yd^3 (1,233 m^3) of excavated rock. Of the 57 identified changes, 15 replacements were for gage cutters.

4.8 SUMMARY

From the time the TBM was installed, excavation of the C11 outbound tunnel required 4,184 shift hours, of which 668 were spent on trailing

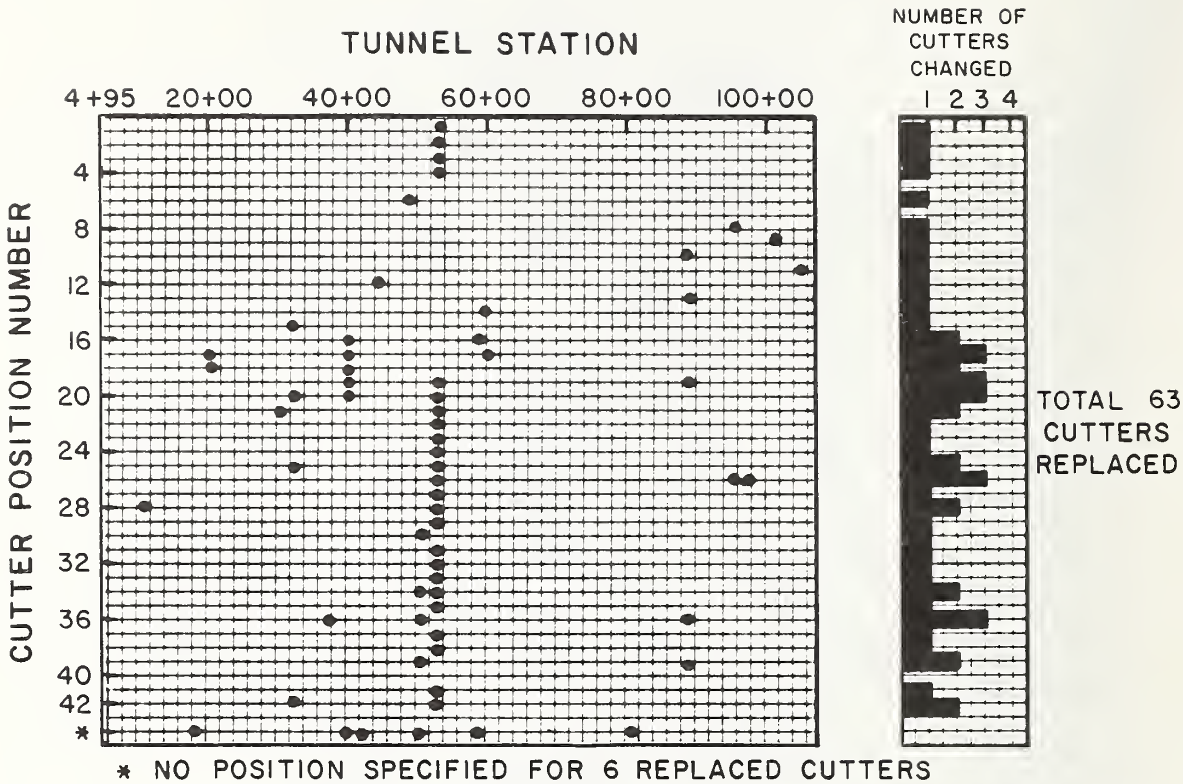


FIGURE 4.11 SUMMARY OF REPLACED CUTTERS, NUMBER OF CHANGES, AND LOCATION ON CUTTERHEAD FACE FOR THE C11 OUTBOUND TBM

gear and shaft mucking equipment assembly. Excluding the time before and during the construction of trailing gear and mucking equipment, the average advance rate was 2.9 ft/hr (0.88 m/hr) for 9,919 ft (3,023 m) of tunnel. The overall TBM utilization was 32 percent.

Major geologic controls on tunneling performance included the presence of heavily jointed rock and high water inflows. The erection of steel support was often accompanied by difficulties with rock jams at the muck intake areas of the TBM, scaling, gripper reaction, and clearance of the trailing gear components. Penetration rates were influenced by the relative amounts of Falkirk and Oatka Members at the face. Relatively high penetration rates were achieved when the face was mostly composed of the Oatka Member. The penetration rate was highly variable in jointed rock where steel supports were used.

Major mechanical causes of downtime included repairs of the shaft mucking equipment, car pass problems and hydraulic repairs of the TBM. Causes of downtime frequently were interrelated as is evidenced by the shaft mucking equipment, which was damaged in part by flooding.

A total of 63 cutters were changed. There was no significant difference in the average number of changes per gage cutter as opposed to face cutter.

CHAPTER 5

C11 INBOUND TUNNEL

5.1 PROJECT OVERVIEW

The C11 inbound tunnel is part of the twin tube construction for Contract C11 of the Buffalo LRRT. Figure 5.1 shows a plan view of the contract work that emphasizes the inbound tunnel. The inset diagram shows the relationship of the C11 Contract to the entire system. The tunnel stations are drawn to scale along the alignment of the tunnel. Work areas, access shafts, and other facilities crossing over the tunnel are shown at their true locations along the alignment and are drawn at an expanded scale for emphasis.

Descriptions of the Buffalo LRRT, tunnel alignment and regional and local geology are included in Chapter 4.

5.2 DESCRIPTION OF MACHINE AND MUCKING SYSTEM

The TBM used in the C11 inbound tunnel was manufactured by The Robbins Company of Seattle, Washington, and was designated as Model 186-206. The machine was part of a dual order from the contractor and was identical in design to the C11 outbound TBM. Table 5.1 summarizes machine dimensions, components, and operating characteristics. The average operating pressure for the thrust cylinders over the entire tunnel was 2,550 psi (17.7 MPa), which is slightly smaller than the average pressure used on the C11 outbound TBM. As indicated in the table, the thrust cylinder pressure required to advance the TBM without face contact was measured as 270 psi (1.9 MPa). This value was determined during tests near the beginning of the drive when the trailing gear was not connected to the TBM.

Profile and cross-sectional views of the TBM are included in Chapter 4. The trailing gear and shaft mucking equipment were the same on both the C11 inbound and outbound tunnels. Accordingly, the description of the backup equipment in Chapter 4 also applies to the inbound tunnel.

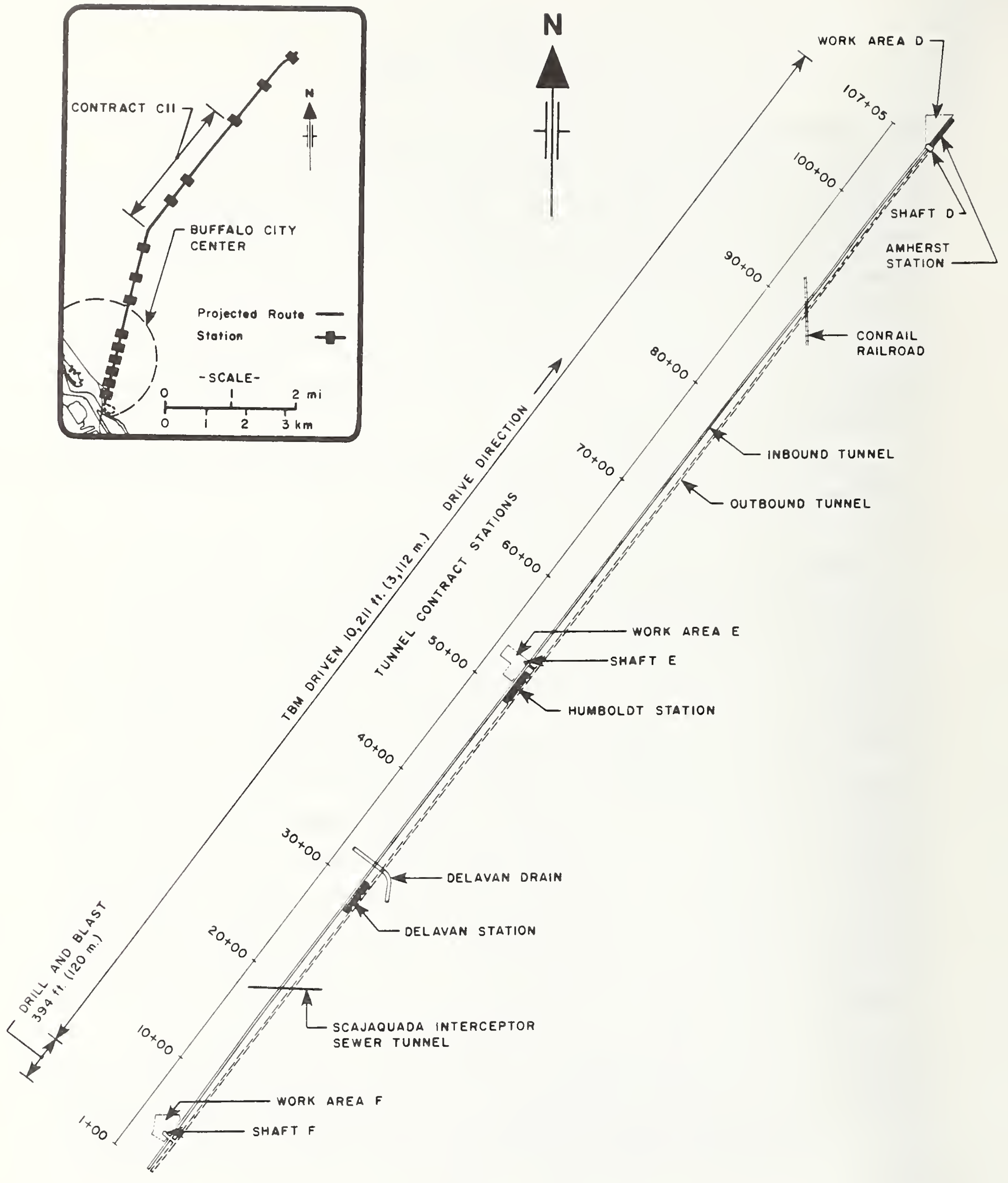


FIGURE 5.1 PLAN VIEW OF CONTRACT C11, INBOUND TUNNEL

TABLE 5.1 SUMMARY OF DIMENSIONS, COMPONENTS, AND OPERATING CHARACTERISTICS OF THE C11 INBOUND TBM

Manufacturer	The Robbins Company, Seattle, Washington
Model Number	186-206
Diameter	18.5 ft (5.6 m)
Length	52.0 ft (15.9 m)
Weight	630 kips (2.80 MN)
Drive Motors	6
Drive Motor Rating	200 hp (149 kW) at 216 amps
Average Operating Amps	not available
Cutterhead Speeds	5.87, 2.93 rpm
Thrust Cylinders	4
Cylinder Diameter	13.0 in. (330 mm)
Stroke Length	5.0 ft (1.5 m)
Maximum Cylinder Pressure	3,500 psi (24.1 MPa)
Average Operating Pressure	2,550 psi (17.6 MPa)
Cylinder Pressure to Move TBM without Face Contact[a]	270 psi (1.9 MPa)
Number and Types of Cutters	38 single disc cutters, 15.5 in. (394 mm) diameter 2 twin disc center cutters, 12.0 in. (305 mm) diameter
Conveyor Belt Width	30.0 in. (762 mm)
Conveyor Belt Speed	374 ft/min (114 m/min)
Conveyor Capacity[b]	540 yd^3/hr (413 m^3/hr)

[b] based on troughing angle of 25 degrees, surcharge angle of 25 degrees, and muck unit weight of 100 lbs/ft^3 (15.7 kN/m^3)

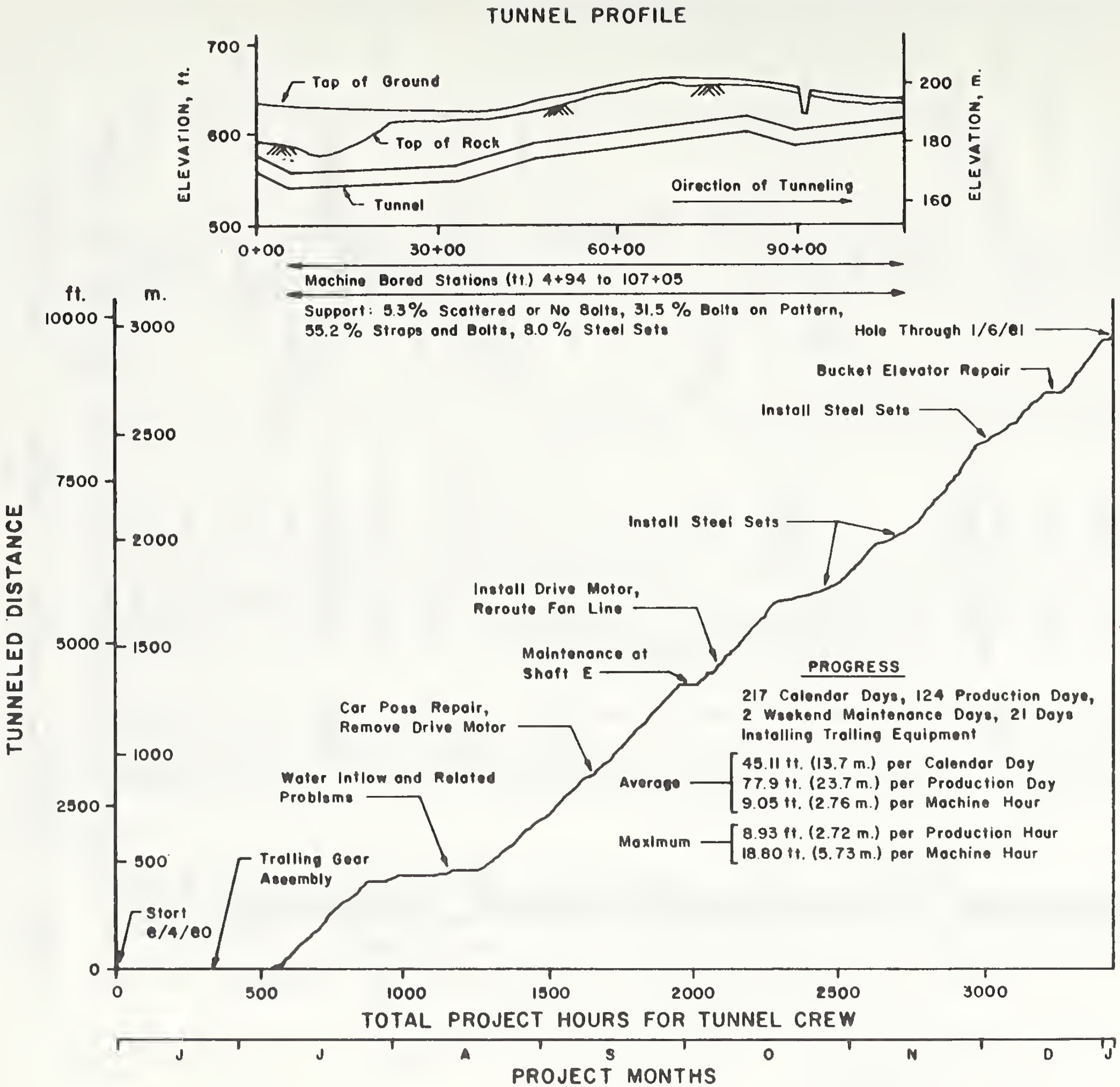
[a] measured without trailing gear in tow.

5.3 CONSTRUCTION EVENTS

Figure 5.2 shows a plot of the tunneled distance versus the total project hours for the tunnel crew on the C11 inbound TBM. Record keeping for this contract did not begin until the trailing gear was installed so the tunneled distance and total project hours axes are referenced to Station 9+89 and 4 June 1980, respectively, as the origin of the plot. Figure 5.2 shows a simplified tunnel profile and summarizes information about the machine, project, and lithologies encountered in the bore. As in the previous chapter, the format is similar to that used by the U.S. Bureau of Reclamation (U.S. Bureau of Reclamation, 1974).

Figure 5.3 summarizes the advance rate, utilization, availability, and penetration rate as a function of tunnel station in histogram form. Each horizontal line segment of the histogram plots corresponds to one shift. The length of the line segment is proportional to the distance tunneled during the shift. Each line segment is plotted above the horizontal axis at a distance proportional to the values of the performance parameter calculated for the shift. The utilization and penetration rates were calculated on the basis of machine boring time determined from the resident engineer shift reports. Tunnel stations used in this report are in units of feet, which is the conventional U.S. practice. If tunneling delays at a given station were longer than the duration of a shift, the performance parameters at that station are equal to zero, and the plot appears as a vertical line intersecting the horizontal axis. The histograms end 62 ft (19 m) before the end of the tunnel at Station 106+43 because complete shift reports were not available for this final distance. The causes and durations of major delays are listed in the plot of penetration rate versus distance at the station where the delays occurred. Figure 5.3 also shows a simplified illustration of the geologic profile as mapped in the excavated tunnel and the types of initial support used at various locations in the tunnel. A detailed record of the geology with stratigraphic identifications, joint planes, overbreak, and support can be found in Appendix A.

In combination, Figures 5.2 and 5.3 provide a summary of the tunneling events and TBM performance referenced by the cumulative hours



MACHINE DATA

Robbins Model 186-206

Diameter 18.5 ft. (5.64 m.)

Length 52 ft. (15.9 m.)

Weight 315 tons (2.80 MN)

Max. Thrust 1858 kips (8.27 MN)

Recycle Stroke 60 in. (1.5 m.)

Cutterhead Rotation 5.87 rpm and 2.93 rpm

Cutters 38 15.5 in. (394 mm.) Single Disc
4 12 in. (305 mm.) Single Disc Center

Motors 6 200 hp

PROJECT INFORMATION

10211 ft. (3112 m.) Total Length

Variable Grade: Uphill Max. 1.91 %
Downhill Max. 1.56 %

Muck Loading by Car Pass

Muck Disposal through Shaft by Rollover, Conveyors and Bucket Elevator

Contractor: Fruin-Colnon Corporation

Owner: Niagara Frontier Transportation Authority, Buffalo, New York

LITHOLOGY

Dolostone and Dolomitic Shale, Unconfined Compressive Strengths from 6 ksi (42 MPa) to 47 ksi (320 MPa)

FIGURE 5.2 TUNNELED DISTANCE VERSUS CUMULATIVE PROJECT HOURS AND PROJECT INFORMATION FOR THE C11 INBOUND TUNNEL

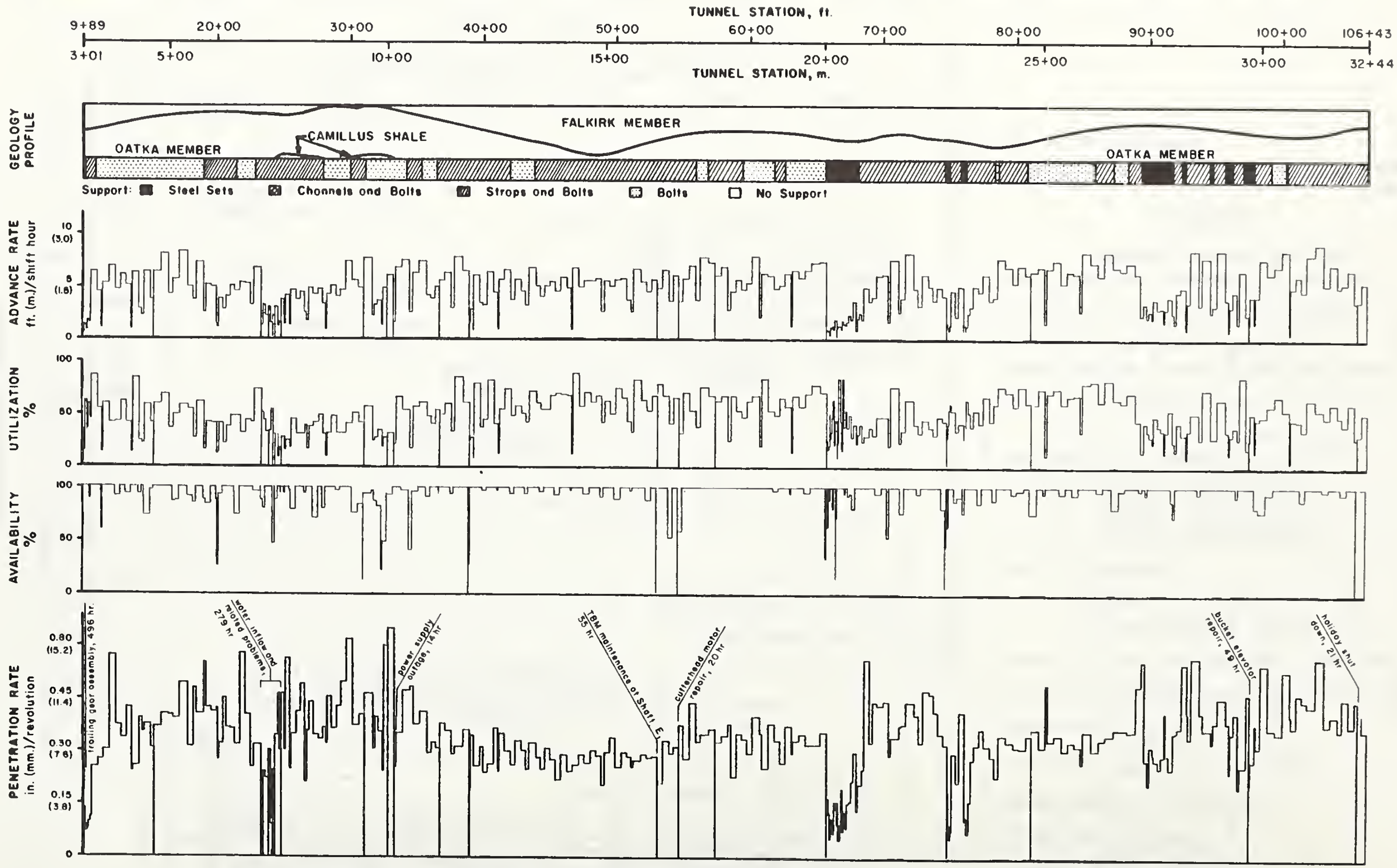


FIGURE 5.3 TBM PERFORMANCE RECORD, TUNNEL GEOLOGY, AND SUPPORT FOR THE C11 INBOUND TUNNEL

and distance tunneled. They index shift time and tunnel stations for the construction of construction events that follow.

The work schedule consisted of a five day work week. The contractor ran three shifts per day of 8.5, 8.0, and 7.5 hour durations.

The TBM was assembled in Work Shaft F at the south end of the contract and was advanced through a drill-and-blast excavated tunnel to begin boring at Station 4+94. The TBM intercepted a 12 in. (305 mm) diameter alignment hole at Station 6+19 where surface water draining through the hole flooded the heading to a depth of 3 ft (0.9 m). At Station 9+89, tunneling was stopped to assemble the trailing gear, which required 21 working days. This delay is labeled on Figures 5.2 and 5.3.

Tunneling with the complete backup system was started on 3 July 1980. Between Stations 16+32 and 23+25, the TBM was operated with only five cutterhead motors. Most of the downtime between Stations 9+89 and 23+28 was caused by repair of the Shaft F conveyors and muck car delays.

On 28 July 1980, the inbound tunnel encountered significant amounts of groundwater which entered the tunnel from seams and vertical joints at the invert near Station 23+28. The initial flow rate was about 2500 gal/min (9500 liters/min)(Guertin and Flanagan, 1982). At this location, the TBM was at an elevation only about 4.5 ft (1.4 m) higher than the lowest point in the tunnel and, when first intercepted, the water rose 5.0 ft (1.5 m) above the invert at the heading. After heavy pumping, the water depth at the heading stabilized at 1.0 ft (0.3 m). The water carried sand and gravel material into the tunnel and this sediment was deposited on the invert in a thickness up to 2.0 ft (0.6 m) so that the rail track had to be reset. Two power outages and a record rainfall over the weekend of 2 August 1980 resulted in the water level at the heading rising again. The deep well dewatering system and tunnel pumps shut off and the standby power system did not operate. The mucking area at Shaft F, the inbound tunnel, and parts of the outbound tunnel were flooded to depths of up to 8 ft (2.4 m). After pumping for several days and making some repairs on shaft mucking equipment, mining was resumed on 8 August. Water inflow continued until Station 24+64 and a third power outage resulted in additional flooding on 11 August. Excavation was stopped on 13 August, at Station 24+76, to repair the equipment in Shaft F. Rollover and conveyor motors and many of the conveyor bearings were replaced. Elevator buckets and chain guides were also repaired or replaced. Mining began again on 18 August, and between Stations 25+92 and 27+27, additional groundwater inflow was encountered. In total, 55 shifts were required to tunnel from Station 23+28 to 27+27. The delay associated with the water inflow is reflected in Figure 5.2 by the nearly horizontal slope of the plot of tunneled distance versus shift hours close to the beginning of the project.

Between Stations 23+28 and 27+27 and in the vicinity of Station 31+00, Camillus Shale was exposed in the tunnel invert. This rock had a solution-pitted, fractured appearance. Where the Camillus was present, the contractor experienced difficulty in keeping the TBM on grade. The TBM was operated with only five cutterhead motors between Station 37+61 and Shaft E at Station 53+03. During this time components of the car pass system were inoperative for three sections totaling 1,132 ft (345 m). Excavation was stopped for eight shifts when the adit from Shaft E was intersected. At this location, 31 cutters were changed, maintenance was performed on car pass components, and a switch and siding tract were installed between Shaft F and Station 7+30.

Between Stations 65+68 and 76+32, three areas were encountered in which steel sets were used for initial rock support. Of the total 1,064 ft (324 m) in this section, 324 ft (99 m) were supported by full circumferential steel sets (WF 6x25) on 4 to 5 ft (1.2 to 1.5 m) centers. When mining these areas, the TBM was often operated at the slow cutterhead rotation rate of 2.93 rpm and reduced thrust pressure. The decline in advance rate throughout this part of the tunnel shows up as an area of reduced slope in Figure 5.2 and as groups of short line segments in Figure 5.3. In addition to time losses caused by steel support installation, the excavation system was also down because of repairs of the car pass system, bucket elevator, and TBM conveyor.

Between Stations 89+57 and 97+95, steel sets were used for initial support in five sections of tunnel. The longest of these sections was located beneath the Conrail tracks and Main Street bridge abutments between Stations 89+62 and 91+39. Of a total 838 ft (255 m), 414 ft (126 m) were supported by full circumferential steel sets (WF 6x25). The sets were placed on 3 ft (0.9 m) centers in the Conrail section and on 4 or 5 ft (1.2 or 1.5 m) centers at other locations. There was no scheduled maintenance before tunneling beneath the Conrail tracks, and nine shifts were required to mine through this section. In addition to delays caused by steel support installation, the bucket elevator pit had to be hand-mucked to allow replacement of bearings and buckets, and to repair chain guides. Repairs also were made on the TBM conveyor.

In summary, tunneling for the C11 inbound tunnel commenced on 21 May 1980 and ended on 6 January 1981. The tunneling required 231 calendar days, of which 134 were production week days. A distance of 495 ft (151 m) was mined before the trailing gear was installed and 9,716 ft (2,961 m) were mined with the trailing gear in tow. The time required to drive the tunnel was 3,189 hours (403 shifts), of which 240 hours (30 shifts) were worked before trailing gear installation. An additional 495 hours of shift time (62 shifts) were required for trailing gear assembly.

5.4 TUNNELING PERFORMANCE

Table 5.2 summarizes the average advance rate, utilization, availability, and penetration rate for the inbound tunnel of Contract C11. The average advance rate and utilization were calculated on the basis of the cumulative project hours from the time the TBM trailing gear was assembled and adjusted at Station 9+89 to holing through of the TBM at Station 107+05. These averages include time devoted to maintenance at Shaft E. The average penetration rate and utilization were calculated in the same manner as the individual shift penetration rates and utilizations by using the boring time from the resident engineer shift reports.

In general, utilization was low in sections where steel supports were installed and in sections with heavy water infiltration. Sustained high values of utilization generally correlate with sections where the rock was unweathered and contained few fractures.

The penetration rate was influenced primarily by four factors: 1) the relative amounts of Falkirk and Oatka Members at the face, 2) the degree of jointing and weathering of the rock, 3) water infiltration, and 4) the number of functioning cutterhead motors. Some of the highest penetration rates were achieved when the face was mostly in the more thinly bedded Oatka Member. The contrast in penetration rate for each

TABLE 5.2 AVERAGE ADVANCE RATE, UTILIZATION, AVAILABILITY, AND PENETRATION RATE FOR THE C11 INBOUND TUNNEL

PARAMETER	AVERAGE VALUE
Advance Rate	3.3 ft/hr (1.00 m/hr)
Utilization	36.2 percent
Availability	93.5 percent
Penetration Rate	9.0 ft/hr (2.8 m/hr)
	0.31 in./revolution (7.8 mm/revolution)

member is shown in Figure 5.3 where the average penetration rate through a nearly full face of the Oatka Member between Stations 28+00 and 37+00 is approximately 45 percent greater than the average rate through a nearly full face of the Falkirk Member between Stations 41+00 and 52+00. In the vicinity of steel supported sections, comparisons of penetration rate made solely on the basis of rock unit are difficult because of variations in the degree of weathering, joint frequency and type of support. The penetration rates in these areas often were highly variable over short distances. The penetration rate was low in areas of water infiltration primarily because of muck removal difficulties with the cutterhead buckets and TBM conveyor, and the relatively low thrust that was used to drive the machine under the difficult conditions. The penetration rate through tunnel sections mined primarily in the Falkirk Member increased nearly 18 percent when the sixth cutterhead motor was reinstalled at Station 54+67.

Availability of the TBM was affected principally by general maintenance and by repairs of the lubricating oil system. In general, low availability correlates with areas of steel support because the TBM conveyor often was damaged by rock jams in zones of weathered and jointed ground.

TABLE 5.3 TABULATION OF DOWNTIME AS A PERCENTAGE OF TOTAL SHIFT HOURS FOR THE C11 INBOUND TUNNEL

TBM Maintenance and Repair	Percentage Downtime	Backup Systems	Percentage Downtime	Ground Conditions	Percentage Downtime	Additional Items	Percentage Downtime
Cutter Change	1.7	Power Supply	1.0	Water Inflow	5.9	Restroke	3.5
General Maintenance and Inspection	2.0	Cable Utilities Fanline	2.1	Steel Sets	5.5	Shaft Downtime	2.2
Lube Oil	0.3	Survey	0.1	Bolts/Straps	1.4	Holiday	0.7
Hydraulics	0.4	Car Pass	4.1	Bolt Drill Repair	0.7	Other (Shift changes, Supplies, Blasting, Special Delays, etc.)	5.5
Motors	1.3	Tripper	not used	Scaling/ Rock Jam	1.2		
TBM Conveyor	2.5	Trailing Gear Conveyor	0.7	Gripper Difficulty	0.5		
Electrical	1.3	Train Delay	7.3	Clearance	negligible		
		Shaft Operations	9.0				
		Laying Rails	1.7				
		Derailment	1.2				
Subtotal	9.5	Subtotal	27.2	Subtotal	15.2	Subtotal	11.9

TOTAL PERCENTAGE DOWNTIME 63.8

5.5 DOWNTIME ANALYSIS

Table 5.3 summarizes the delay, or downtime, associated with various components of the C11 inbound tunneling. As described in Chapter 4, individual causes of delay have been arranged into the four categories shown. A detailed description of downtime categories and a discussion of tunneling delays for the C11 inbound tunnel is given in Appendix B. The downtime percentages were calculated on the basis of total project hours excluding time before and during the assembly of the trailing gear.

Figure 5.4 shows the downtime percentages in the form of a pie chart. Approximately 64 percent of the shift hours was spent on delays resulting in an average machine utilization of 36 percent.

The major causes of downtime under the category of TBM maintenance and repair were TBM conveyor repair and general maintenance and inspection, particularly of the cutterhead. Of the total shift time, 2.5 and 2.7 percent were spent on conveyor repairs and general maintenance and inspection, respectively.

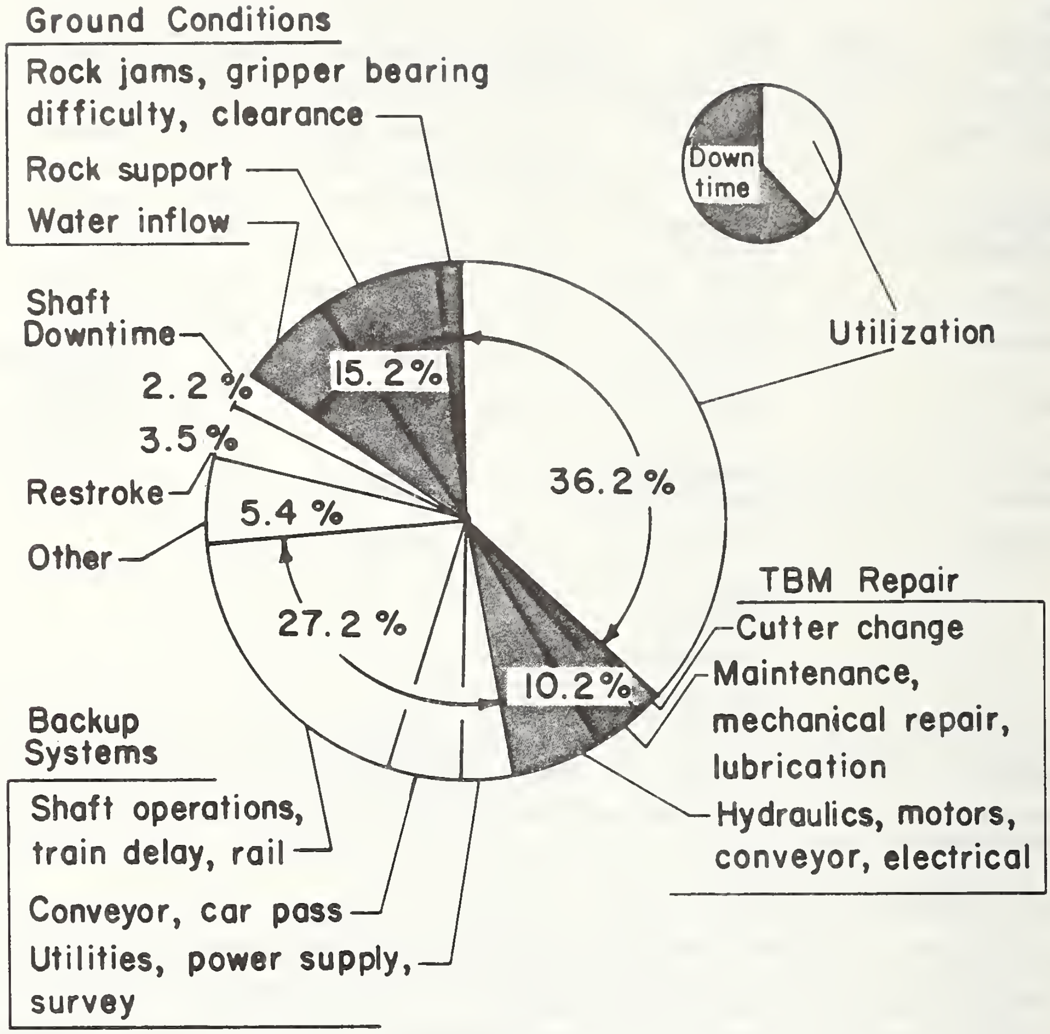


FIGURE 5.4 SUMMARY OF DOWNTIME AS A PERCENTAGE OF TOTAL SHIFT HOURS FOR THE C11 INBOUND TUNNEL

Shaft mucking equipment and car pass difficulties were principal causes of downtime under the general category of backup systems. Repair of shaft equipment required 9.0 percent of the total shift time. Nearly two thirds of this time was spent on repairs of the bucket elevator, most of which were made shortly after the shaft was flooded. Car pass problems required 4.1 percent of the shift time. As in the outbound tunnel, mechanical difficulties with the car pass system led to difficulties in the coordination of trains traveling to and from the heading. Accordingly, car pass problems contributed indirectly to train delays that were associated with 7.3 percent of the shift time.

Downtime associated with ground conditions was principally related to water inflow and the installation of steel sets. The water inflow category includes time losses incurred while pumping flooded sections, and cleaning up and resetting track. Water inflow was directly responsible for a loss of 5.9 percent of the total shift time and indirectly responsible for delays related to repair of the shaft mucking equipment. Steel set installation accounted for 5.5 percent of the shift time. In total, the precentage downtime associated with steel sets, rock jams, scaling, and gripper difficulties was 7.3 percent.

The category of "shaft downtime" includes scheduled downtime at Shaft E for cutter changes and system maintenance. The category of "holiday" includes maintenance shifts operated during the Christmas holiday shutdown. The category of "other" includes downtime for shift changes, waiting for dust to clear so the laser could be read, and bringing supplies to the heading. Shift changes were the principal causes of delay in this category.

5.6 CUTTER CONSUMPTION

The layout of the cutterhead was the same for the machines in both the C11 inbound and outbound tunnels. Accordingly, the description of the cutter locations in Chapter 4 also applies to the inbound TBM.

A total of 60 cutters were changed over 10,211 ft (3,112 m) of tunnel bore. Cutters needing repair were transported to a shop located on site, where rings were replaced and hubs reconstructed. No records were available on the type of repairs made.

Figure 5.5 summarizes information regarding the number and location of replaced cutters. Cutter changes are referenced according to tunnel station. The replacements are shown in histogram form for all but two cutters. Thirty-one cutters were changed at Shaft E during scheduled maintenance. The remaining 29 cutters were changed in the tunnel. The contractor changed cutters at an average rate of one cutter per 1,694 yd^3 (1,295 m^3) of excavated rock. Of the 58 identified changes, 19 replacements were for gage cutters.

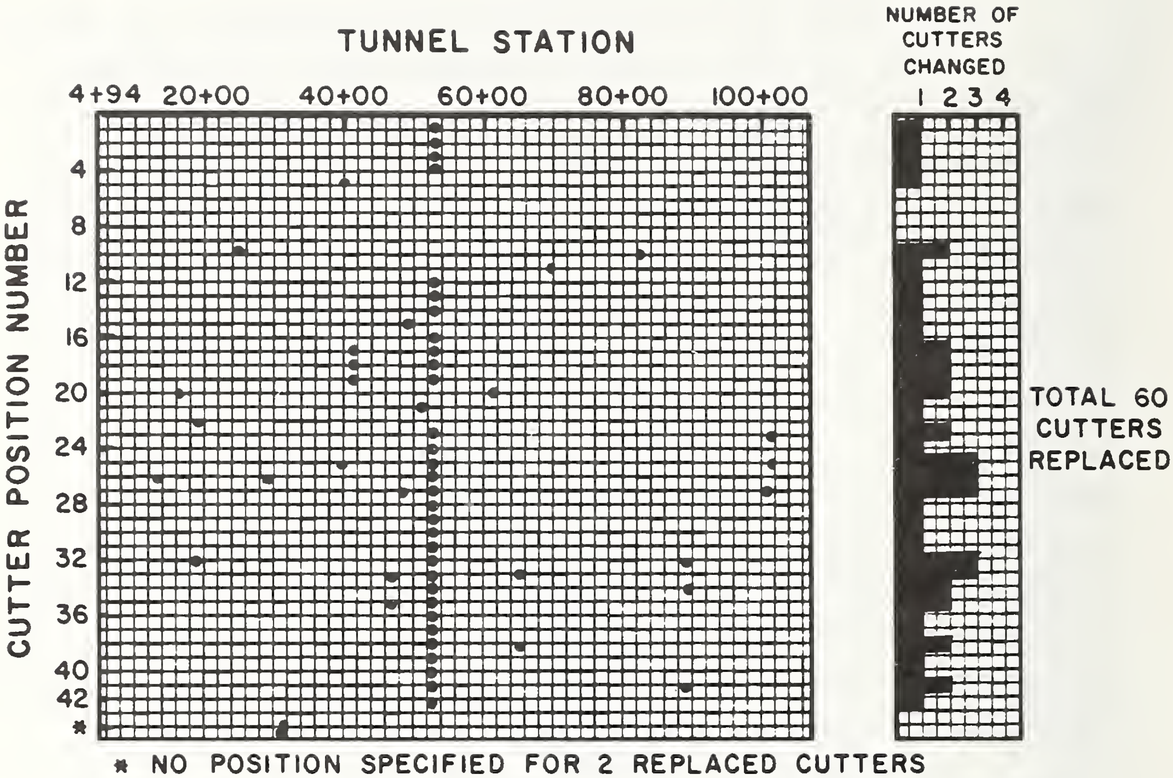


FIGURE 5.5 SUMMARY OF REPLACED CUTTERS, NUMBER OF CHANGES, AND LOCATION ON CUTTERHEAD FACE FOR THE C11 INBOUND TBM

5.7 SUMMARY

From the time the TBM was installed, excavation of the C11 inbound tunnel required 3,684 shift hours, of which 495 were spent on trailing gear assembly. Excluding the time before and during the construction of the trailing gear, the average advance rate was 3.3 ft/hour (1.0 m/hour) for 9,654 ft (2,943 m) of tunnel. The overall TBM utilization was 36 percent.

Major geologic controls on tunneling performance included large inflows of water and the presence of heavily jointed rock. Flooding of the tunnel caused delays from pumping, clean-up, and resetting track in addition to indirectly affecting the shaft mucking equipment. The erection of steel support was often accompanied by difficulties with rock jams at muck intake areas of the TBM, scaling, and gripper reaction. Penetration rates were influenced by the relative amounts of Falkirk and Oatka Members at the face. Relatively high penetration rates were achieved when the face was mostly in the Oatka Member.

Major mechanical causes of downtime included repairs of the shaft mucking equipment, train delays, and car pass problems. The train delays often were affected indirectly by car pass problems.

A total of 60 cutters were changed. There was no significant difference in the average number of changes per gage cutter as opposed to face cutter.

CHAPTER 6

C31 OUTBOUND TUNNEL

6.1 PROJECT OVERVIEW

Construction for the C31 Contract of the Buffalo LRRT was performed by S & M Constructors, Inc. of Solon, Ohio, as part of the joint venture of S & M Constructors, Inc., James McHugh Construction Company, and Kenny Construction Company. The C31 Contract involved the construction of two 16.0 ft (4.9 m) internal diameter tunnels, each approximately 7,200 ft (2,195 m) in length. The excavation diameter of the tunnels was approximately 18.5 ft (5.6 m). Figure 6.1 shows a plan view of the contract that emphasized the outbound tunnel construction. The inset diagram shows the relationship of the C31 Contract to the entire system. The tunnel stations are drawn to scale along the alignment of the tunnel. Work areas, access shafts, and other facilities crossing the tunnel alignment are shown at their true locations along the alignment and are drawn at an expanded scale for emphasis. The contract was worked from 350 ft (107 m) north of South Campus Station to the northern end of Amherst Station. A general description of the Buffalo LRRT is provided in Chapter 4.

The contractor began at the north end of the contract section, at Work Areas A and B, and excavated two access shafts, each 35 ft (11 m) by 95 ft (29 m) in cross-section to depths of 62 ft (19 m). The initial 235 ft (72 m) segment of the outbound tunnel between Shafts A and B, and a starter tunnel for the TBM were excavated by drill-and-blast methods. A recovery shaft at the future Amherst Station, Work Area D, was excavated with plan dimensions of 35 ft (11 m) by 57 ft (17 m) and used to remove the TBMs after the completion of both the inbound and outbound drives.

Horizontal alignment for most of the contract was set with the tunnels on 75 ft (23 m) centers to maximize the rock pillar sizes at La Salle Station. At the southern end of the contract, this spacing was reduced to 33 ft (10 m) by shifting the outbound tunnel westward so that construction for Amherst Station could be performed away from business properties on the east side of Main Street. At the northern end of the contract work, the horizontal curve for the outbound tunnel was set at a

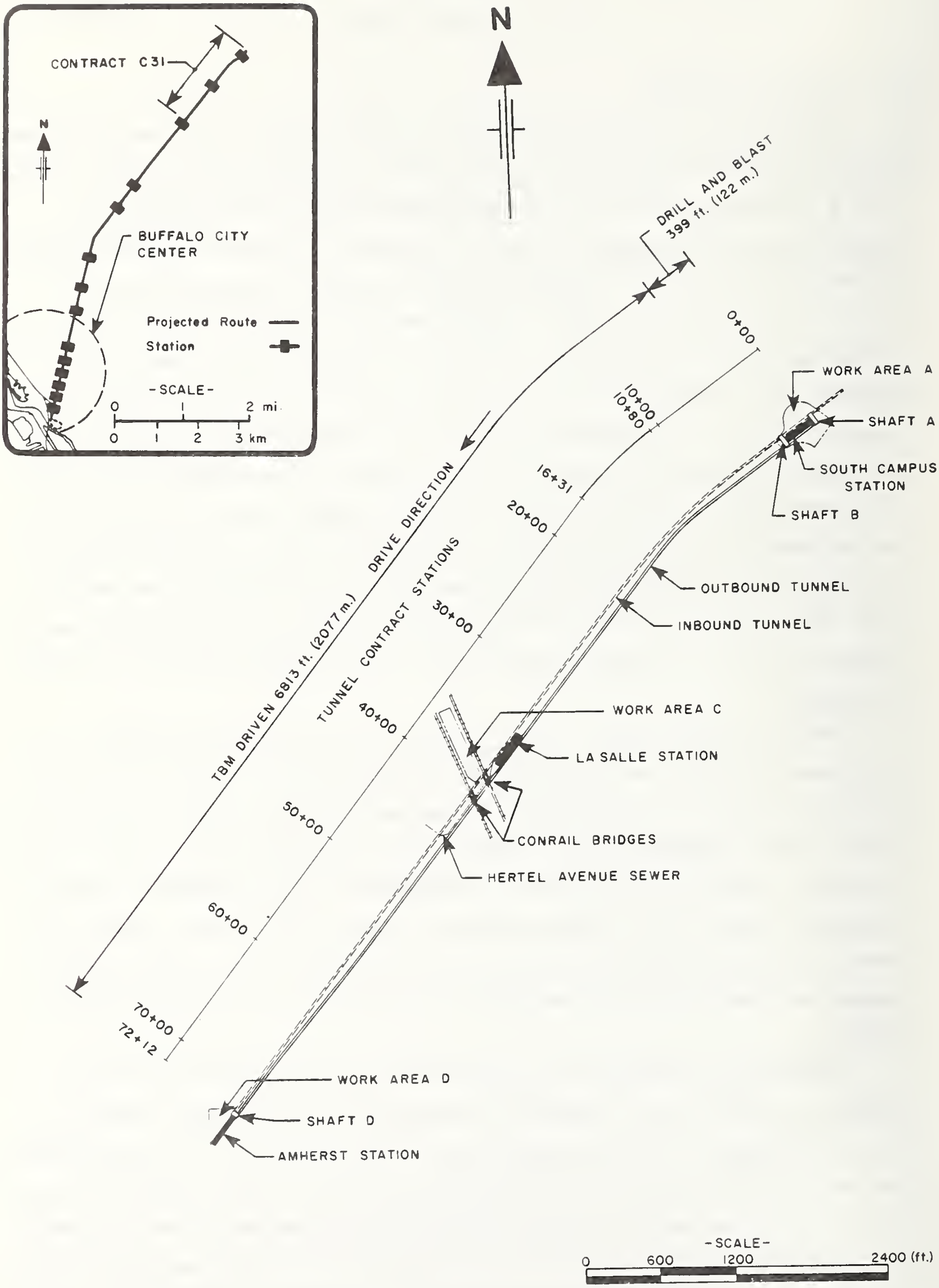


FIGURE 6.1 PLAN VIEW OF CONTRACT C31, OUTBOUND TUNNEL

1,100 ft (335 m) radius in contrast to the 4,500 ft (1,512 m) radius of the inbound tunnel. In this area, the separation between the outbound and inbound tunnels is a minimum 25 ft (8 m).

To the south of South Campus Station, the vertical alignment was set to provide a minimum 10 ft (3 m) of rock cover beneath sediments in a buried valley that extends 25 ft (8 m) below the street surface. South of LaSalle Station, the C31 tunnels pass beneath the abutments for two Conrail bridges, where the depth of rock cover was set at 20 ft (6 m). Nearby, rock cover of 8 to 12 ft (2.4 to 3.7 m) was provided between the contract tunnels and the Hertel Avenue Sewer. The locations of the Conrail bridges and Hertel Avenue Sewer are shown in Figure 6.1.

6.2 GEOLOGIC SETTING

The subsurface geology, as interpreted from site exploration borings, is shown in Figure 6.2. The tunnel alignment has been superimposed on the cross-section. The tunnel is well below the potentially abrasive chert at the base of the Onondaga Formation. The invert of the tunnel was positioned to avoid the top of the Camillus Shale because of potential water inflow and possible difficulties in maintaining TBM grade in lower strength and fractured rock. The contractor was required to install a deep well dewatering system to maintain the water level at a point at least 2 ft (0.6 m) below the tunnel invert.

A description of the general geology in the Buffalo area and a summary of average rock properties is provided in Chapter 4. Detailed mapping of the tunnel wall geology and of installed support was performed as the tunnels were excavated. Maps and support descriptions are included in Appendix A.

6.3 DESCRIPTION OF MACHINE AND MUCKING SYSTEM

The TBM used in the C31 outbound tunnel was manufactured by The Robbins Company of Seattle, Washington, and was designated as Model 185-178. The machine originally was operated by the James McHugh Construction Company of Chicago, Illinois, to drive a 18.2 ft (5.5 m) diameter tunnel 10,670 ft (3,253 m) through dolostone and dolomitic shale as part of the Tunnel and Reservoir Plan sponsored by the Metropolitan Sanitary District of Greater Chicago. After completing

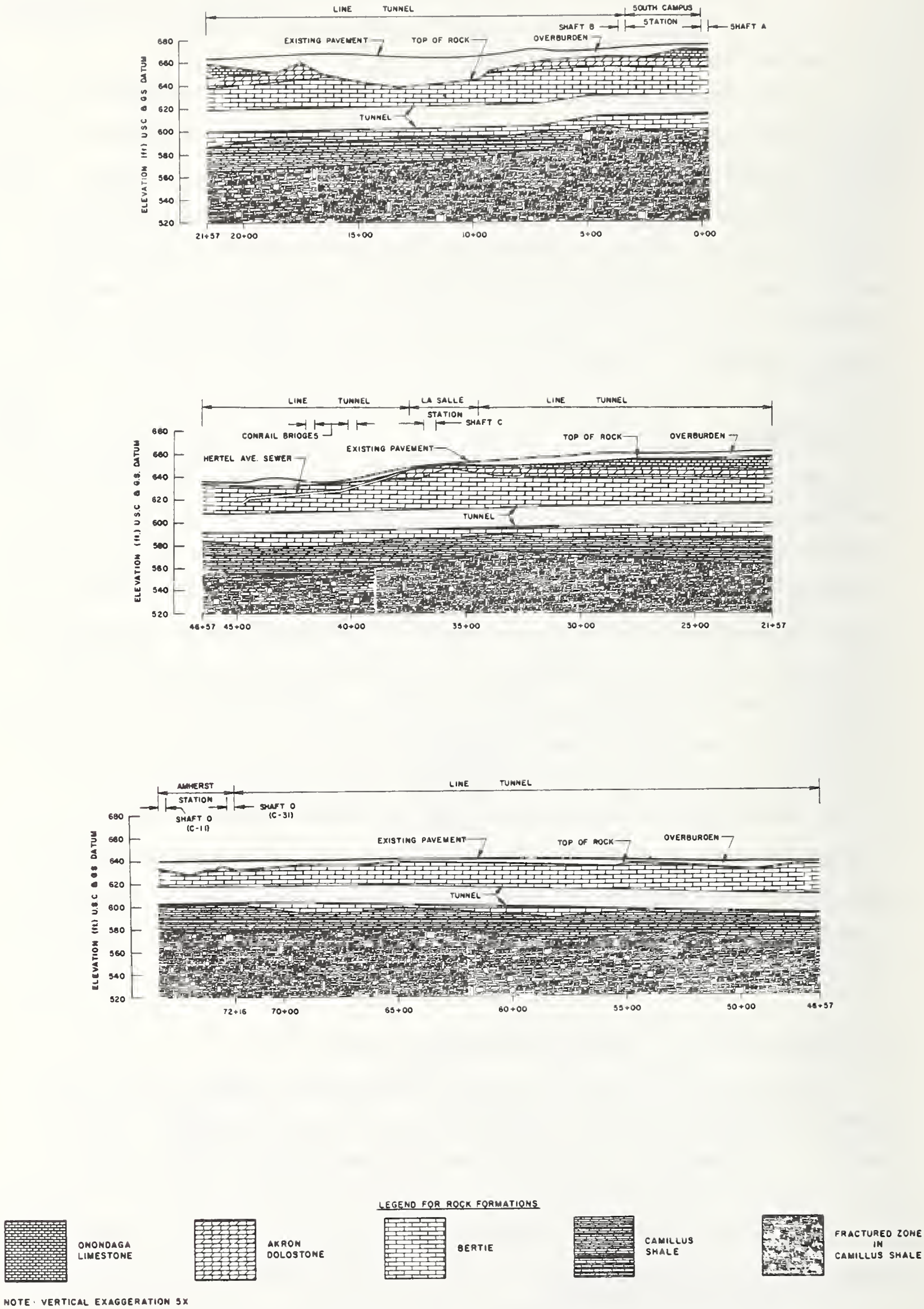


FIGURE 6.2 GEOLOGIC PROFILE FOR CONTRACT C31

the job, the machine was stored in an "as is" condition until it was purchased by the C31 contractor. The diameter of the machine was changed to 18.6 ft (5.7 m) by extending the muck buckets on the cutterhead and adding a gage cutter. Other changes included the replacement of the main bearing seal, rebuilding the hydraulic system, and replacing electronic components. A discussion of these and other alterations is given by Scaravilli (1981).

Figure 6.3 shows a profile and two cross-sectional views of the machine. The figure is drawn to scale and prominent components are labeled. Table 6.1 summarizes machine dimensions, components, and operating characteristics. The machine was 52 ft (15.9 m) long with thrust cylinders retracted, as measured from the front of the cutterhead to the rear of the conveyor assembly. The maximum cylinder pressure was 3,600 psi (24.8 MPa) pressure. Two cutterhead speeds were available at 5.11 and 2.56 rpm, and the higher speed was used during most of the tunneling. The cutterhead was driven by six 150 hp (112 kW) motors at an average operating amperage of 150 amps. The drive motor horsepower available with this machine was the lowest of all TBMs used on the Buffalo LRRT. As indicated in Table 6.1, the thrust cylinder pressure required to advance the TBM without face contact was measured as 500 psi (3.4 MPa). This value was determined during tests near the beginning of the drive when the trailing gear was connected to the TBM.

The trailing gear and car pass system were similar to those used in the C11 tunnels. The trailing gear was composed of a series of sleds that carried the trailing conveyor, fan line, high voltage transformer, and a variety of other mechanical and electrical equipment. The full trailing gear system extended approximately 290 ft (88 m) behind the TBM face where a ramp for train access from the main line track was located. The trailing conveyor was equipped with a deflector arrangement to load trains on either side of the tunnel at a distance of approximately 170 ft (52 m) behind the TBM face. The trailing floor components were manufactured by the Moran Engineering Sales Company of Montebello, California.

The car pass was composed of a pulling and pushing mechanism on opposite sides of the tunnel. Empty muck cars on one side of the trailing gear were automatically pulled forward, disengaged from the

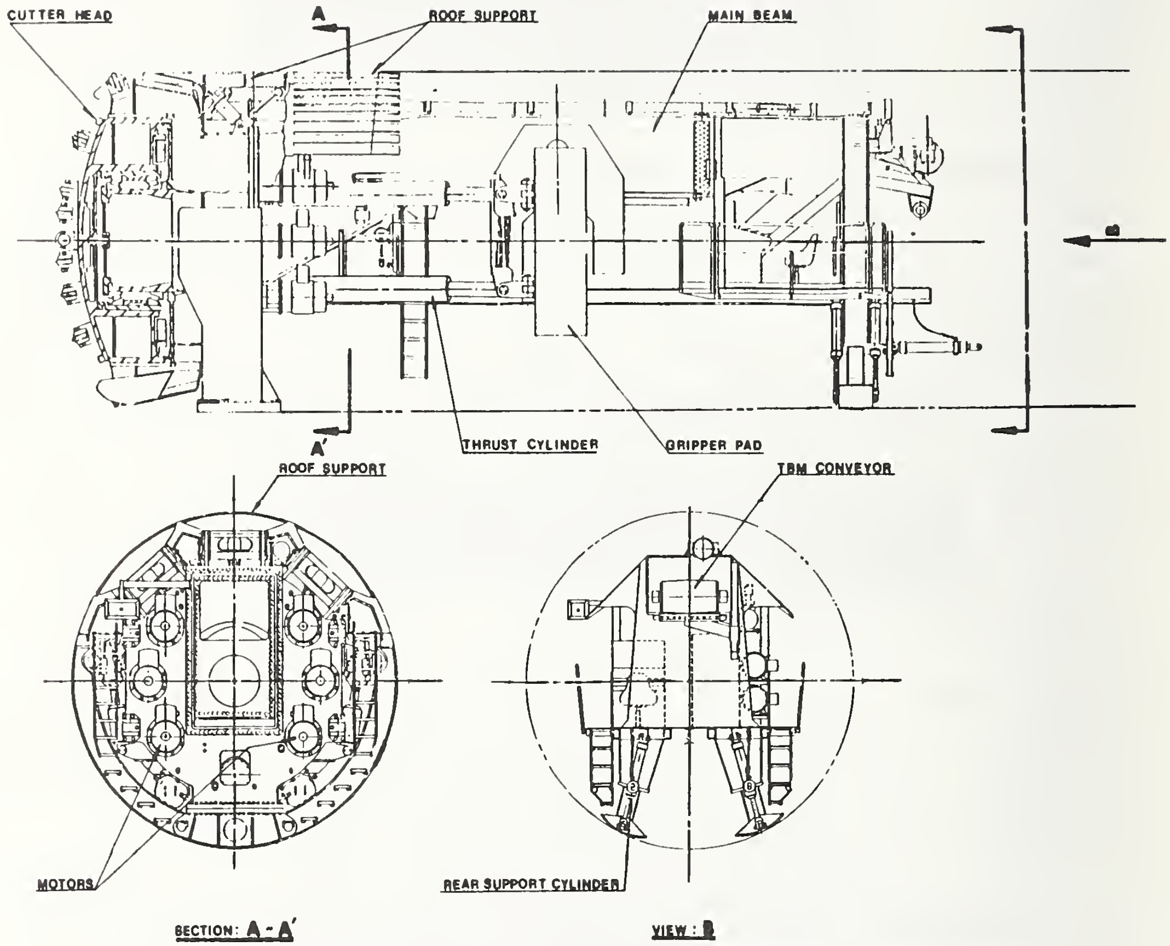


FIGURE 6.3 PROFILE AND CROSS-SECTIONAL VIEWS OF THE C31 OUTBOUND TBM

train, and transferred by means of a sliding track to the opposite side of the tunnel where they were filled. Cars were moved forward successively by the full car pusher to make up a loaded train. The train was taken to the muck shaft by a locomotive.

Each muck car had a capacity of 10 yd^3 (7.6 m^3) and was designed with a lift-off mechanism so that the car could be disengaged from its

TABLE 6.1 SUMMARY OF DIMENSIONS, COMPONENTS, AND OPERATING CHARACTERISTICS OF THE C31 OUTBOUND TBM

Manufacturer	The Robbins Company, Seattle, Washington
Model Number	185-178
Diameter	18.6 ft (5.7 m)
Length	52.0 ft (15.9 m)
Weight	470 kips (2.10 MN)
Drive Motors	6
Drive Motor Rating	150 hp (112 kW) at 165 amps
Average Operating Amps	150 amps
Cutterhead Speeds	5.11, 2.56 rpm
Thrust Cylinders	4
Cylinder Diameter	13.0 in. (330 mm)
Stroke Length	5.0 ft (1.5 m)
Maximum Cylinder Pressure	3,600 psi (24.8 MPa)
Average Operating Pressure	2,100 psi (14.5 MPa)
Cylinder Pressure to Move TBM without Face Contact[a]	500 psi (3.4 MPa)
Number and Types of Cutters	39 single disc cutters, 15.5 in. (394 mm) diameter 2 twin disc center cutters, 12.0 in. (305 mm) diameter
Conveyor Belt Width	36.0 in. (914 mm)
Conveyor Belt Speed	387 ft/min (118 m/min)
Conveyor Capacity[b]	830 yd^3/hr (633 m^3/hr)

[b] based on troughing angle of 25 degrees, surcharge angle of 25 degrees, and muck unit weight of 100 lbs/ft^3 (15.7 kN/m^3).

[a] measured with trailing gear in tow.

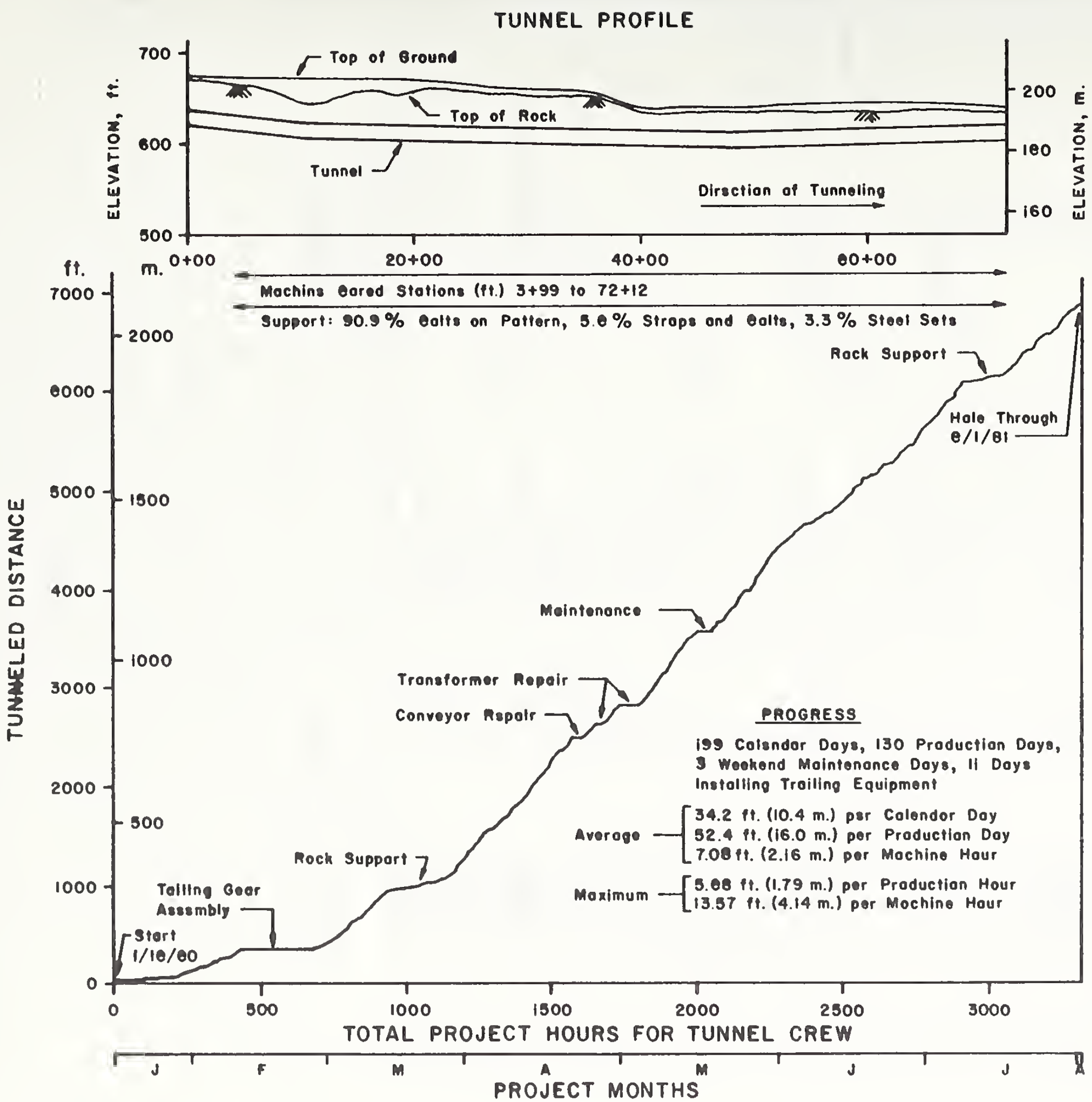
underlying wheel base and frame. At the shaft, muck cars were centered on vertical guide rails and lifted by crane to the surface. Empty cars were returned by crane and reconnected with their wheel bases.

6.4 CONSTRUCTION EVENTS

Figure 6.4 shows a plot of the tunneled distance versus the total project hours for the tunnel crew. The figure shows a simplified tunnel profile and summarizes information on the machine, project, and lithologies encountered in the bore. The format is similar to that used by the U. S. Bureau of Reclamation (U.S. Bureau of Reclamation, 1974), as described in Chapter 4.

Figure 6.5 summarizes the advance rate, utilization, availability, and penetration rate as a function of tunnel station in histogram form. Each horizontal line segment of the histogram plots corresponds to one shift. The length of the line segment is proportional to the distance tunneled during the shift. Each line segment is plotted above the horizontal axis at a distance proportional to the value of the performance parameter calculated for the shift. If tunneling delays at a given station were longer than the duration of a shift, the performance parameters at the station are equal to zero, and the plot appears as a vertical line intersecting the horizontal axis. Tunnel stations used in this report are in units of feet, conforming with conventional U.S. practice. The causes and durations of major delays are listed at the stations where they occurred in the plot of penetration rate versus distance. The utilization and penetration rates were calculated on the basis of machine boring times recorded by the contractor and read from the machine clock. The clock was activated when the air clutch for the cutterhead motors was engaged. Because clock readings were not recorded before Station 5+01, all plots in Figure 6.5 are referenced to this location. Figure 6.5 also shows a simplified illustration of the geologic profile as mapped in the excavated tunnel and the types of initial support used at various locations in the tunnel. A detailed record of the geology with stratigraphic identifications, joint planes, overbreak, and support is given in Appendix A.

In combination, Figures 6.4 and 6.5 provide a summary of the tunneling events and TBM performance referenced by the cumulative hours



MACHINE DATA

Robbins Model 185-178-1

Diameter 18.58 ft. (5.66 m.)

Length 53 ft. (16.2 m.)

Weight 235 tons (2.09 MN)

Max. Thrust 1911 kips (8.50 MN)

Recycle Stroke 60 in. (1.5 m.)

Cutterhead Rotation 5.11 rpm, 2.56 rpm

Cutters 39 15.5 in. (394 mm.) Single Disc

4 12 in. (305 mm.) Single Disc Center

Motors 6 150 hp.

PROJECT INFORMATION

7212 ft. (2198 m.) Total Length

Variable Grade: Uphill Max. 0.56 %
Downhill Max. 2.46 %

Muck Loading by Car Pass

Muck Disposal Through Shaft by Crane Dumping of Muck Cars

Contractor: S & M Constructors, Inc.

Owner: Niagara Frontier Transportation Authority, Buffalo, New York

LITHOLOGY

Dolostone and Dolomitic Shale, Unconfined Compressive Strengths from 6 ksi (42 MPa) to 47 ksi (320 MPa)

FIGURE 6.4 TUNNELED DISTANCE VERSUS CUMULATIVE PROJECT HOURS AND PROJECT INFORMATION FOR THE C31 OUTBOUND TUNNEL

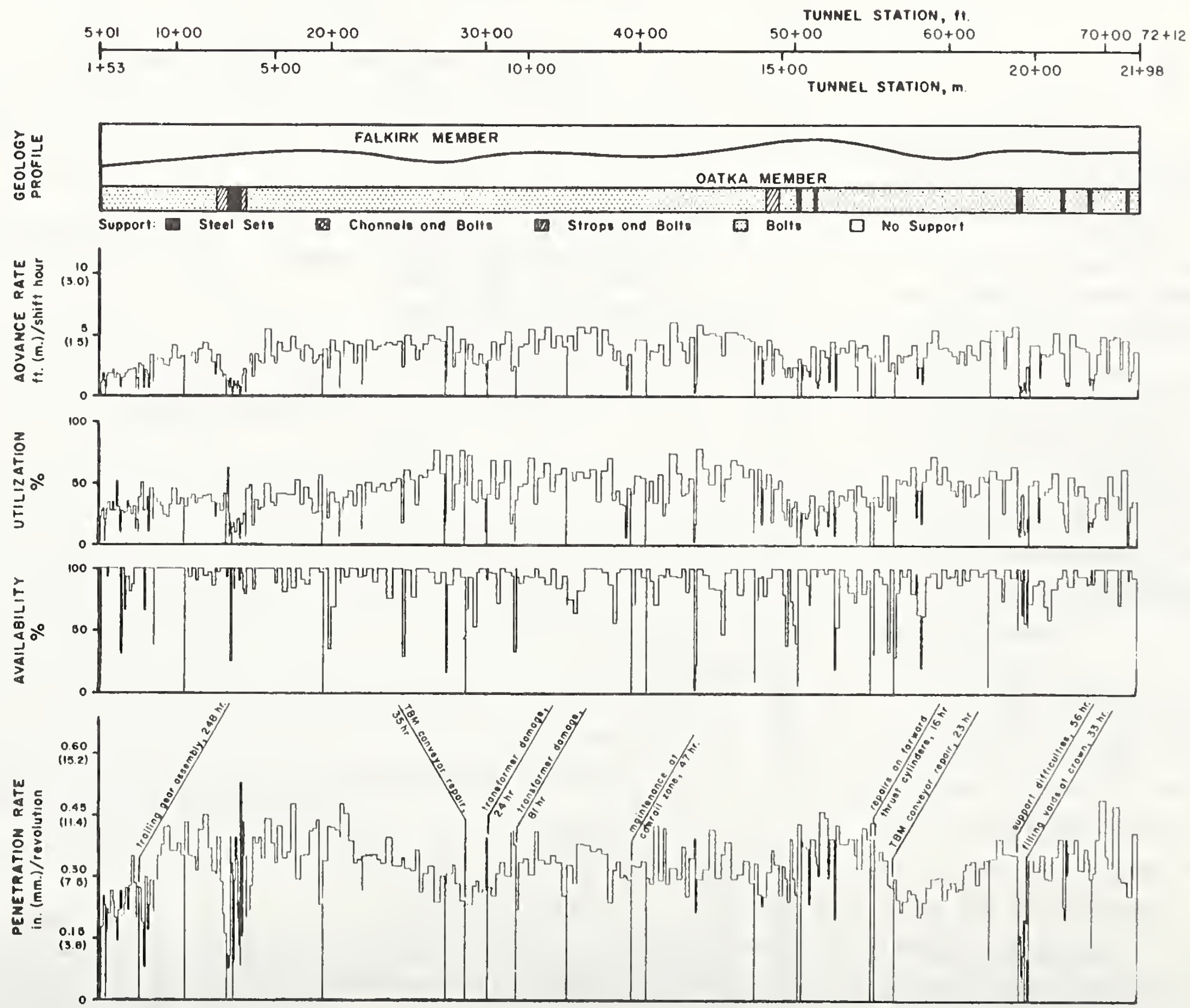


FIGURE 6.5 TBM PERFORMANCE RECORD, TUNNEL GEOLOGY, AND SUPPORT FOR THE C31 OUTBOUND TUNNEL

and distance tunneled. They index shift time and tunnel performance for the discussion of construction events that follows.

The work schedule consisted of a five day week. Initially, the shifts were of 8.0, 7.5, and 7.0 hour durations, but beginning 11 April 1980, the contractor ran 8.5, 8.0, and 7.5 hour shifts.

The TBM was assembled in Work Shaft B and was advanced through a drill-and-blast excavated tunnel to Station 3+99. In lieu of constructing a concrete form along the tunnel springline, the contractor started the TBM with the gripper pads bearing directly on the tunnel walls. This operation caused some delay because the grippers had to be cribbed after each advance to develop an adequate reaction. The TBM excavated 366 ft (112 m) from Station 3+99 to 7+35 where production was halted on 13 February 1980 to erect the trailing sleds and install muck handling equipment. Trailing gear assembly required 11 working days.

On 28 February 1980 boring was resumed. From approximately Station 11+00 to 16+50, the rock was heavily jointed. Excavated rock often jammed inside the main beam and damaged the TBM conveyor belt. Steel sets were installed as initial support over 78 ft (24 m) of this section.

Most of the downtime between Stations 16+50 and 39+33 was associated with TBM conveyor, electrical system, and car pass repairs. Excavation was stopped for four shifts at Station 28+63 to repair a broken bearing on the TBM conveyor. At Station 30+08 four shifts were spent repairing the high voltage circuit breaker in the transformer, and at Station 31+91 excavation was stopped for 11 shifts to repair the transformer after damage by fire. The car pass drive chain was repaired four times in this tunnel section.

Tunneling was stopped at Station 39+33 on 17 May 1980 at a location beneath the Conrail bridge abutments. During six weekend shifts, the heading was stocked with utility line segments and rock support materials, cutters were changed, and maintenance was performed on the TBM. Eight shifts were required to mine to the end of the Conrail zone at Station 41+39, and bolts and straps were installed in the tunnel crown on 3 ft (0.9 m) spacings along the tunnel.

Between Stations 41+39 and 64+26, the principal delays were caused by equipment repair and the installation of rock support. The seal pump, which supplies oil to lubricate the main bearing and drive motor pinions, caused delays 11 times before the pump was replaced at Station 53+74. One of the thrust cylinder connections to the cutterhead support failed at Station 54+83 and two shifts were required to repair the cylinder and reinforce its welds. Steel sets were installed as initial support at two locations and at several places, rock slabs dropped from the crown and excavation was stopped to break up and remove the pieces from the TBM roof supports. Muck jams in the TBM main beam damaged the conveyor and at Station 56+33, three shifts were spent replacing the damaged TBM conveyor belt.

From Station 64+26 to the end of the tunnel at Station 72+12, steel sets were used at four locations. Near Station 64+30, jointed and weathered rock produced overbreak up to 10 ft (3 m) above the tunnel crown, and excavation was stopped for five shifts to fill the overbreak voids with concrete. At other locations, steel ribs were installed where lateral overbreak, 8 to 10 ft (2.4 to 3.0 m) deep, developed above springline in rock that was more thinly bedded and weathered than elsewhere in the tunnel. In addition to time losses caused by rock support, the excavation was also down for train delays and hydraulic system repairs, including hydraulic pump replacement.

In summary, tunneling for the C31 outbound tunnel commenced on 16 January 1980 and ended on 1 August 1980. The tunneling required 199 calendar days, of which 130 were production weekdays. A distance of 336 ft (112 m) was mined before the trailing gear was installed and 6,477 ft (1,974 m) were mined with the trailing floor in tow. The total number of tunnel shift hours was 3,116 (339 shifts), of which 481 hours (64 shifts) were worked before trailing gear installation. An additional 248 hours (33 shifts) were required for trailing gear and shaft mucking equipment assembly.

6.5 TUNNELING PERFORMANCE

Table 6.2 summarizes the average advance rate, utilization, availability, and penetration rate for the outbound tunnel of Contract C31. The average advance rate and utilization were calculated on the basis of the cumulative project hours from the time the TBM trailing gear was assembled at Station 7+35 to holing through of the TBM at Station 72+12.

TABLE 6.2 AVERAGE ADVANCE RATE, UTILIZATION, AVAILABILITY, AND PENETRATION RATE FOR THE C31 OUTBOUND TUNNEL

PARAMETER	AVERAGE VALUE
Advance rate	2.5 ft/hr (0.75 m/hr)
Utilization	31.1 percent
Availability	86.1 percent
Penetration Rate	7.9 ft/hr (2.4 m/hr) 0.31 in./revolution (7.8 mm/revolution)

These averages include the time devoted to maintenance at the Conrail railroad bridges. The average penetration rate and utilization were calculated in the same manner as the individual shift penetration rates and utilization by using the machine clock times as recorded by the contractor.

In general, utilization was low in sections where steel supports were installed. Sustained high values of utilization generally correlate with sections where the rock contained few fractures, and where the car pass and TBM hydraulic systems were in good working order.

The penetration rate was influenced primarily by two factors: 1) the degree of jointing and weathering of the rock, and 2) the number of functioning drive motors. The relative amounts of the Falkirk and Oatka Members at the face did not vary greatly along the tunnel. The Oatka Member was encountered between the springline and invert, and most often was highly jointed with medium to thin bedding. The highest penetration rates were achieved near the start of the tunnel where rock of the Falkirk Member above the springline had a high joint frequency, and near the end of the tunnel where the Falkirk Member was thinly bedded and weathered. The penetration rate was highly variable at many locations where steel sets were installed. In particular, this variation is shown by the sharp fluctuations in rate between Stations 12+57 and 15+00. When the TBM was operated with fewer than six drive motors, the thrust pressures were diminished, and the penetration rates were lower. The decrease in rate associated with the loss of a drive motor is shown in Figure 6.5 where the average penetration rate between Stations 55+56 and 60+02, when five drive motors were used, is approximately 33 percent lower than the average rate between Stations 20+80 and 25+10, when six drive motors were used.

Availability of the TBM was limited principally by three main factors: 1) repair of the thrust cylinder connections to the cutterhead support, 2) repair of the TBM conveyor and muck hoppers, and 3) repair of the seal oil pump. The pump began malfunctioning at Station 34+86 and problems continued until the pump was replaced at Station 53+74. Availability was low toward the end of the drive, primarily due to hydraulic system repairs.

6.6 DOWNTIME ANALYSIS

Table 6.3 summarizes the delay, or downtime, associated with various components of the C31 outbound tunneling. As described in Chapter 4, individual causes of delay have been arranged into the four categories. A detailed discussion of downtime categories and a description of tunneling delays for the C31 outbound tunnel is given in Appendix B. The downtime percentages were calculated on the basis of total project hours excluding time before and during the assembly of trailing gear.

Figure 6.6 shows the downtime percentages for all categories in the form of a pie chart. Approximately 69 percent of the shift hours was spent on delays, resulting in an average machine utilization of 31 percent.

The major causes of downtime under the category of TBM maintenance and repair were repair of electric components on the TBM and trailing floor and general maintenance and inspection, particularly of the cutterhead and the cutterhead main bearing. Of the total shift time, 4.5 percent was spent on transformer and methane meter repair and 4.6 percent was spent on general maintenance and inspection.

TABLE 6.3 TABULATION OF DOWNTIME AS A PERCENTAGE OF TOTAL HOURS FOR C31 OUTBOUND TUNNEL

TBM Maintenance and Repair	Percentage Downtime	Backup System	Percentage Downtime	Ground Conditions	Percentage Downtime	Additional Items	Percentage Downtime
Cutter Change	2.2	Power Supply	0.2	Water Inflow	0.0		
General Maintenance and Inspection	4.6	Cable Utilities Fanline	4.8	Steel Sets	7.9	Shaft Downtime	0.0
Lube Oil	1.7	Survey	0.5	Bolts/Straps	2.1	Conrail	1.8
Hydraulics	2.9	Car Pass	4.4	Bolt Drill Repair	3.4	Other (Supplies, Blasting, Shift Changes, Restroke, etc.)	9.1
Motors	1.5	Tripper	not used	Scaling/ Rock Jam	5.3		
TBM Conveyor	3.2	Trailing Gear Conveyor	1.8	Gripper Difficulty	0.0		
Electrical	4.5	Train Delay	4.0	Clearance	negligible		
		Shaft Operations	0.7				
		Laying Rails	0.7				
		Derailment	1.3				
Subtotal	20.6	Subtotal	18.4	Subtotal	19.0	Subtotal	10.9

TOTAL PERCENTAGE DOWNTIME 68.9

Installation of utility lines and repair of the car pass equipment were principal causes of downtime under the general category of backup systems. Extending utility services to the heading required 4.8 percent of the total shift time, and approximately half of this time was spent hanging the fanline and installing booster fans. Car pass repair required 4.4 percent of the shift time, most of which was associated with the sliding track mechanism. Car pass problems slowed the movement of cars through the muck transport system and indirectly led to train delays which accounted for 4.0 percent of the shift time.

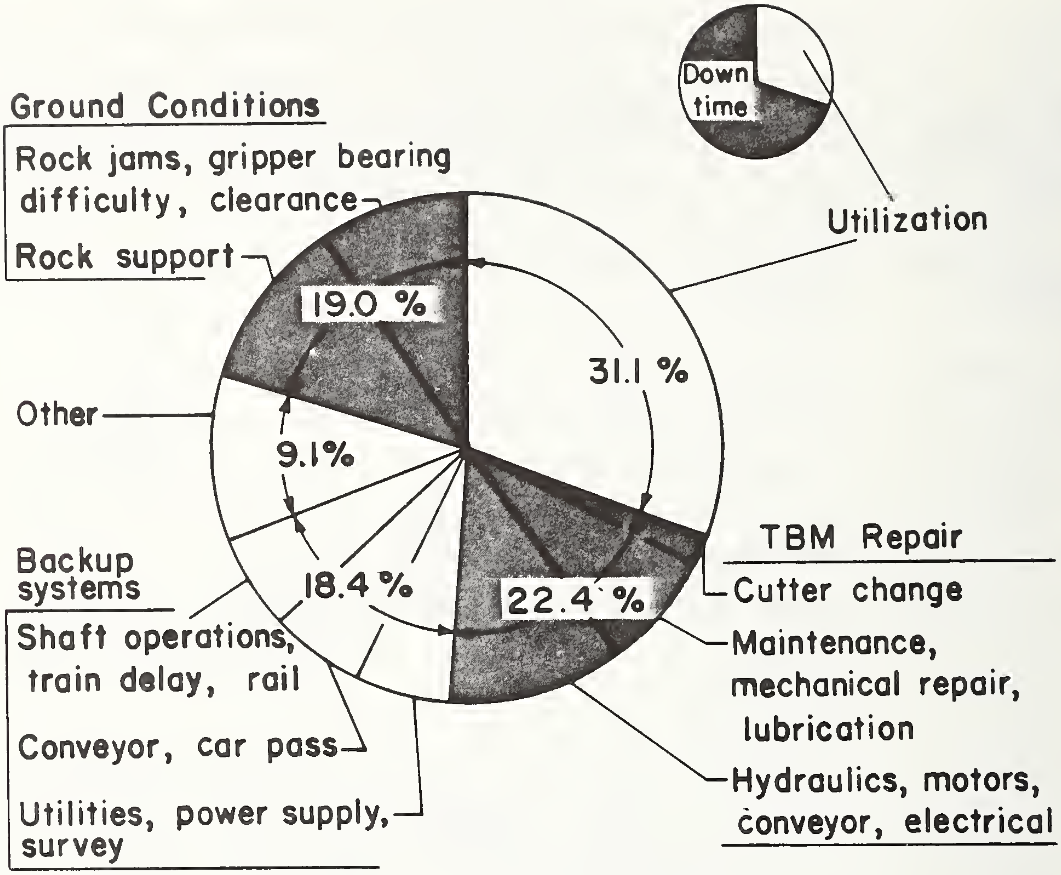


FIGURE 6.6 SUMMARY OF DOWNTIME AS A PERCENTAGE OF TOTAL SHIFT HOURS FOR THE C31 OUTBOUND TUNNEL

Downtime associated with ground conditions was principally related to the installation of steel sets, which accounted for 7.9 percent of the shift hours. In some sections, clearing rock jams at muck intake areas of the cutterhead, scaling loose rock between the springline and crown, and breaking up large pieces of rock on the TBM roof supports caused additional delays. In total, the percentage downtime associated with steel sets, rock jams, scaling, and clearance of trailing gear components was 13.5 percent. Time losses associated with rock bolt drill repair amounted to 3.4 percent of the shift time.

The category of "Conrail" includes scheduled downtime near the Conrail track crossings. This time was used to stock the heading with utility line segments and rock support materials, and to perform maintenance on the TBM. The category of "other" includes downtime for shift changes, bringing supplies to the heading, and evacuation of the crew when cross passages were blasted between the outbound and inbound tunnels. Records were not available for the time required to reset the thrust cylinders in preparation for a forward stroke, and this delay also is included within the category of other.

6.7 CUTTER CONSUMPTION

Complete records of cutter changes were not kept by either the contractor or the resident engineer. The contractor did not repair cutters on site. Cutters needing repair were removed and shipped to the supplier, Atlas Copco Jarva,Inc., of Solon, Ohio.

The number and location of cutters replaced during maintenance at Station 39+33 were not available, but the contractor's shift reports do contain records of 29 cutter changes made at other locations in the tunnel. Specific cutter position locations were noted for only 24 of these replacements. Of these, nine were for cutters in the outer 14 gage positions.

6.8 SUMMARY

From the time the TBM was installed, excavation of the C31 outbound tunnel required 3,364 hours, of which 248 were spent on trailing gear assembly. Excluding the time before and during the construction of the trailing floor and mucking equipment, the average advance rate was 2.5 ft/hr (0.75 m/hr) for 6,813 ft (2,076 m) of tunnel. The overall TBM utilization was 31 percent.

Major geologic controls on tunneling performance included the presence of heavily jointed and weathered rock. The erection of steel support was often accompanied by difficulties with rock jams at muck intake areas of the TBM, and scaling and removing loose rock from the tunnel walls and TBM shield components. Penetration rates were influenced by the frequency of joints and extent of weathering in the Falkirk

Member. Relatively high penetration rates were achieved when the joint frequency increased and the Falkirk was weathered and thinly bedded.

Major mechanical causes of downtime included car pass problems and repairs of the TBM hydraulic and conveyor systems. Train delays were often indirectly caused by slow movement of cars through the muck transport system during car pass system repairs. Problems with the wiring of the methane detection meter and repairs of the step-down transformer were also major sources of delay.

CHAPTER 7

C31 INBOUND TUNNEL

7.1 PROJECT OVERVIEW

The C31 inbound tunnel was part of the twin tube construction for Contract C31 of the Buffalo LRRT. Figure 7.1 shows a plan view of the contract that emphasizes the inbound tunnel. The inset diagram shows the relationship of the C31 Contract to the entire system. The tunnel stations are drawn to scale along the alignment of the tunnel. Work areas, access shafts, and other facilities crossing the tunnel alignment are shown at their true locations along the tunnel and are drawn at an expanded scale for emphasis.

Descriptions of the Buffalo LRRT, tunnel alignment, and regional geology are included in Chapter 4. A discussion of the local geology for Contract C31 is included in Chapter 6.

7.2 DESCRIPTION OF MACHINE AND MUCKING SYSTEM

The TBM used in the C31 inbound tunnel was manufactured by The Robbins Company of Seattle, Washington, and designated as Model 181-122. The machine was first operated in the White Pine Copper Mine, White Pine, Michigan, where it drove several lengths of 18.2 ft (5.6 m) diameter tunnel in sandstone and shale. The machine was manufactured with two concentric cutterheads rotating at 4.5 and 9.0 rpm in opposite directions and was equipped with 34 12-in. (305 mm) diameter single disc cutters. A discussion of the original machine and its performance is given by Talvensaari (1974).

The machine was purchased by S & M Constructors, who rebuilt several of its components. It was fitted with a single cutterhead. The muck buckets were restructured, and the existing cutters were replaced with 42, 15.5-in. (394 mm) diameter cutters. The machine was driven approximately 8,000 ft (2,440 m) to excavate an 18.5 ft (5.6 m) diameter tunnel in dolostone as part of the construction of the Genesee River Interceptor Southwest (GRIS) Tunnel in Rochester, N.Y. Rock properties and field instrumentation associated with the GRIS Tunnel are described by Guertin and Flanagan (1979). In-situ rock characteristics and tunneling performance are discussed by Kulhawy and O'Rourke (1981).

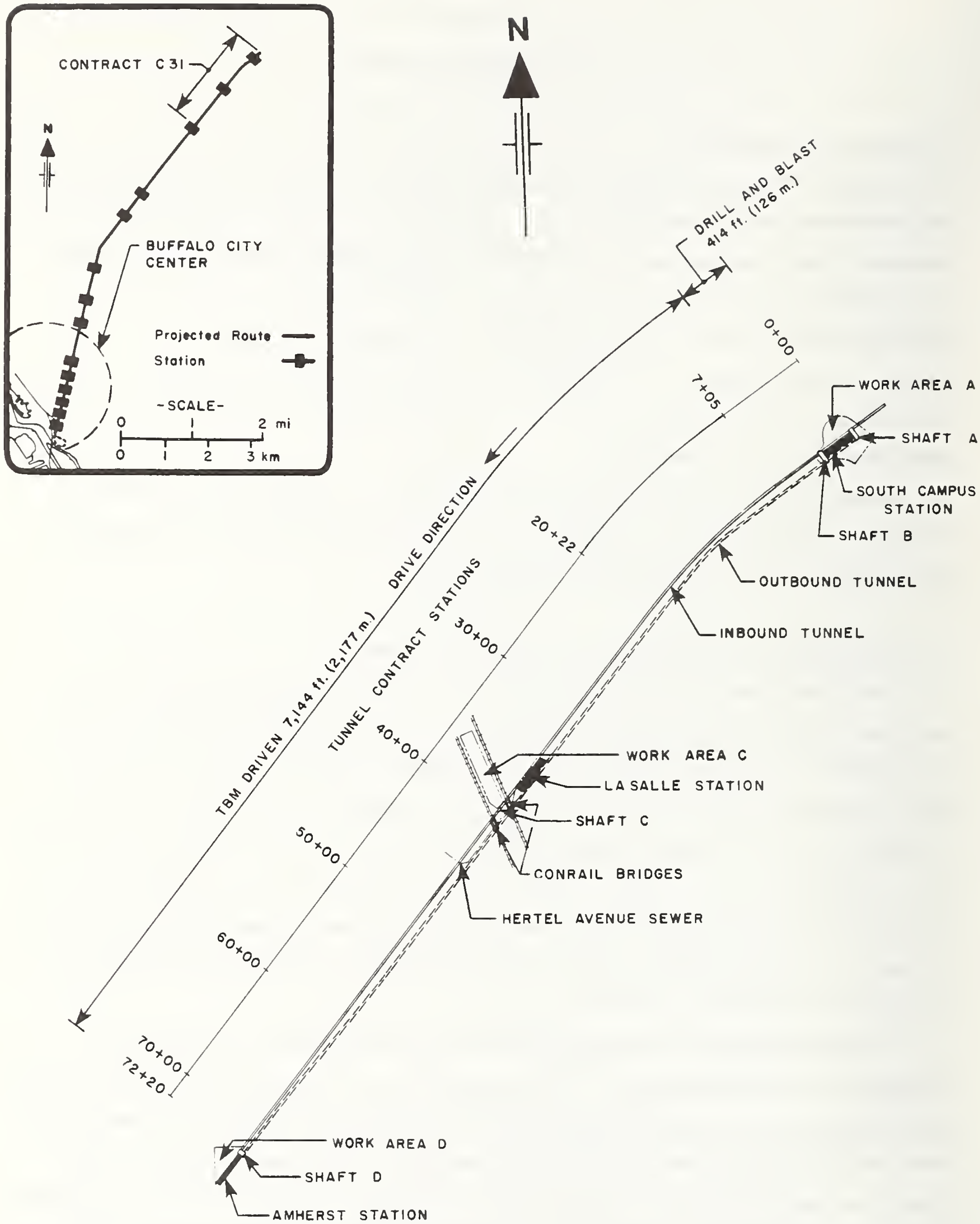


FIGURE 7.1 PLAN VIEW OF CONTRACT C31, INBOUND TUNNEL

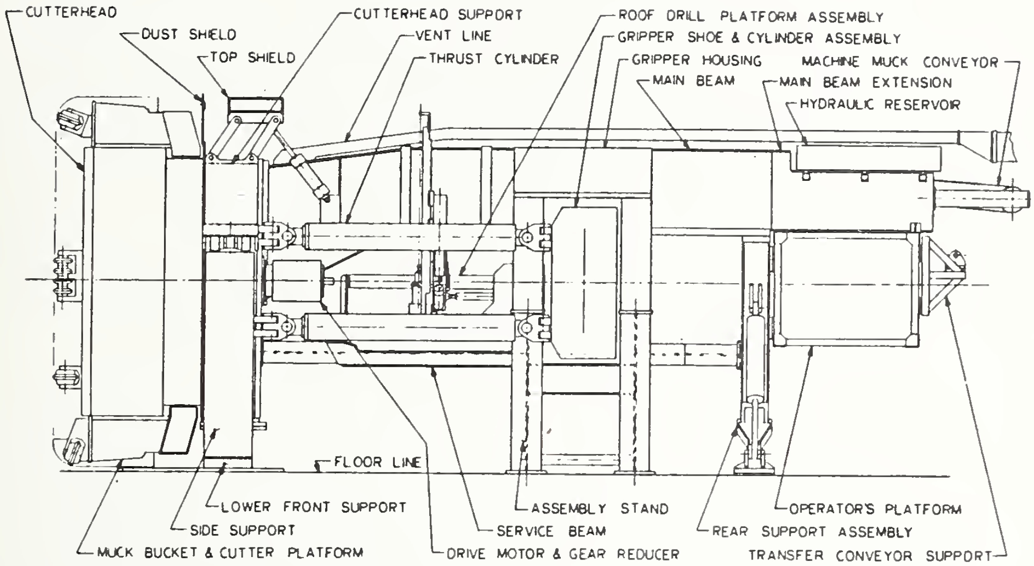


FIGURE 7.2 PROFILE VIEW OF THE C31 INBOUND TBM

The machine was substantially rebuilt for tunneling on the Buffalo LRRT. The cutterhead was converted from a domed to a flat face profile, and the main beam was lengthened by 4 ft (1.2 m). The machine was fitted with 14-in. (356 mm) diameter thrust cylinders, and the hydraulic system was completely reconditioned. A detailed discussion of these and other changes is given by Scaravilli (1981).

Figure 7.2 shows a profile view of the machine. The figure is drawn to scale and prominent components are labeled. The machine was approximately 48 ft (14.6 m) long with thrust cylinders retracted, as measured from the front of the cutterhead to the rear of the conveyor assembly. The maximum cylinder pressure was 3,500 psi (24.3 MPa) for a maximum forward thrust of 2,150 kips (9,560 kN). During tunneling, the thrust cylinders were operated at an average 1,700 psi (11.8 MPa) pressure. One cutterhead speed was available at 7.5 rpm. The cutterhead was driven by six 200 hp (149 kW) motors at an average amperage of 190 to 200 amps per motor.

Table 7.1 summarizes machine dimensions, components, and operating characteristics. As indicated in the table, the thrust cylinder pressure required to advance the TBM without face contact was not measured.

The trailing gear was similar to that used in the C11 and C31 outbound tunnels. The trailing gear was composed of a series of sleds that carried the trailing conveyor, fan line, high voltage transformer, and a variety of other mechanical and electrical equipment. The trailing conveyor transported muck to a loading station approximately 170 ft (52 m) behind the TBM face. The trailing floor components were manufactured by the Moran Engineering Sales Company of Montebello, California.

Muck was transported from the trailing conveyor to muck cars by means of a tripper system. The tripper was a mobile deflector. Starting from the leading end of the floor, the tripper was positioned at locations along the trailing conveyor to deflect muck into cars on one side of the tunnel. After the train was loaded, the tripper was returned to its starting position and used to load a train on the opposite side of the tunnel.

Each muck car had a capacity of 10 yd^3 (7.6 m^3) and was designed with a lift-off mechanism so that the car could be disengaged from its underlying wheel base and frame. At the shaft, muck cars were centered on vertical guide rails and lifted by crane to the surface. Empty cars were returned by crane and reconnected with their wheel bases.

7.3 CONSTRUCTION EVENTS

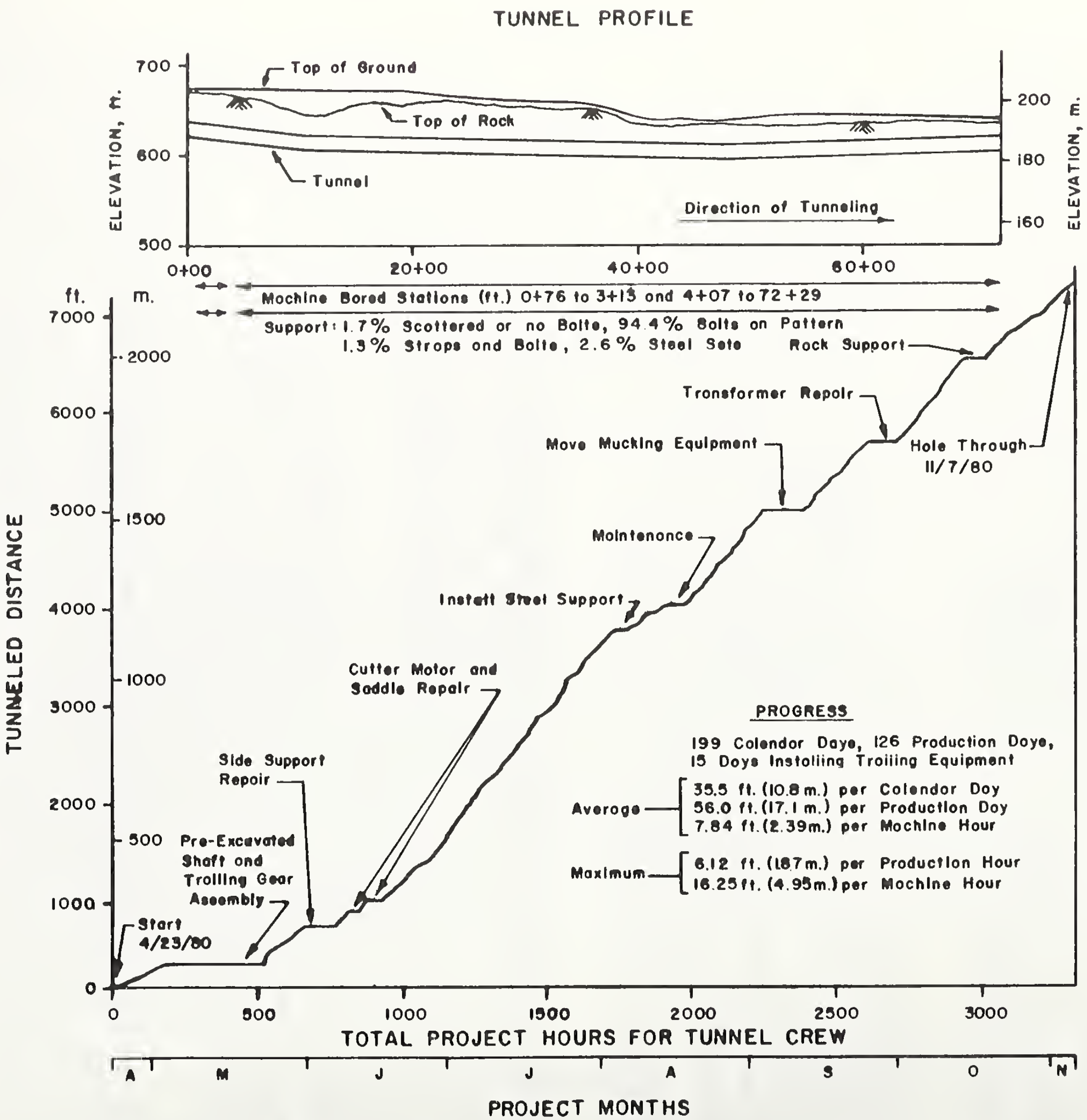
Figure 7.3 shows a plot of the tunneled distance versus the total project hours for the tunnel crew. This figure also shows a simplified tunnel profile and summarizes information about the machine, project, and lithologies encountered in the bore. As in previous chapters, the format is similar to that used by the U. S. Bureau of Reclamation (U.S. Bureau of Reclamation, 1974).

Figure 7.4 summarizes the advance rate, utilization, availability, and penetration rate as a function of tunnel station in histogram form. Each horizontal line segment of the histogram plots corresponds to one shift. The length of the line segment is proportional to the distance tunneled during the shift. Each line segment is plotted above the horizontal axis at a distance proportional to the value of the performance

TABLE 7.1 SUMMARY OF DIMENSIONS, COMPONENTS, AND OPERATING CHARACTERISTICS OF THE C31 INBOUND TUNNEL

Manufacturer	The Robbins Company, Seattle, Washington
Model Number	181-122, substantially rebuilt
Diameter	18.5 ft (5.6 m)
Length	48.0 ft (14.6 m)
Weight	700 kips (3.11 MN)
Drive Motors	6
Drive Motor Rating	200 hp (149 kW) at 216 amps
Average Operating Amps	200 amps
Cutterhead Speeds	7.5 rpm
Thrust Cylinders	4
Cylinder Diameter	14.0 in (356 mm)
Stroke Length	4.0 ft (1.2 m)
Maximum Cylinder Pressure	3,500 psi (24.3 MPa)
Average Operating Pressure	1,700 psi (11.7 MPa)
Cylinder Pressure to Move TBM without Face Contact	not measured
Number and Types of Cutters	39 single disc cutters, 15.5 in. (394 mm) diameter 2 twin disc center cutters, 12.0 in. (305 mm) diameter
Conveyor Belt Width	26.0 in. (762mm)
Conveyor Belt Speed	340 ft/min (104 m/min)
Conveyor Capacity[a]	360 yd^3/hr (275 m^3/hr)

[a] based on troughing angle of 25 degrees, surcharge angle of 25 degrees, and muck unit weight of 100 lbs/ft^3 (15.7 kN/m^3)



MACHINE DATA

Robbins Model 181-122

Diameter 18.5 ft. (5.64 m)

Length 68 ft (20.7 m)

Weight 350 tons (3.11 MN)

Max. Thrust 2155 kips (9.59 MN)

Recycle Stroke 48 in. (1.22 m.)

Cutterhead Rotation 7.5 rpm

Cutters 39 15.5 in. (394 mm.) Single Disc
4 12 in. (305 mm.) Single Disc Center

Motors 6 200 hp.

PROJECT INFORMATION

7059 ft. (2152 m.) Total Length

Variable Grade: Uphill Max. 0.56 %
Downhill Max. 2.46 %

Muck Loading by Tripper

Muck Disposal Through Shaft by Crane Dumping of Muck Cars

Contractor: S & M Constructors, Inc.

Owner: Niagara Frontier Transportation Authority, Buffalo, New York

LITHOLOGY

Dolostone and Dolomitic Shale, Unconfined Compressive Strengths from 6 ksi (42 MPa) to 47 ksi (320 MPa)

FIGURE 7.3 TUNNELED DISTANCE VERSUS CUMULATIVE PROJECT HOURS AND PROJECT INFORMATION FOR THE C31 INBOUND TUNNEL

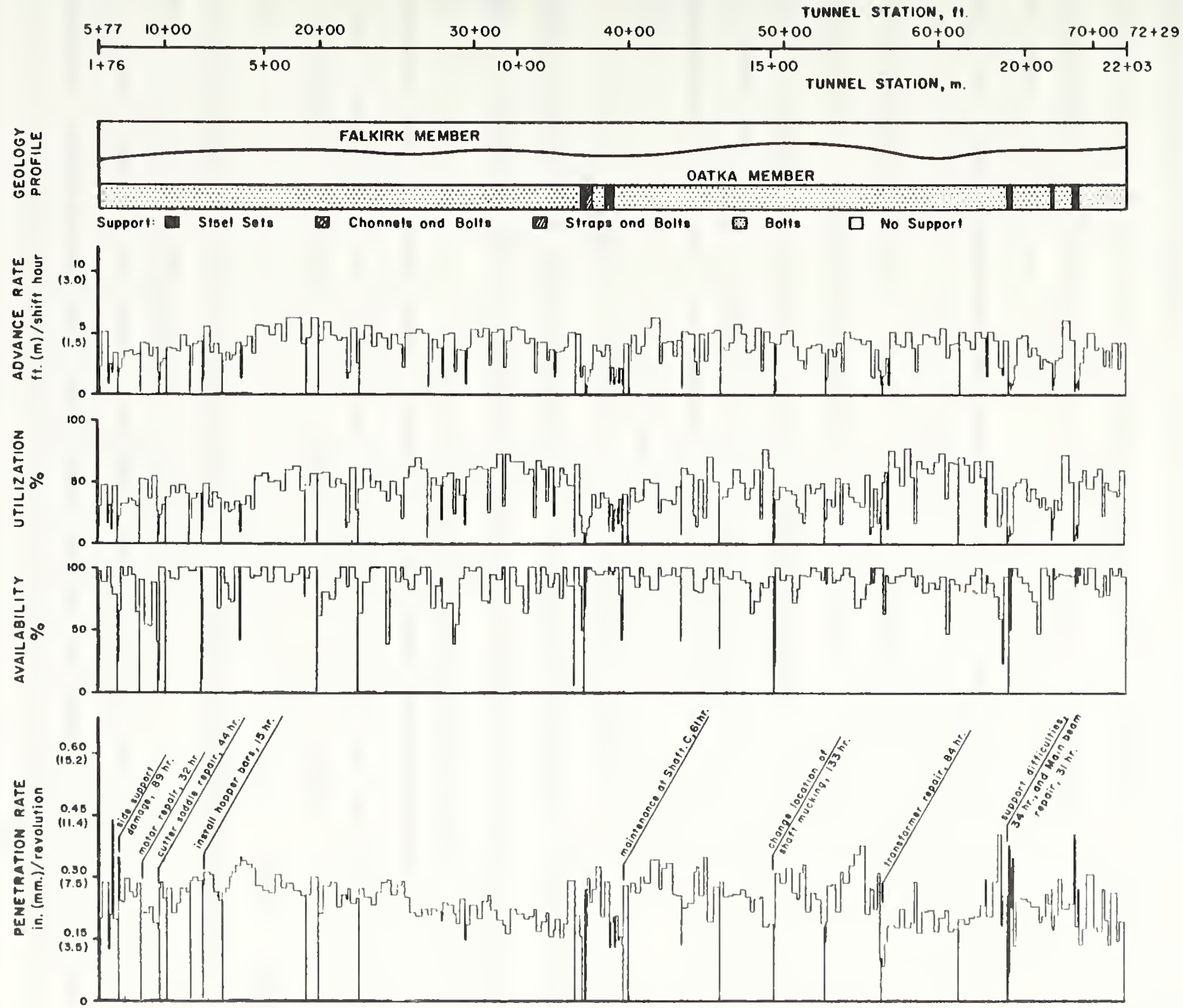


FIGURE 7.4 TBM PERFORMANCE RECORD, TUNNEL GEOLOGY, AND SUPPORT FOR THE C31 INBOUND TBM

parameter calculated for the shift. The utilization and penetration rates were calculated on the basis of machine boring time as recorded by the contractor and read on the machine clock at the start and end of each shift. Tunnel stations used in this report are in units of feet, conforming with conventional U.S. practice. The clock was started at tunnel Station 5+77, and the histograms begin at this point. Machine clock readings were not recorded for the final 8 ft (2.4 m) of tunnel excavation, so that the hours during the final two shifts of the project were not included in any of the calculations.

If tunneling delays at a given station were longer than the duration of a shift, the performance parameters at that station are equal to zero, and the plot appears as a vertical line intersecting the horizontal axis. The causes and durations of major delays are listed in the plot of penetration rate versus distance at the station where the delays occurred. Figure 7.4 also shows a simplified illustration of the geologic profile as mapped in the excavated tunnel, and the types of initial support used at various locations in the tunnel. A detailed record of the geology with stratigraphic identifications, joint planes, overbreak, and support is included in Appendix A.

In combination, Figures 7.3 and 7.4 provide a summary of the tunneling events and TBM performance referenced by the cumulative hours and distance tunneled. They index shift time and tunnel station for the discussion of construction events that follows.

The work schedule consisted of a five day work week. The contractor ran three shifts per day of 8.5, 8.0, and 7.5 hour durations except between 28 April and 10 June, when the shift times were 8.0, 7.5, and 7.0 hours.

The TBM was assembled in Work Shaft A, and was advanced through a drill-and-blast tunnel to Station 0+76 where boring was started. Twenty-four shifts were required to reach Shaft B, Station 3+13. Construction of the trailing floor sleds and mucking equipment was started 3 May 1980, and 15 working days were required for completion.

On 23 May 1980, boring started again and the next three shifts were used to improve the trailing floor operations. Before Station 6+92, the presence of weak rock in the invert had caused the TBM to loose grade. The TBM operators used 2 ft (0.6 m) recycle strokes and fully extended the cutterhead side supports in an effort to regain grade. At Station 6+92, the left side support was torn at the pivot, and excavation was stopped for 13 shifts for repairs. When boring started again, two cutterhead motors burned out. One motor was repaired and the TBM was operated with five motors on line until Station 8+40 when the starter contacts burned out on two other motors. Five shifts were required to replace the contacts and the TBM was again operated with five motors until Station 10+09, when a new sixth motor was installed. Between the start of the tunnel and Station 9+63, several of the gage cutter saddles were damaged and at Station 9+63, excavation was stopped for six shifts for welding repairs.

The TBM was operated with all six cutterhead motors between Stations 10+09 and 25+85. At several locations between Stations 10+09 and 16+50, rock became jammed in the main beam. At Station 12+39, excavation was stopped for two shifts to install bars across the mouth of the TBM conveyor hopper. As boring continued, muck jams formed at the cutterhead buckets and the TBM was operated at relatively low thrust pressures to avoid overheating the cutterhead motors. At Station 14+88, the bars were removed.

At Station 25+85, one cutterhead motor burned out and was removed. This motor was replaced at Station 27+26, when another motor burned out. The contacts on a third motor burned out at Station 31+53, and the TBM was operated with only four functioning cutterhead motors from this location to Station 39+67, near the midpoint of the tunnel.

Excavation was stopped on 18 August 1980 for eight shifts at Shaft C, between the two Conrail bridges. This delay appears as a horizontal line near the center of the plot of tunneled distance versus project hours in Figure 7.3. Thirty-two cutters were changed, a new cutterhead motor was installed, and the rock bolt drills were repaired. Between Stations 39+67 and 56+37, the TBM was operated with five cutterhead motors. Steel sets were installed in two areas in this tunnel section, and the excavation was often down due to rock bolt drill repair. At Station 39+97, the circuit breakers in the transformer burned out and had to be replaced. At Station 49+53, excavation was stopped for 19 shifts to move the surface mucking equipment, ventilation line exit, and power supply to Shaft C so that the contractor could begin concreting operations in the north half of the tunnel. Switches and a section of double track were installed at the floor of Shaft C and one cutterhead motor was replaced. From Station 49+53 to the end of the tunnel, there were many train delays primarily caused by the limited space for maneuvering the crane boom and muck cars in Work Area C.

At Station 56+37, the transformer breakers burned out and excavation was stopped for 11 shifts to install and rewire a new transformer. Boring started again on 3 October 1981 with four motors on line. From Station 56+37 to the end of the tunnel, only four or five motors were operating. Steel sets were installed in three areas of this tunnel section. Rock slabs occasionally fell onto the TBM roof supports and had to be broken up and removed. At Station 64+64, a crack was found in the TBM main beam and welding repairs were made over the next six shifts. At Station 66+88, the control panel transformer burned out and had to be replaced.

In summary, tunneling for the C31 inbound tunnel commenced on 23 April 1980 and ended on 7 November 1980. The tunneling required 199 calendar days, of which 126 were production days. Between Shafts A and B, a distance of 237 ft (72 m) was mined before the trailing equipment was assembled. Between Shafts B and D, 6,814 ft (2,077 m) were mined with the trailing gear in tow. The time required to drive the tunnel between Shafts A and B was 170 hours (24 shifts). Trailing gear installation required 331 hours (44 shifts) and the main tunnel was bored during 2,783 hours (353 shifts), of which 113 hours (15 shifts) were worked before the machine clock was activated.

7.4 TUNNELING PERFORMANCE

Table 7.2 summarizes the average advance rate, utilization, availability, and penetration rate for the inbound tunnel of Contract C31. The average advance rate and utilization were calculated on the basis of the cumulative project hours from the time the TBM trailing gear was assembled and the machine clock was operating at Station 5+77, to Station 72+21, 8 ft (2.4 m) before holing through at Shaft D. These averages include time devoted to maintenance at Shaft C and time required to move the mucking system to Shaft C. The average penetration rate and utilization were calculated in the same manner as the

TABLE 7.2 AVERAGE ADVANCE RATE, UTILIZATION, AVAILABILITY, AND PENETRATION RATE FOR THE C31 INBOUND TUNNEL

PARAMETER	AVERAGE VALUE
Advance Rate	2.5 ft/hr (0.76 m/hr)
Utilization	28.9 percent
Availability	81.6 percent
Penetration Rate	8.6 ft/hr (2.6 m/hr)
	0.23 in/revolution (5.8 mm/revolution)

individual shift penetration rates and utilizations by using the time elapsed on the machine clock and recorded on the contractor's shift reports.

In general, utilization was low in sections where the rock was highly jointed and weathered, as in the first 1,600 ft (488 m) of the drive and at other places where steel sets were installed. Sustained high values of utilization generally correlate with sections where the rock was unweathered and contained few fractures, and where train delay and rock bolt drill repair times were minimal.

The penetration rate was influenced primarily by two factors: 1) the degree of jointing and weathering of the rock, and 2) the number of functioning drive motors. Some of the highest penetration rates were achieved when the face was in heavily jointed and weathered rock. The contrast in penetration rate for boring with five and six cutterhead motors is shown in Figure 7.4 where the average penetration rate between Stations 19+92 and 25+85, with six motors on line, is approximately 19 percent greater than the average rate between Stations 25+85 and 31+91, with five motors on line.

Availability of the TBM was affected principally by general maintenance and repairs of the cutter saddles, main beam, and hydraulic

TABLE 7.3 TABULATION OF DOWNTIME AS A PERCENTAGE OF TOTAL SHIFT HOURS FOR THE C31 INBOUND TUNNEL

TBM Maintenance and Repair	Percentage Downtime	Back up Systems	Percentage Downtime	Ground Conditions	Percentage Downtime	Additional Itmes	Percentage Downtime
Cutter Change	2.5	Power Supply	negligible	Water Inflow	0.0	Shaft Downtime	2.3
General Maintenance and Inspection	7.7	Cable Utilities Fanline	5.0	Steel Sets	5.7	Other (Supplies, Blasting, Shift Changes, Restroke, etc.)	7.3
Lube Oil	1.4	Survey	0.8	Bolts/Straps	1.7		
Hydraulics	5.3	Car Pass	not used	Bolt Drill Repair	3.5		
Motors	3.5	Tripper	0.4	Scaling/ Rock Jam	2.3		
TBM Conveyor	0.4	Trailing Gear Conveyor	1.1	Gripper Difficulty	0.1		
Electrical	5.7	Train Delay	5.6	Clearance	0.3		
		Shaft Operations	5.7				
		Laying Rails	0.2				
		Derailment	2.3				
Subtotal	26.5	Subtotal	21.1	Subtotal	13.6	Subtotal	9.9

GRAND TOTAL PERCENTAGE DOWNTIME 71.1

system components. In contrast with TBM applications on the other Buffalo LRRT tunnels, there was little or no correlation of low availability with areas where steel sets were installed.

7.5 DOWNTIME ANALYSIS

Table 7.3 summarizes the delay, or downtime, associated with various components of the C31 inbound tunneling. As described in Chapter 4, individual causes of delay have been grouped into the four categories shown. A description of downtime categories and a detailed discussion of tunneling delays for the C31 inbound tunnel is included in Appendix B. The downtime percentages were calculated on the basis of total

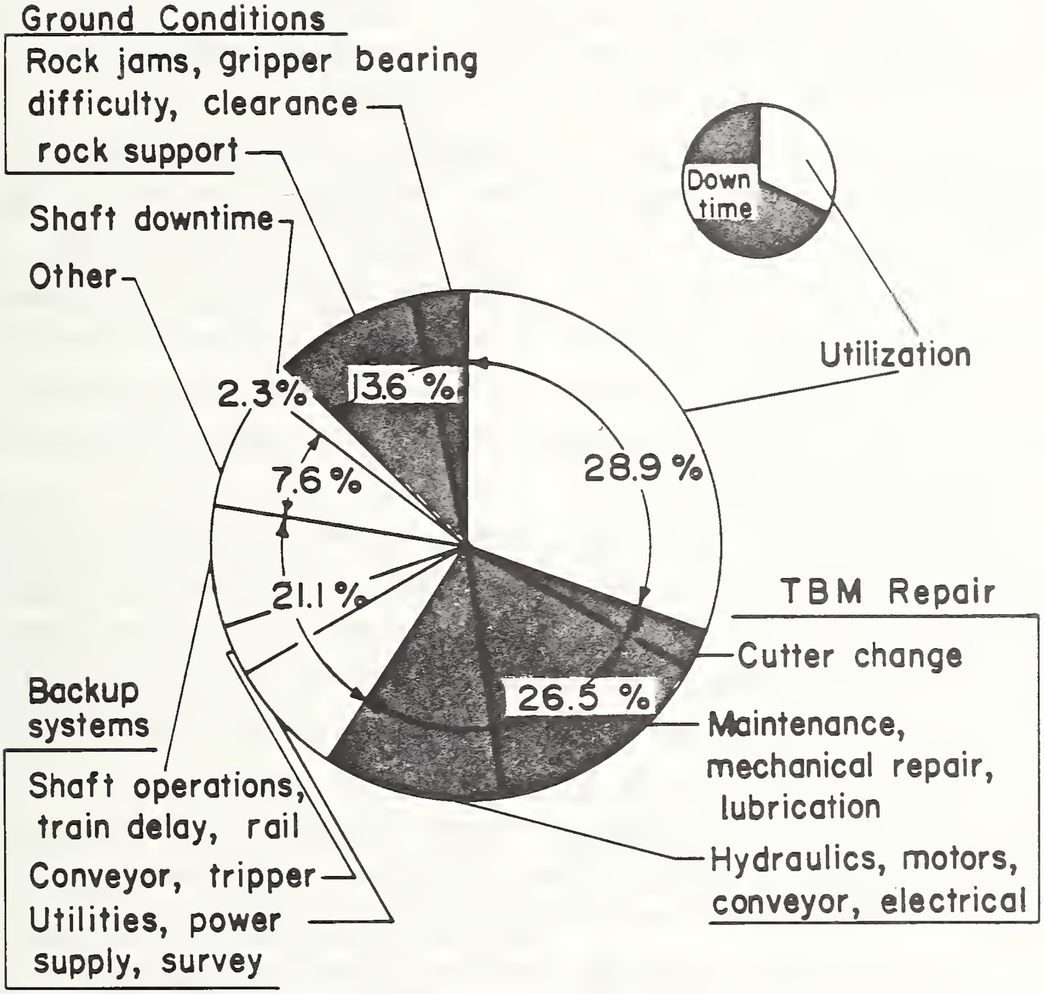


FIGURE 7.5 SUMMARY OF DOWNTIME AS A PERCENTAGE OF TOTAL SHIFT HOURS FOR THE C31 INBOUND TUNNEL

project hours excluding time before the machine clock was put into operation.

Figure 7.5 shows the downtime percentages in the form of a pie chart. Approximately 71 percent of the shift hours was spent on delays resulting in an average machine utilization of 29 percent.

The major causes of downtime under the category of TBM maintenance and repair mechanical and hydraulic repairs on the TBM and problems with electrical components on the TBM and trailing floor. Of the total shift time, 7.7 percent was spent on TBM maintenance and repairs, particularly of cutterhead components and the main beam, and 5.3 and 5.7 percent were spent on hydraulic and electric repairs, respectively.

Utility service, train delays, and shaft operations were the principal causes of downtime under the category of backup systems. Repair and relocation of the shaft equipment required 5.7 percent of the total shift time, of which 5.3 percent was required for the move to Shaft C. Train delays amounted to 5.6 percent of the total shift time, with many of these delays associated with slow muck removal at Shaft C. Utility supply required 5.0 percent of the total shift time, more than 60 percent of which was used to extend the electric cable to the heading and to install transformers.

Downtime associated with ground conditions was principally related to steel set installation and bolt drill repair. Steel set installation accounted for 5.7 percent of the total shift time, and downtime associated with steel sets, rock jams, scaling, clearance, and gripper difficulties amounted to 8.4 percent. Rock bolt drill repairs required 3.5 percent of the total shift time.

The category of shaft downtime includes scheduled downtime at Shaft C for cutter changes and system maintenance. The category of other includes downtime for shift changes, bringing supplies to the heading, and evacuation of the TBM crew when methane was detected or when blasting was performed for side passages. Records were not available for the time required to reset the thrust cylinders in preparation for a forward stroke, and this delay also is included in the category of "other". Shift changes and reset times were the principal causes of delay in this category.

7.6 CUTTER CONSUMPTION

There were a total 48 cutters on the cutterhead of the C31 inbound TBM. Single disc, 15.5-in. (394 mm) diameter cutters were used in the outer 39 positions and twin disc, 12-in. (305 mm) diameter cutters were used at the four center positions.

Records of 54 cutter changes were available for the 7,059 ft (2,152 m) of machine bored tunnel. Cutters needing repair were removed and shipped to the manufacturer, Atlas Copco Jarva, Inc., of Solon, Ohio.

Neither the contractor nor the resident engineer kept complete records on cutter changes. Thirty-two cutters were changed at Shaft C during scheduled maintenance. The remaining 22 cutters were changed at other locations in the tunnel.

The contractor changed cutters at the rate of one cutter per 1,301 yd^3 (995 m^3) of excavated rock. For 25 of the changes, the records indicate whether the cutter was in a face or gage position. Of these 25, 18 replacements were made in the outer 12 gage positions.

7.7 SUMMARY

From the time the TBM was installed, excavation of the C31 inbound tunnel required 3,284 shift hours, of which 331 were spent on trailing gear assembly and 170 were spent on excavation of the short tunnel between Shafts A and B. Excluding the time before and during the erection of the trailing gear and before the machine clock was in operation, the average advance rate was 2.5 ft/hr (0.76 m/hr) for 6,644 ft (2,025 m) of tunnel. The overall TBM utilization was 29 percent.

Major geologic controls on tunneling performance included the presence of highly jointed rock. Penetration rates were relatively high in areas of jointed and weathered rock, while utilizations were relatively low in these same sections.

Major mechanical causes of downtime included repairs of the main beam and cutter saddles, TBM hydraulic system components, and rock bolt drills. Long train delays occurred early in the drive and after the surface mucking operations were moved to Shaft C. Electrical problems with the transformer and the cutterhead motors were also major sources of downtime.

CHAPTER 8

CULVER-GOODMAN TUNNEL

8.1 PROJECT OVERVIEW

The Culver-Goodman Tunnel is part of a combined sewer overflow storage and transmission system in the metropolitan area of Rochester, New York. The Culver-Goodman Tunnel is owned by the Rochester Pure Waters District and other system components are owned by either the Rochester or the Irondequoit Pure Waters Districts. When completed, the system will be operated by the Monroe County Department of Wastewater Management. Funding for the project is provided by the U.S. Environmental Protection Agency, the New York State Department of Environmental Conservation, and the Rochester Pure Waters District.

A plan view of the system is shown in Figure 8.1. The Culver-Goodman Tunnel conveys waste water from Culver Road and Goodman Street by gravity drainage into the Cross-Irondequoit Interceptor Tunnel, which directs the flow north to a pump station and a waste water treatment facility. The next generation of tunnels, the Combined Sewer Overflow Abatement Project (CSOAP), has been designed and is scheduled for initial construction in 1983.

The overall system design was performed by Lozier Engineers, Inc., of Rochester, New York, with design of the Culver-Goodman Tunnel performed by Jenny Engineering Corporation of South Orange, New Jersey. The geotechnical consultant for the Culver-Goodman Tunnel was H & A of New York, P.C. Construction of the tunnel and drop shafts was performed by the joint venture of J.F. Shea Company, Inc., and Peter Kiewit Sons, Inc.

The project involved construction of 28,322 ft (8,633 m) of 16.7 ft (5.1 m) internal diameter tunnel, 2,500 ft (762 m) of 13.0 ft (4.0 m) internal diameter tunnel, and 880 ft (268 m) of 8.0 ft (2.4 m) internal diameter tunnel. In addition, 15 drop shafts, three diversion structures and one control structure at the northeast end of the project were built. Figure 8.2 shows a plan view of the contract work which includes the tunnel, drop shaft, and diversion structure locations. The main tunnel is subdivided into three sections, or legs. Excavation of the Densmore and Goodman legs was completed during this investigation. The

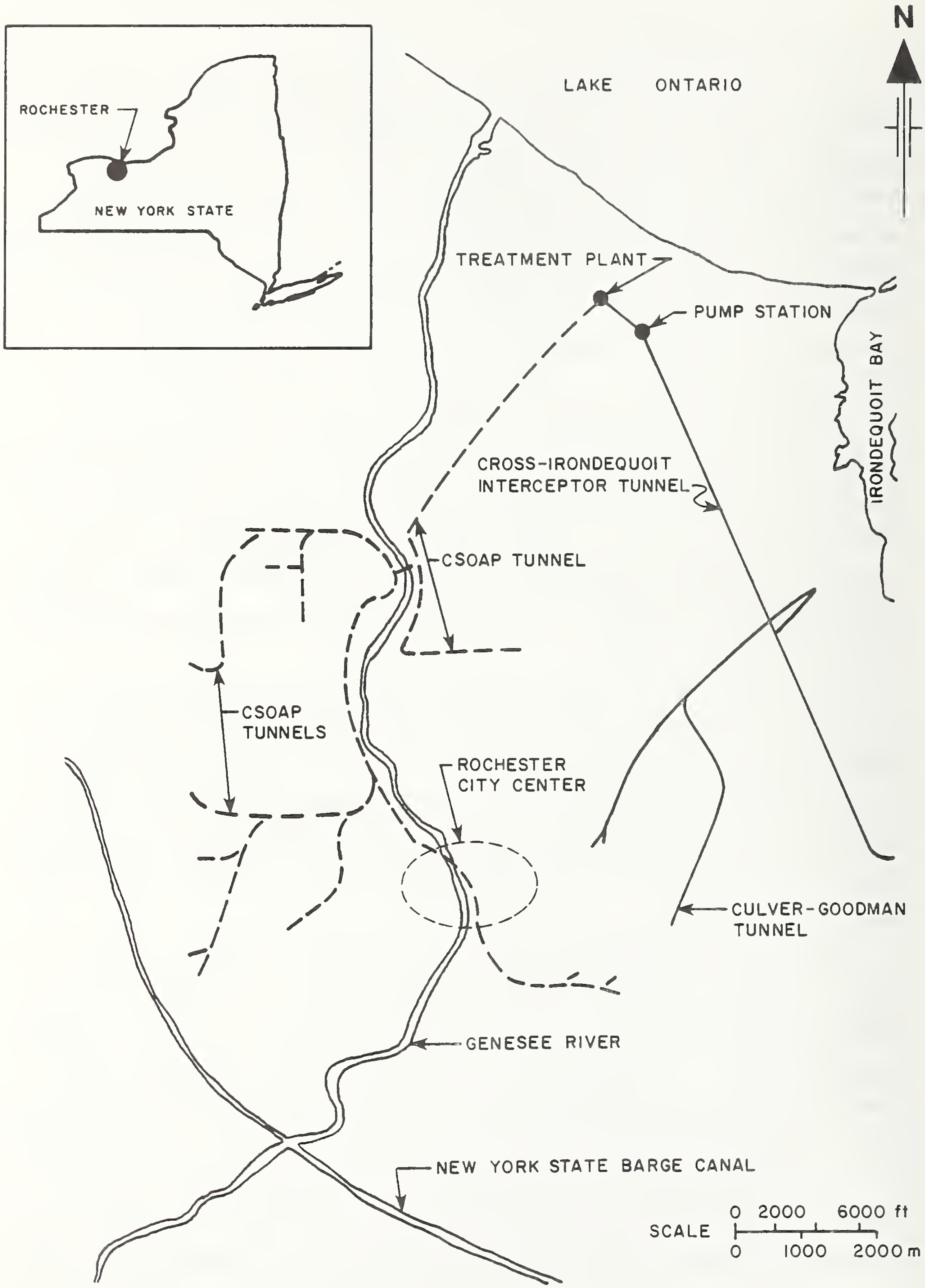


FIGURE 8.1 PLAN VIEW OF THE ROCHESTER STORM WATER AND SEWER TUNNEL SYSTEM

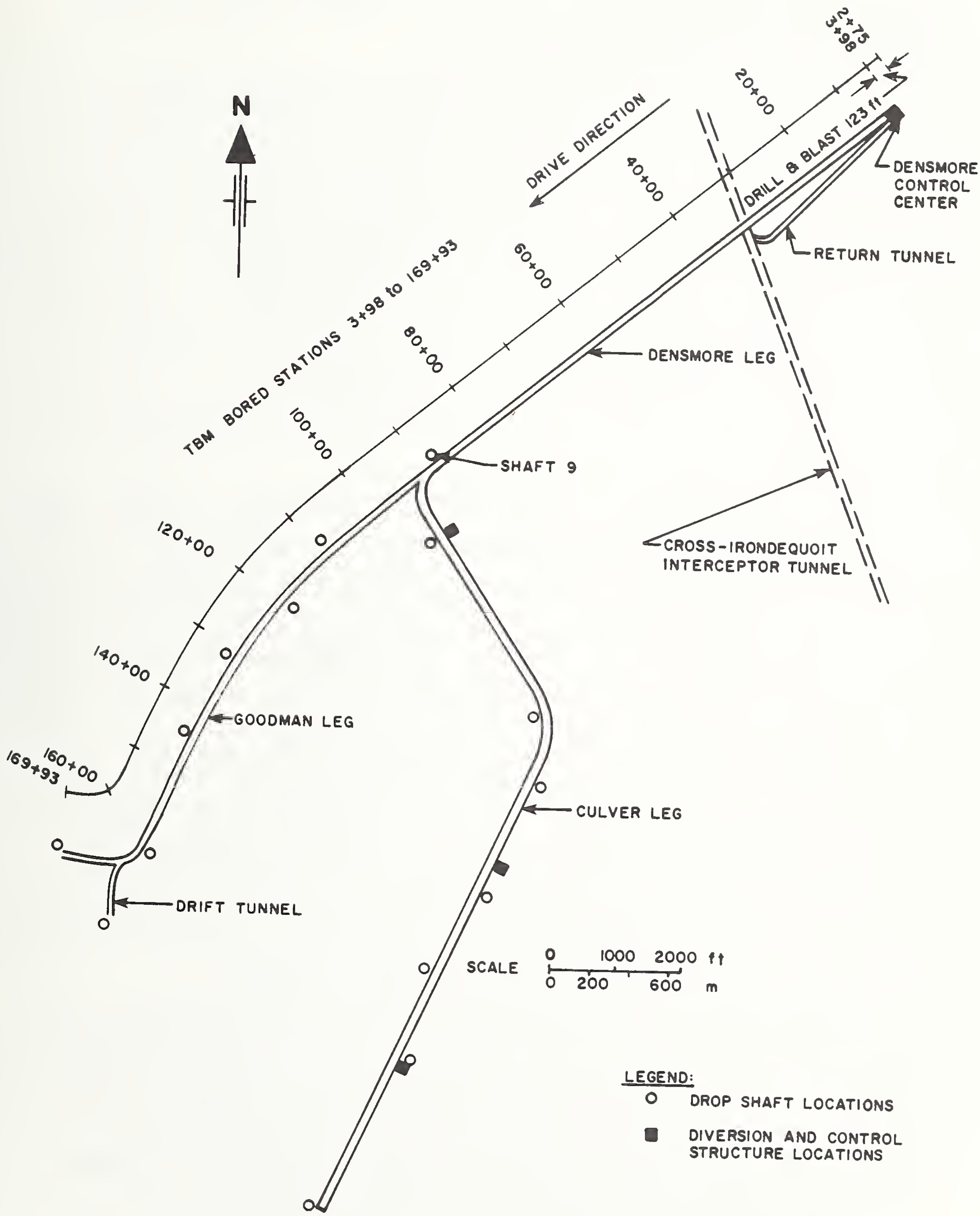


FIGURE 8.2 PLAN VIEW OF THE CULVER-GOODMAN TUNNEL

tunnel stations for these two segments are drawn to scale along the alignment of the tunnel in Figure 8.2.

The contractor began at the work area at the northeast end of the contract, and excavated an adit from the portal by drill-and-blast methods. The adit was supported by full circular steel ribs (WF 6x25) at 4 to 5 ft (1.2 to 1.5 m) centers and served as a starter tunnel for the TBM. Most drop shaft excavation was performed by drill-and-blast techniques after TBM mining in each leg had been completed. The drop shaft at the southwest end of the Goodman leg was used as a TBM maintenance area. Drop Shaft 9, shown in Figure 8.2 near the intersection of the three legs, was excavated before the TBM mined past it. During the excavation of the Goodman leg, this shaft was used to vent the fan line exhaust from the tunnel.

Horizontal alignment of the tunnel was designed to intercept sewer overflow from locations along Goodman Street and Culver Road. To intercept an additional overflow location, a 500 ft (152 m) radius curve and a drift tunnel were included in the horizontal alignment at the southern end of the Goodman leg. The northeast end of the tunnel was located so that overflow from the Culver-Goodman Tunnel, during peak flows, could be directed into Densmore Creek. Vertical alignment was set to allow gravity drainage into the Cross-Irondequoit Interceptor Tunnel. The Culver-Goodman Tunnel was bored from the northeast to the southwest on an uphill grade of 0.10 percent. The return tunnel grade was set at 0.15 percent to connect the Densmore Control Structure to an existing stub of the Cross-Irondequoit Tunnel. The Densmore leg crosses approximately 60 ft (18 m) above the Cross-Irondequoit Tunnel.

The equipment mobilization area in the vicinity of Densmore Creek had previously been used as a source of borrow material for highway construction. Muck produced in tunnel excavation was used as fill material on site. After completion of the project, the land will be donated to the Town of Irondequoit, which will reclaim the area as a town park.

8.2 GEOLOGIC SETTING

The subsurface geology in the Rochester area consists of a sequence of glacial deposits of varying thickness overlying a several thousand foot thick sequence of lower Paleozoic sedimentary rocks. The rock beds strike approximately east-west and dip to the south at about 40 to 50 ft/mile (12 to 15 m/km).

Glaciation in the area was extensive. Glacially derived deposits show great variability in terms of gradation, sorting, thickness, and lateral extent. Glacial landforms found near Rochester include drumlins, terminal moraines, lake beds, beach deposits, kames and eskers.

The bedrock in the vicinity of the Culver-Goodman tunnel consists of limestone, dolostone, shale and sandstone beds deposited during the Ordovician and Silurian periods. A stratigraphic column that includes the near surface bedrock in the tunnel area is shown in Figure 8.3.

Members of the Lockport group are at the top of rock at many locations in the Rochester area. The group includes fossiliferous dolostone in which bedding frequency decreases with depth. Vuggy zones and shale partings are common, and the lower part of the unit is characterized by a high shale content. The Lockport Group is approximately 180 ft (55 m) thick, and was only encountered during drop shaft construction.

The Rochester Shale underlies the Lockport Group. This formation is the youngest member of the Clinton Group, and is approximately 85 ft (26 m) thick. The Rochester Shale is a dark gray, fossiliferous, calcareous mudstone. Thin beds of dolostone and limestone are common. The lower 10 to 15 ft (3 to 5 m) of the unit are often shaley and may be subject to slaking. The Rochester Shale was encountered in drop shaft excavation and in the Culver leg of the tunnel.

Beneath the Rochester Shale is the Irondequoit Limestone. This unit is approximately 18 ft (5.5 m) thick and is a thinly to medium bedded, medium to coarsely crystalline, fossiliferous limestone. Thin interbeds of dolomitic shale are common, and are thickest in the lowest quarter of the formation, where they are 3 to 6 in. (76 to 152 mm) thick. The Irondequoit Limestone was the youngest unit penetrated by tunneling in the Densmore and Goodman legs.

The Williamson Shale underlies the Irondequoit, and is approximately 7 ft (2.1 m) thick. This unit appears as a dark green or black shale with a few thin limestone beds. The contact between the Williamson and the underlying Lower Sodus Shale is unconformable, and represents an erosion surface.

SYSTEM	GROUP	FORMATION	MEMBER	LITHOLOGIC DESCRIPTION
SILURIAN	LOCKPORT			180 ft (55 m) thick, gray, fossiliferous DOLOSTONE
SILURIAN	LOCKPORT / CLINTON	ROCHESTER	GATES	80 - 115 ft (24-35 m) thick, dark gray gray, fossiliferous, MUDSTONE and SHALE. Upper 25 ft (8 m) dark gray, slightly fossiliferous, fine to medium-grained DOLOSTONE. Shale, calcareous with occasional gypsum-filled seams and vugs.
SILURIAN	CLINTON	IRONDEQUOIT		15-23 ft (4.6-7.0 m) thick, light gray, thin to medium bedded, medium to coarse-grained LIMESTONE.
SILURIAN	CLINTON	WILLIAMSON		6-10 ft (1.8-3.0 m) thick, dark green SHALE with thin LIMESTONE beds.
		UNCONFORMABLE CONTACT		
SILURIAN	CLINTON	LOWER SODUS		15-18 ft (4.6-5.5 m) thick, green or purple, moderately to thinly bedded fossiliferous SHALE with occasional limestone seams.
SILURIAN	CLINTON	REYNALES	WALLINGTON	14-16 ft (4.3-4.9 m) thick, thin to medium bedded, crystalline, dolomitic LIMESTONE.
SILURIAN	CLINTON	REYNALES	FURNACEVILLE	1-2 ft (0.3-0.6 m) red, oolitic, hematitic LIMESTONE.
SILURIAN	CLINTON	REYNALES	HICKORY CORNERS	1.5-3 ft (0.5-0.9 m) LIMESTONE AND SHALE interbeds.
SILURIAN	CLINTON	MAPLEWOOD		15-21 ft (4.6-6.4 m) thick, green, thinly bedded SHALE, calcareous in places.
SILURIAN	CLINTON	THOROLD		1-3 ft (0.3-0.9 m) fine-grained, cemented SANDSTONE.
SILURIAN	MEDINA	GRIMSBY		≈55 ft (117 m) thick, red and green mottled, fine to coarse-grained, well cemented, medium to massive bedded SANDSTONE. Middle more argillaceous with beds of red and green shale .
ORDOVICIAN		QUEENSTON		>1000 ft (>3000 m) thick, red, fine-grained, micaceous, thinly bedded silty SHALE and shaley SILTSTONE. Several SANDSTONE beds present at top.

FIGURE 8.3 STRATIGRAPHIC COLUMN, ROCHESTER, NEW YORK

The Lower Sodus Shale is a green or purple, medium to thinly bedded, fossiliferous shale with occasional limestone seams. The green shale occurs primarily in the upper part of the unit, where most of the limestone seams are found. Its average thickness is 17 to 18 ft (5.2 to 5.5 m).

Beneath the Lower Sodus is the Reynales Limestone. This formation is approximately 20 ft (6.1 m) thick and has been subdivided into three members. The youngest member, the Wallington Limestone Member, is 14 to 16 ft (4.3 to 4.9 m) thick and generally appears as a gray, thinly to medium bedded, crystalline, dolomitic limestone with shale interbeds and partings. Beneath the Wallington is the Furnaceville Hematite Member, which is a red, oolitic, fossiliferous, hematitic limestone, approximately 1 to 2 ft (0.3 to 0.6 m) thick. At the base of the Reynales is the Hickory Corners Limestone Member. This unit is composed of interbedded crystalline limestone and shale, and is approximately 1.5 to 3.0 ft (0.5 to 0.9 m) thick.

The Maplewood Shale underlies the Reynales Limestone. The Maplewood is approximately 21 ft (6.4 m) thick and is a slightly calcareous, green, finely laminated shale. The lower 3 ft (0.9 m) are more sandy, contain red and green mottling, and represent a gradational transition to the underlying Thorold Sandstone.

The Thorold is a light gray to green, fine-grained, well-cemented, slightly calcareous sandstone. The Thorold Sandstone has been measured as 5 to 10 ft (1.5 to 3.0 m) thick in surface outcrops, but when intercepted by the Culver-Goodman Tunnel, the Thorold was only 1.5 to 2.5 ft (0.5 to 0.8 m) thick. The Thorold has also been referred to as the Kodak Sandstone.

Beneath the Thorold Sandstone is the Grimsby Sandstone, which is approximately 55 ft (17 m) thick. This unit is generally described as a coarse grained, medium bedded, red and green-mottled sandstone and some shaley sandstone. The middle portion of the Grimsby is more thinly bedded than either the top or the bottom of the formation, and contains some beds of red and green shale. The contact between the Grimsby and the underlying Queenston Formation is not clearly defined because there is no abrupt change in lithology between the two units.

TABLE 8.1 SUMMARY OF AVERAGE RQD AND UNCONFINED COMPRESSIVE STRENGTH FOR ROCK FORMATIONS IN THE ROCHESTER AREA (Haley and Aldrich, 1978)

Stratigraphic Unit	AVERAGE RQD (%)	Average Unconfined Compressive Strength	
		ksi	MPa
Lockport	83	31.9	(220)
Rochester	85	16.5	(114)
Irondequoit	91	17.8	(123)
Williamson	81	11.9	(82)
Lower Sodus	80	10.8	(74)
Reynales	83	21.3	(147)
Maplewood	80	9.5	(65)
Thorold	90	18.8	(130)
Grimsby	94	19.4	(134)
Queenston	91	14.1	(97)

The Queenston consists of thinly bedded shales, siltstones and fine-grained sandstones. The rock is typically red and green-mottled, well-cemented, laminated to thinly bedded, and micaceous. The upper 10 to 15 ft (3.0 to 4.6 m) of the Queenston Formation contains several 3 to 5 ft (0.9 to 1.5 m) thick beds of medium to fine-grained sandstone. The total thickness of the Queenston is greater than 1,000 ft (305 m). Only the upper 10 ft (3 m) of the unit were encountered at the start of the Densmore leg.

The site exploration program covering the length of the Culver-Goodman contract included 60 NX-size, 2.13 in. (54 mm) diameter, borings at spacings of 400 to 1,000 ft (122 to 305 m). Borings along the tunnel alignment were drilled from 78 to 226 ft (24 to 69 m) below the ground surface. All rock core was photographed, logged and stored. Logging consisted of a lithologic and stratigraphic description of the rock, and determination of the Rock Quality Designation (RQD). Samples were selected for laboratory testing. Average values of the RQD and unconfined compressive strength for each formation are listed in Table 8.1.

The subsurface geology for the Densmore and Goodman legs of the tunnel, as interpreted from the site exploration borings, is shown in Figure 8.4. The tunnel alignment has been superimposed on the cross-section, and tunnel stations are shown in units of feet. The tunnel was excavated in eight rock units, from the Queenston Shale to the Irondequoit Limestone. Only the Grimsby Sandstone, the Maplewood Shale, and the Reynales Limestone were thick enough for full face excavation. Because several of the rock units are known to contain natural gas, the contractor was required to drill an advance, or probe, hole to investigate the rock ahead of the TBM. Two-in. (51 mm) diameter holes were drilled from which the resident engineer recorded drilling rates. A methane detection meter was used to detect natural gas entering the tunnel from the probe hole. At all times, the contractor was required to probe at least 15 ft (4.6 m) ahead of the TBM.

Bedding planes, joints and seams are the predominant geologic discontinuities in the rock units encountered in the tunnel. Joints typically occur in orthogonal sets, with joint frequencies usually greater than 10 ft (3 m). In the Grimsby Formation many faults are present, showing as much as 3 to 4 ft (1.0 to 1.2 m) of displacement. These near vertical faults are oriented approximately perpendicular to the axis of the tunnel. The displacement along the fault shown in Figure 8.4 was estimated from the exploratory borings, as 12 ft (3.7 m) (H & A of New York, 1978) but was found to be only about 3 ft (0.9 m) when intercepted by the tunnel. Detailed mapping of the tunnel wall geology and of the installed support was performed as the tunnel was excavated. Maps and support descriptions are included in Appendix A.

High horizontal in-situ stresses have been measured in the Rochester area, in rock slightly higher in the stratigraphic section than the Culver-Goodman Tunnel (Guertin and Flanagan, 1979). On other tunneling projects in Rochester, spalling at the crown and the opening of springline discontinuities have been cited as evidence for the high horizontal stresses (H & A of New York, 1978).

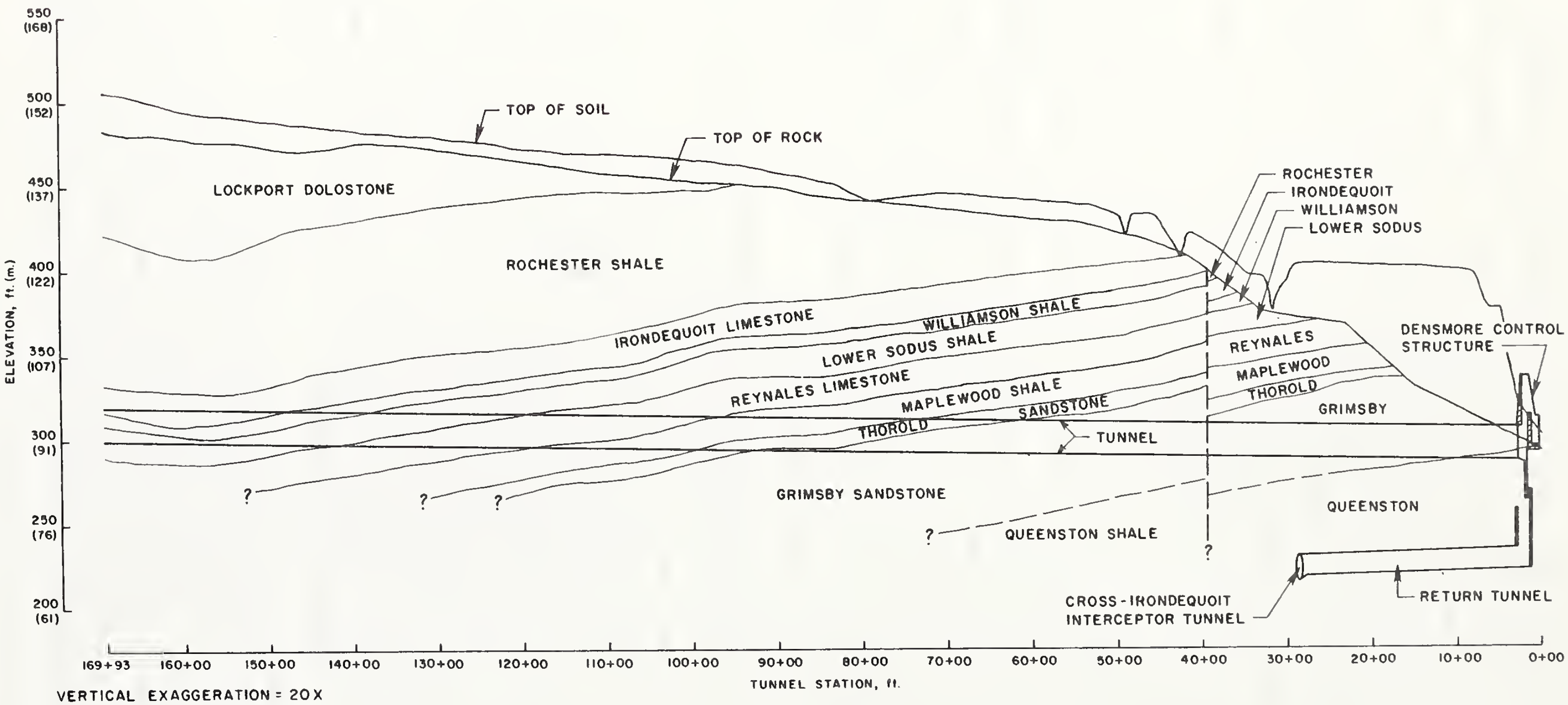


FIGURE 8.4 GEOLOGIC PROFILE, CULVER-GOODMAN TUNNEL

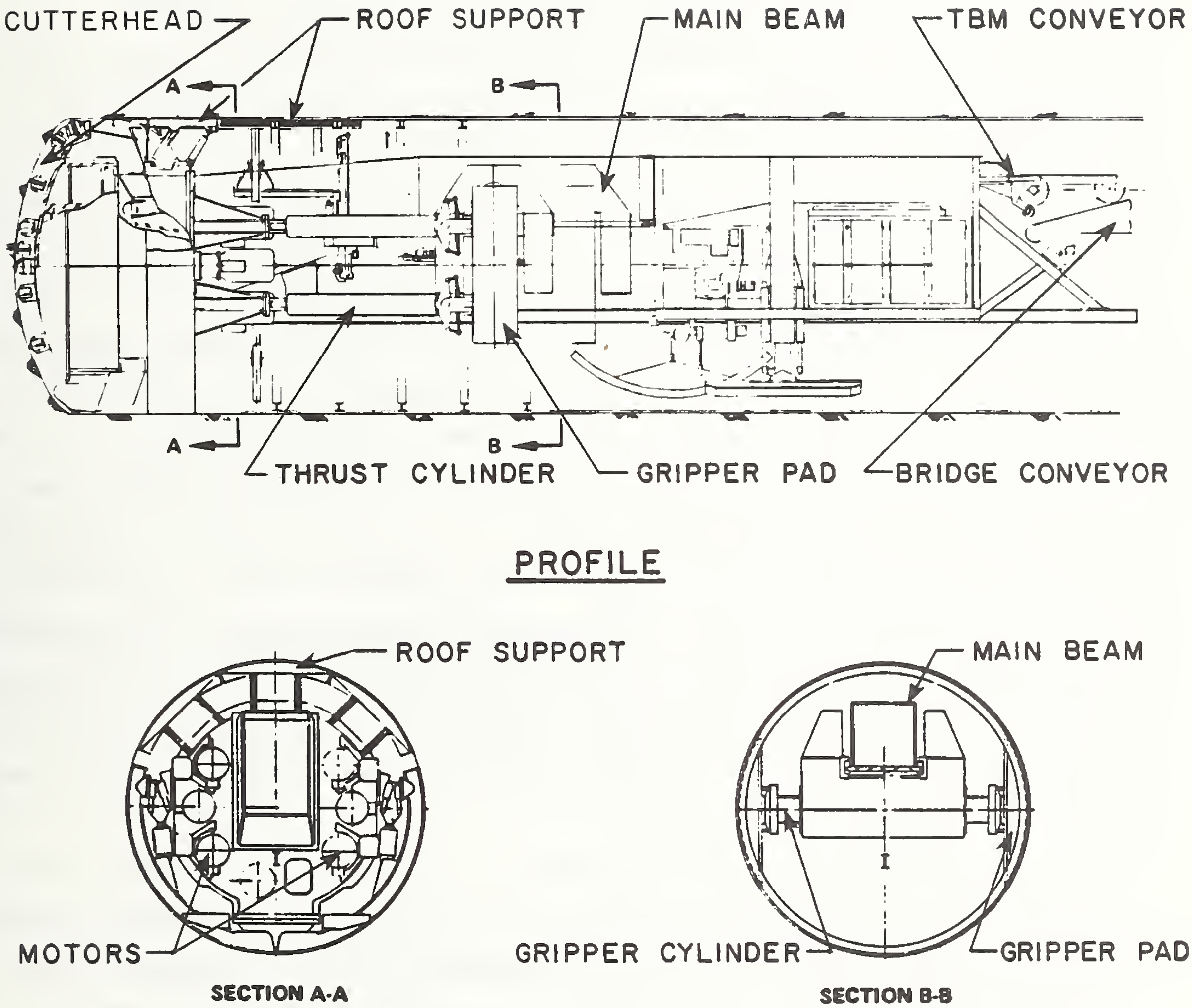


FIGURE 8.5 PROFILE AND CROSS-SECTIONAL VIEW OF THE CULVER-GOODMAN TBM

8.3 DESCRIPTION OF MACHINE AND MUCKING SYSTEM

The TBM used on the Culver-Goodman Tunnel was manufactured by The Robbins Company, of Seattle, Washington and was designated as Model 191-161. The machine had been used on three previous projects during construction of the Washington, D.C. Metro for a total length of 53,277 ft

(16,239 m). Table 8.2 summarizes the dates of construction, contractor, lithology, and tunnel length for each project.

The TBM was modified before the Culver-Goodman Tunnel was started. Major modifications included ten new cutterhead buckets with crusher-type edges, a new seal ring for the cutterhead main bearing, and installation of a separate lubrication system for the main bearing.

Figure 8.5 shows a profile and two cross-sectional views of the machine. The figure is drawn to scale and prominent components are labeled.

Table 8.3 summarizes machine dimensions, components, and operating characteristics. The machine was 71 ft (21.6 m) long with thrust cylinders retracted. The maximum cylinder pressure was 3,500 psi (24.3 MPa) for a maximum forward thrust of 1,860 kips (8,275 kN). During the tunneling, the thrust cylinders were operated at an average 2,570 psi (17.7 MPa) pressure. Two cutterhead speeds were available at 4.61 and 2.30 rpm. The lower cutterhead speed was used when positioning the cutterhead, to change cutters, and to drill the probe hole. The higher speed was used during tunneling. When excavation began, the TBM was equipped with six 150 hp (112 kW) motors. These motors were operated at 175 amps for the first 2,400 ft (732 m) of tunnel, and at 230 amps for the next 3,800 ft (1158 m). The 150 hp (112 kW) motors were then replaced with 200 hp (149 kW) motors and operated at an average 260 amps for the remainder of the job.

The trailing gear was composed of a series of 13 balanced sleds pulled forward on track laid in the 70 ft (21 m) space between the TBM and the first sled. The sleds carried the conveyors, fanline, high voltage transformer, and a variety of other mechanical and electrical equipment. The trailing floor was 320 ft (98 m) long and the last sled included a ramp and switching system between the single tunnel track and the double trailing floor tracks. The trailing floor components were designed by Moran Engineering Sales Company of Montebello, California.

Muck was transferred from the belt conveyor to muck cars by means of a tripper system, similar to that described in Chapter 7. The tripper platform had about 200 ft (61 m) of travel and the closest load point to the TBM was approximately 140 ft (43 m) behind the rear of the TBM conveyor. Each muck train typically was composed of six 16 yd^3

TABLE 8.2 PREVIOUS APPLICATIONS OF THE CULVER-GOODMAN TBM

Dates	Project	Contractor	Lithology	Tunnel Length[a]
1 March 74 to 19 Sept. 75	Contract 1A0061, Washington, DC Metro	Morrison-Knudsen Company, Inc., Boise, Idaho	Granitic schist, schistose hornblende gneiss, and schist	19,012 ft (5,795 m)
19 Sept. 75 to 8 Nov. 76	Contract 1A0091, Washington, DC Metro	Morrison-Knudsen Company	Diorite gneiss, schistose gneiss, and schist	15,239 ft (4,645 m)
25 March 77 to 10 Oct. 78	Contract 1A0111, Washington, DC Metro	J.F. Shea Company, Inc., Walnut, California	Granitic gneiss, schistose hornblende gneiss, and schist	19,026 ft (5,799 m)

[a] sum of inbound and outbound tunnel lengths

TABLE 8.3 SUMMARY OF DIMENSIONS, COMPONENTS, AND OPERATING CHARACTERISTICS FOR THE CULVER-GOODMAN TBM

Manufacturer	The Robbins Company, Seattle, Washington
Model Number	191-161-2
Diameter	19.1 ft (5.8 m)
Length	71.0 ft (21.6 m)
Weight	570 kips (2.54 MN)
Drive Motors	6
Drive Motor Rating	150 hp (112 kW) at 172 amps changed to 200 hp (149 kW) at 212 amps
Average Operating Amps	175 and 230 amps,[a] 260 amps
Cutterhead Speeds	4.61, 2.30 rpm
Thrust Cylinders	4
Cylinder Diameter	13.0 in. (330 mm)
Stroke Length	5.0 ft (1.5 m)
Maximum Cylinder Pressure	3,500 psi (24.1 MPa)
Average Operating Pressure	2,570 psi (17.7 MPa)
Cylinder Pressure to Move TBM without Face Contact[b]	490 psi (3.4 MPa)
Number and Types of Cutters	41 single disc cutters, 15.5 in. (394 mm) diameter 2 twin disc center cutters, 12.0 in. (394 mm) diameter
Conveyor Belt Width	32.0 in. (813 mm)
Conveyor Capacity[c]	250 yd^3/hr (190 m^3/hr)

[a] used during initial 6,200 ft (1,890 m) of tunneling.

[b] measured with trailing gear in tow.

[c] estimated on basis of discussion with contractor.

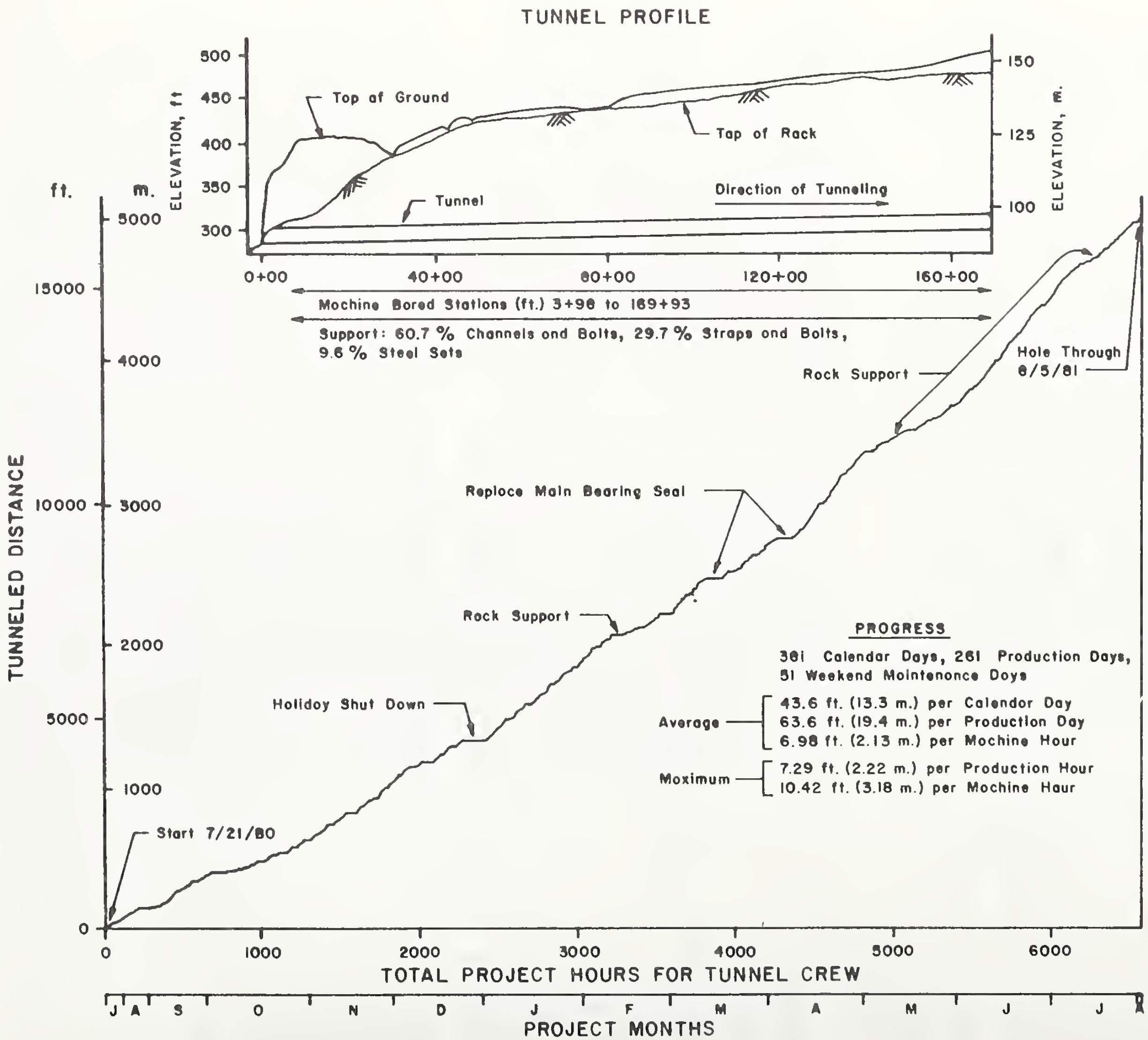
($12\ m^3$) cars. The cars were loaded sequentially from front to rear, and the train was taken to the portal by a locomotive.

The cars were emptied at the portal by a rollover dump, and the muck was passed through a hopper to a transfer conveyor. The muck was then transported to a stacking conveyor which lifted the muck onto a long conveyor. At its end, the long conveyor was mounted on a moveable gantry so the muck could be piled for eventual use as fill material on site.

8.4 CONSTRUCTION EVENTS

Figure 8.6 shows a plot of the tunneled distance versus the total project hours for the tunnel crew on the Densmore and Goodman legs of the Culver-Goodman Tunnel. This figure also shows a simplified tunnel profile and summarizes information about the machine, project and lithologies encountered in the bore. As in previous chapters, the format is similar to that used by the U.S. Bureau of Reclamation (U. S. Bureau of Reclamation, 1974).

Figures 8.7 and 8.8 summarize the advance rate, utilization, availability, and penetration rate as a function of tunnel station in histogram form. Figure 8.7 pertains to the Densmore leg, Station 3+98 to 85+71, and Figure 8.8 pertains to the Goodman leg, Station 85+71 to 169+93. Each horizontal line segment of the histogram plots corresponds to one shift. The length of the line segment is proportional to the distance tunneled during the shift. Each line segment is plotted above the horizontal axis at a distance proportional to the value of the performance parameter calculated for the shift. If tunneling delays at a given station were longer than the duration of a shift, the performance parameters at that station are equal to zero, and the plot appears as a vertical line intersecting the horizontal axis. Performance parameters for weekend maintenance shifts are not plotted in Figures 8.7 and 8.8. The utilization and penetration rates were calculated on the basis of machine clock time during weekday shifts. The clock was activated when the air clutch for the cutterhead motors was engaged. The causes and durations of major delays are listed in the plot of penetration rate versus distance at the stations where the delays occurred. Tunnel stations used in the text of this report are in units of feet, which is



MACHINE DATA

Robbins Model 191-161

Diameter 19.25 ft. (5.87 m.)

Length 71 ft. (21.6 m.)

Weight 285 tons (2.54 MN)

Max. Thrust 1850 kips (8.23 MN)

Recycle Stroke 60 in. (1.5 m.)

Cutterhead Rotation 4.61 rpm, 2.30 rpm

Cutters 41 15.5 in. (394 mm.) Single Disc

4 12 in. (305 mm.) Single Disc Center

Motors 6 150 hp. Changed to 6 200 hp.

PROJECT INFORMATION

16595 ft. (5058 m.) Study Length out of Total 28322 ft. (8633 m.)

Uphill Grade 0.10 %

Muck Loading by Tripper

Muck Disposal through Portal by Roll-over and Conveyors

Contractor: J.F. Shea Company, Inc. & Peter Kiewit Sons, Inc.

Owner: Monroe County, New York

LITHOLOGY

Sandstone, Shale, Limestone, Unconfined Compressive Strengths from 9 ksi (60 MPa) to 38 ksi (264 MPa)

FIGURE 8.6 TUNNELED DISTANCE VERSUS CUMULATIVE PROJECT HOURS AND PROJECT INFORMATION FOR THE CULVER-GOODMAN TUNNEL

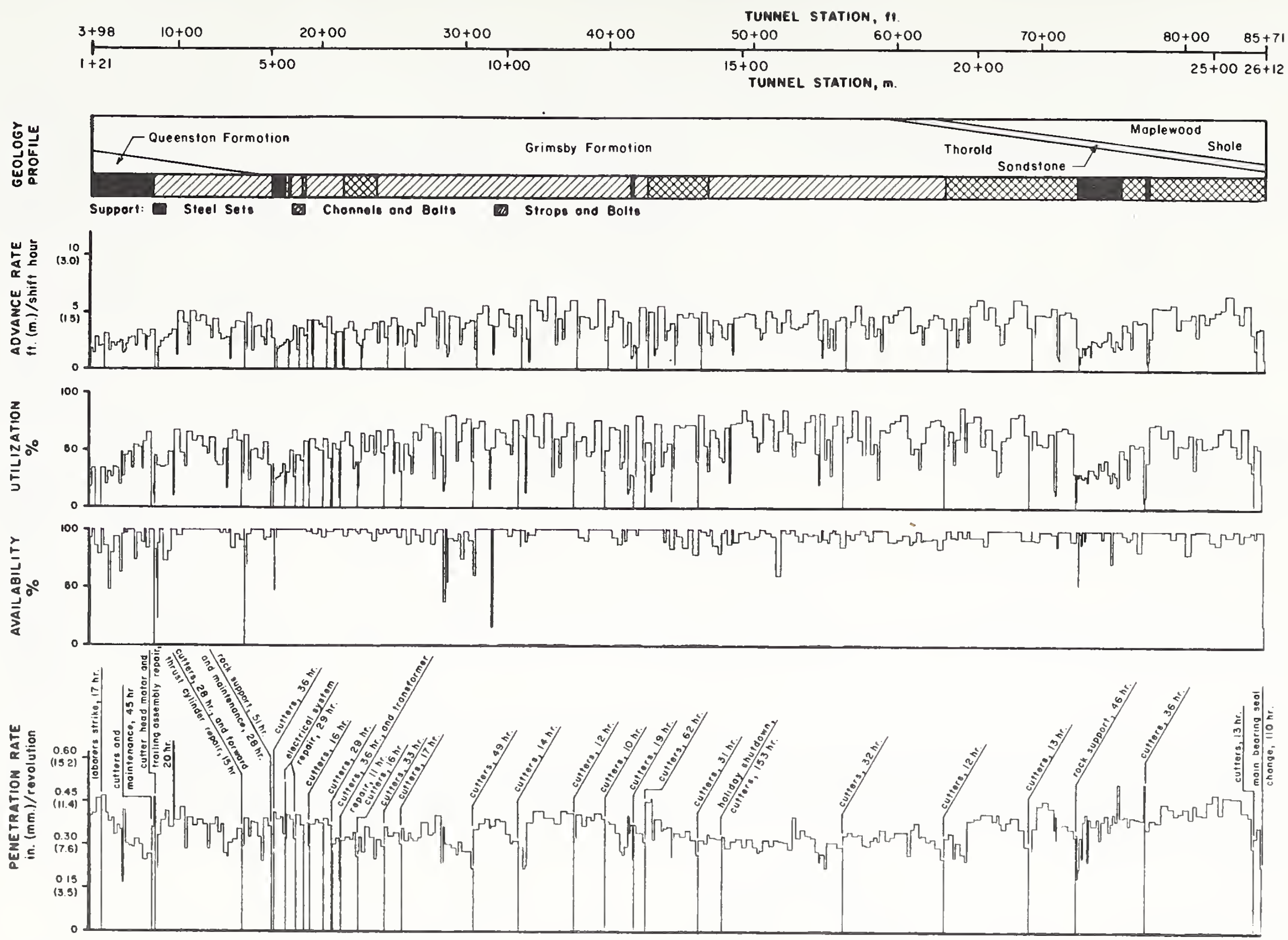


FIGURE 8.7 TBM PERFORMANCE RECORD, TUNNEL GEOLOGY, AND SUPPORT FOR THE DENSMORE LEG OF THE CULVER-GOODMAN TUNNEL

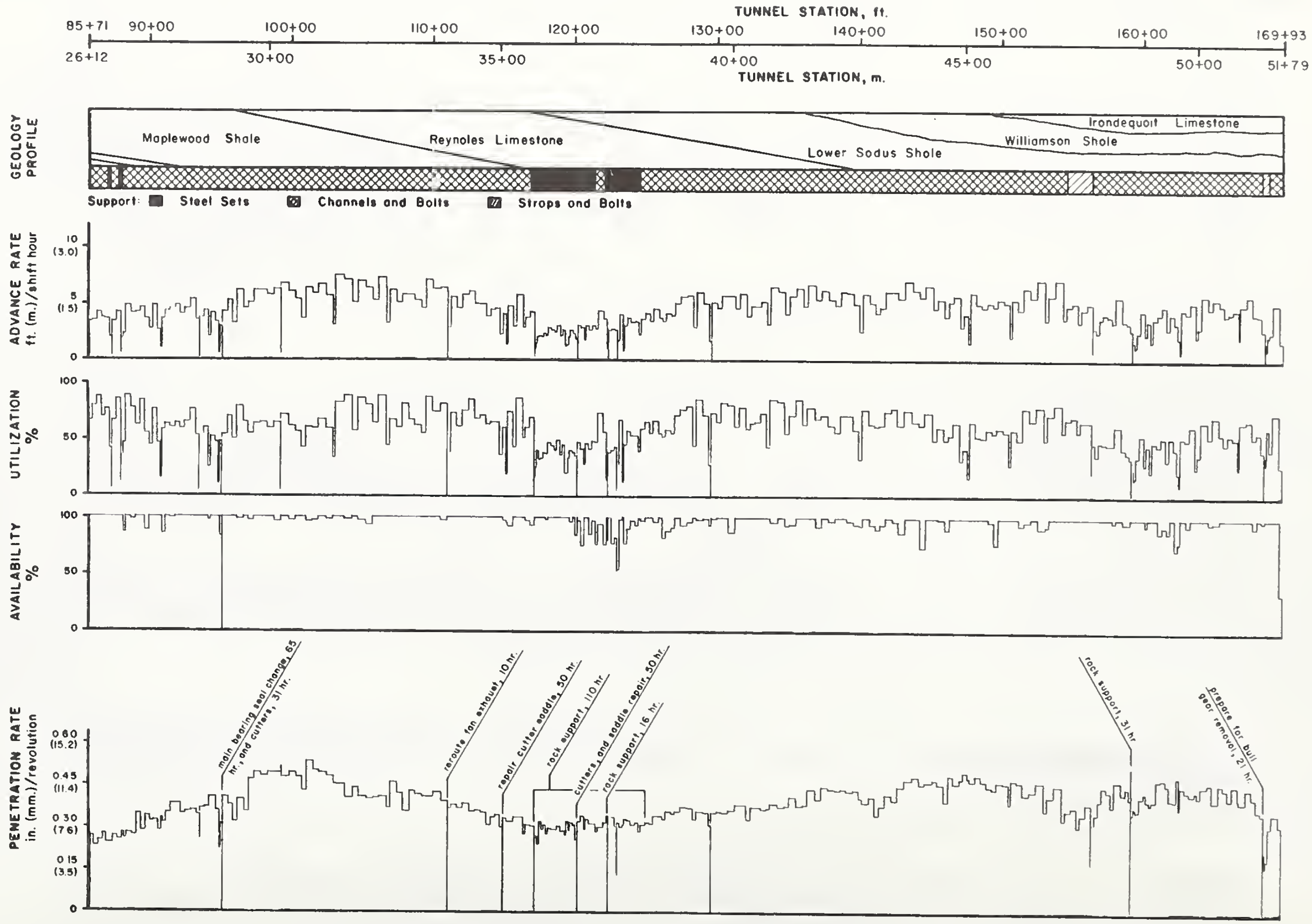


FIGURE 8.8 TBM PERFORMANCE RECORD, TUNNEL GEOLOGY, AND SUPPORT FOR THE GOODMAN LEG OF THE CULVER-GOODMAN TUNNEL

the conventional U.S. practice. Figures 8.7 and 8.8 also show simplified illustrations of the geologic profile as mapped in the excavated tunnel and the types of initial support used at various locations in the tunnel. A detailed record of the geology with stratigraphic identifications, joint planes, overbreak and support is included in Appendix A.

The work schedule consisted of a five day work week, with at least one maintenance shift every Saturday. The contractor worked with one 8.5 or 10.5 hour shift per day until 15 September 1980 and then gradually increased the number of shifts until 30 September 1980 when three shifts per day were operated with 8.5, 8.0, and 7.5 hour durations.

The TBM was assembled in the portal area at the northeast end of the tunnel and was advanced 123 ft (37.5 m) through a drill-and-blast excavated tunnel to begin boring at Station 3+98. The contractor applied shotcrete on the drill-and-blast tunnel walls to prepare them for gripper bearing. The entire trailing floor was assembled outside of the portal and the TBM began boring with the complete mucking system in working order. As assembled, however, there was not enough room for the locomotive to reach the front of the trailing floor on both rail lines. At Station 8+45, the trailing conveyor was moved laterally 10 in. (0.25 m) to allow access for the locomotive on both trailing floor tracks.

Between Stations 3+98 and 62+20, the tunnel was excavated in the Queenston, Grimsby, and Thorold Formations. The lithology present was mostly sandstone with some shaley areas and shale interbeds. Most of the downtime in this section of tunnel was associated with cutter changes, cutter saddle and cutterhead bucket repair, and rock support. The cutterhead motors were often operated with large amperage draw, and vibrations of the cutterhead increased in areas where shale interbeds were exposed at the heading. Cutter saddle bolts were often loose or missing when mining in these areas. Steel cutter rings broke off their hubs and, at Station 34+01, one disengaged cutter tore eight other cutters from their saddles. At Station 42+78, excavation was stopped for eight shifts to change cutters and to repair the cutter saddles and cutterhead buckets which had been damaged by the abrasive sandstone muck. Production was stopped for the Christmas holidays when the TBM was at Station 48+14. Between 24 December 1980 and 3 January 1981, the contractor ran 19 maintenance shifts during which 35 cutters were changed, the cutterhead bucket lips were reinforced, and the TBM lubrication pumps were repaired. The frequency of cutter changes in this section was high, as can be seen in the annotations in Figure 8.7.

Steel sets (WF 6x25) were installed between the portal and Station 8+27 and at two other locations in the Grimsby Formation. Joints and interbedded shale caused overbreak in the vicinity of Station 16+84. At Station 17+04, production was stopped to extend the TBM roof supports.

The TBM dust shield was installed at Station 13+35. A new breaker transformer was installed at Station 21+69 and one of the cutterhead side supports was repaired at Station 30+87.

The contractor mined to Station 52+56 using six 150 hp (112 kW) cutterhead motors. Until Station 27+30, these motors were operated at approximately 175 amps. Between Stations 27+30 and 52+66, the motors are operated at 230 amps. With the higher level of amperage, several motors overheated and one motor was replaced at Station 30+87. From Station 52+66 to 72+74 the contractor replaced the existing motors with 200 hp (149 kW) motors, generally during weekend shifts at a rate of one motor per week. In the Grimsby Formation, the new motors were operated at an average 230 to 250 amps, although the current draw was occasionally as high as 290 amps.

Between Stations 62+20 and 91+50, the TBM excavated a mixed face of Grimsby and Thorold Sandstones and Maplewood Shale. When exposed in the crown, the shale tended to split along and at angles to the bedding planes causing areas of loosened rock and overbreak to develop. The crown rock was supported either by steel channel sections or by full steel sets. Rock support and scaling of loose crown rock were significant causes of downtime until Station 95+75.

At Station 74+49, an oil leak developed in the cutterhead main bearing seal. By flushing the seal with hydraulic fluid after each forward stroke cycle, the contractor was able to reach Station 85+71, near Drop Shaft 9 at the intersection of the three tunnel legs. At this point, excavation was stopped and 14 shifts were devoted to changing the main bearing seal. Mining after the seal change was intentionally slow to test the new seal. Excavation was again stopped at Station 95+09 and eight shifts were used to change the seal a second time. The two seal replacements are shown as horizontal line segments near the center of the plot of tunneled distance versus project hours in Figure 8.6.

Between Stations 95+75 and 116+80, the Reynales Limestone was present in the tunnel crown, and the amount of Maplewood Shale in the face gradually decreased. The major sources of downtime in this section of tunnel included cutter changes and delays due to lack of empty muck cars at the heading. At Station 111+01, parts of two shifts were required to reroute the fan line exhaust through Drop Shaft 9. At Station 115+17, one of the cutter saddles was torn from the cutterhead and four shifts were spent repairing the damage.

From Station 116+80 to 149+00, the tunnel crown was in the Lower Sodus and Williamson Shales. Full steel sets or steel channel sections were used as initial rock support in these areas. At Station 122+00, the TBM roof supports were again extended to restrain loosening crown rock. At Station 120+18, excavation was stopped for seven shifts to change 30 cutters and to build up several of the face cutter saddles. When the TBM was at Station 129+61, a derailment occurred in the tunnel and two shifts were required to repair the track.

The gripper pads often slipped on the muck-covered walls while mining in the Lower Sodus and Williamson Shales. During many shifts, excavation was stopped to clean muck from the tunnel walls. This problem continued even when the gripper cylinder pressure was increased to a maximum 3,500 psi (24.3 MPa).

Between Stations 154+30 and 160+10, the TBM bored around a 500 ft (152 m) radius horizontal curve. Difficulties developed when components of the trailing floor equipment blocked the laser beam. At Station 156+55, the trailing conveyor belt was shortened and a muck train with only three cars was used until Station 162+68 when the full length conveyor belt was reinstalled. The shorter trains and the increasing travel distance between the heading and the portal led to significant delays in excavation progress because of the lack of empty muck cars at the heading. Other delays were caused by trailing floor sled derailments, and snagging and jamming of trailing floor equipment along the sides of the tunnel.

During a cutterhead inspection at Station 148+68, it was noticed that several teeth on the cutterhead bull gear had broken off. From this location to the end of boring at Station 169+93, the TBM was operated at reduced thrust cylinder pressures to reduce the torque transferred from the cutterhead motor pinions to the bull gear. By the end of the tunnel, a total of eight gear teeth had broken off. A new bull gear was installed in the shaft at the end of the Goodman leg.

In summary, the tunneling for the Densmore and Goodman legs of the Culver-Goodman Tunnel commenced on 21 July 1980 and ended on 5 August 1981. The tunneling required 380 calendar days, of which 260 were production week days. The trailing gear was assembled before the TBM entered the tunnel. The time required for the drive was 6,572 hours (810 shifts) of which 153 hours (19 shifts) were used for scheduled maintenance during the Christmas holidays, and 861 hours (107 shifts) were used for weekend shifts. The contractor used weekend shifts primarily for cutter changes, probe hole drilling, and general TBM maintenance.

8.5 TUNNELING PERFORMANCE

Table 8.4 summarizes the average advance rate, utilization, availability and penetration rate for the Culver-Goodman Tunnel. The average advance rate and utilization were calculated on the basis of the cumulative project hours from the time boring started at Station 3+98 to holing through of the TBM at Station 169+93. These averages include the time devoted to maintenance during the scheduled Christmas shut-down. The average penetration rate and utilization were calculated in the same manner as the individual shift penetration rates and utilizations by using the elapsed machine clock times as recorded on the contractor's shift reports.

In general, utilization was low in sections where steel supports were installed and near Station 160+00, where the 500 ft (152 m) radius curve was located. Sustained high values of utilization generally correspond to sections of tunnel mined in the Maplewood, Lower Sodus and Williamson Shales, and in the Reynales Limestone. High utilization in the shales generally occurred in areas where channel sections, rather than steel sets, were installed as initial rock support.

The penetration rate was influenced primarily by two factors: 1) the rock type present at the heading, and 2) the number, capacity, and

TABLE 8.4 AVERAGE ADVANCE RATE, UTILIZATION, AVAILABILITY, AND PENETRATION RATE FOR THE CULVER-GOODMAN TUNNEL

Parameter	Average Value
Advance Rates	2.5 ft/hr (0.77 m/hr)
Utilization	36.1 percent
Availability	92.2 percent
Penetration Rate	7.0 ft/hr (2.1 m/hr)
	0.30 in./revolution (7.7 mm/revolution)

operating amperage of functioning drive motors. Highest penetration rates were achieved when the face was mostly in the Maplewood, Lower Sodus, and Williamson Shales. The contrast in penetration rate associated with the different lithologies is shown in Figure 8.8 where the average penetration rate through the nearly full-face Maplewood Shale between Stations 96+00 and 103+00 is approximately 60 percent greater than the average penetration rate through a nearly full face of the Reynales Limestone between Stations 115+00 and 118+00. Furthermore, the lower penetration rate in the Reynales was attained with a thrust cylinder pressure 30 percent higher than that used in the Maplewood. An increase in the operating amperage of the cutterhead motors generally resulted in an increase in penetration rate. With motors operated at 230 amps between Stations 31+00 and 41+00 in the Grimsby Sandstone, the average penetration was approximately 10 percent greater than the penetration rate between Stations 17+50 and 24+50 where the motors were operated at 175 amps.

Availability of the TBM was limited principally by three factors: 1) maintenance and repair of the cutterhead and cutter saddles, especially in areas of abrasive rock, 2) repair and extension of the TBM roof support components, especially in areas where shale was in the tunnel crown, and 3) replacement of the main bearing seal. Availability was low at the start of the tunnel, primarily due to TBM and crew break-in.

8.6 DOWNTIME ANALYSIS

Table 8.5 summarizes the delay, or downtime, associated with various components of the Culver-Goodman tunneling. As described in Chapter 4, individual causes of delay have been arranged into four categories shown. A detailed description of downtime categories and a discussion of tunneling delays for the Culver-Goodman Tunnel is included in Appendix B. The downtime percentages were calculated on the basis of total project hours, including weekend shifts and time spent on maintenance during the Christmas holiday.

Figure 8.9 shows the downtime percentages in the form of a pie chart. Approximately 64 percent of the shift hours was spent on delays, resulting in an average machine utilization of 36 percent.

The major causes of downtime under the category of TBM maintenance and repair were cutter changes and general maintenance and inspection, particularly of the cutterhead, main bearing, and roof support components. Of the total shift time, 16.5 percent was required for cutter changes, and 5.8 percent was spent on general maintenance and inspection.

Installation and extension of utility service lines, and train delay and derailments were principal causes of downtime under the general category of backup systems. Utility service downtime amounted to 4.6 percent of the total shift time, with 85 percent of this spent extending the air, water, and ventilation lines. Train delays and derailments required 3.9 and 2.3 percent of the total shift time, respectively.

Downtime associated with ground conditions was principally related to installing steel sets, scaling loose rock, and removing muck jams from the cutterhead buckets. Steel set installation accounted for 5.1 percent of the total shift time. In total, the percentage downtime associated with steel sets, rock jams, scaling, and clearance of trailing gear components was 8.7 percent. Downtime required to install steel

TABLE 8.5 TABULATION OF DOWNTIME AS A PERCENTAGE OF TOTAL SHIFT HOURS FOR THE CULVER-GOODMAN TUNNEL

TBM Maintenance and Repair	Percentage Downtime	Backup System	Percentage Downtime	Ground Conditions	Percentage Downtime	Additional Items	Percentage Downtime
Cutter Change	16.5	Power Supply	0.2	Water Inflow	0.0	Restroke	3.5
General Maintenance and Inspection	5.8	Cable Utilities Fanline	4.6	Steel Sets	5.1	Holiday	2.3
Lube Oil	0.4	Survey	0.2	Bolts/Straps/ Channels	2.3	Methane Probe	3.6
Hydraulics	0.9	Car Pass	Not Used	Bolt Drill Repair	1.4	Other (Supplies, Shift Changes, Special Delays, etc.)	2.0
Motors	0.6	Tripper	0.5	Scaling/ Rock Jam	3.1		
TBM Conveyor	0.1	Trailing Gear Conveyor	1.2	Gripper Difficulty	0.3		
Electrical	1.5	Train Delay	3.9	Clearance	0.5		
		Portal Operations	0.8				
		Laying Rails	0.3				
		Derailment	2.3				
Subtotal	25.8	Subtotal	14.0	Subtotal	12.7	Subtotal	11.4

TOTAL PERCENTAGE DOWNTIME 63.9

straps and channel sections accounted for 2.3 percent of the total shift time, with most of this time loss associated with channel installation.

The category of "holiday" includes maintenance shifts which were operated between Christmas 1980, and the start of production in 1981. Most of the downtime used to drill the methane probe hole occurred during weekend shifts, but in areas of high advance rate, excavation often had to be stopped to extend the probe hole. The category of "other" includes downtime for shift changes, waiting for dust to clear so the laser could be read, and bringing supplies to the heading. Shift changes were principal causes of delay in this category.

8.7 CUTTER CONSUMPTION

Figure 8.10 shows a front view of the TBM cutterhead on which each cutter position is designated by a number. Numbers 34 through 45 refer to gage cutters and 1 through 33 to face cutters. Single disc, 15.5-in.

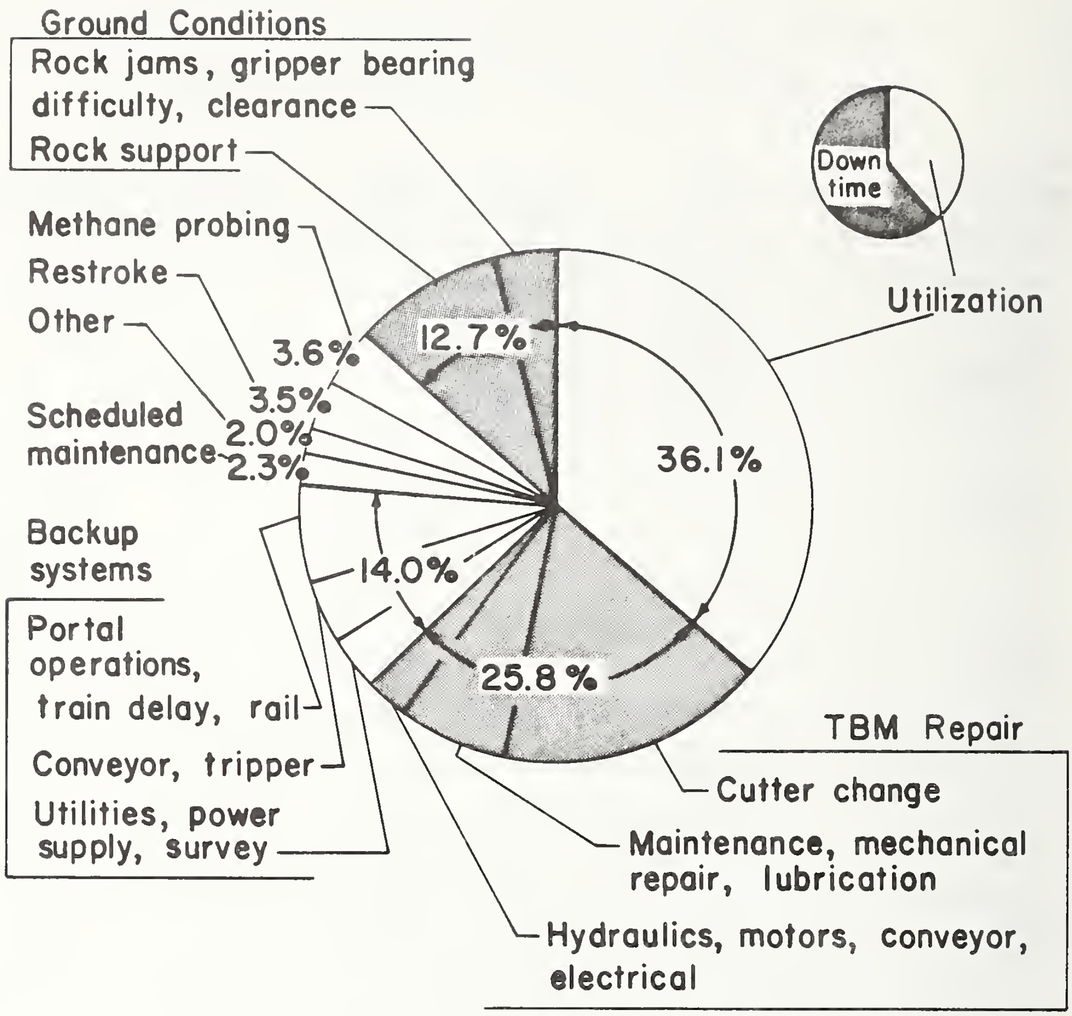


FIGURE 8.9 SUMMARY OF DOWNTIME AS A PERCENTAGE OF TOTAL SHIFT HOURS FOR THE CULVER-GOODMAN TUNNEL

(394 mm) diameter cutters were used at the positions shown by numbers 5 through 45 and twin disc, 12-in. (305 mm) diameter cutters were used at the four center positions. Cutter rings with a 90 degree included edge angle were used in all positions at the start of the tunnel.

A total of 810 cutters were changed over the 16,595 ft (5,058 m) of tunnel bore. Cutters needing repair were transported to a shop located on site, where rings were replaced and hubs reconstructed. No complete records were available on the type of repairs made.

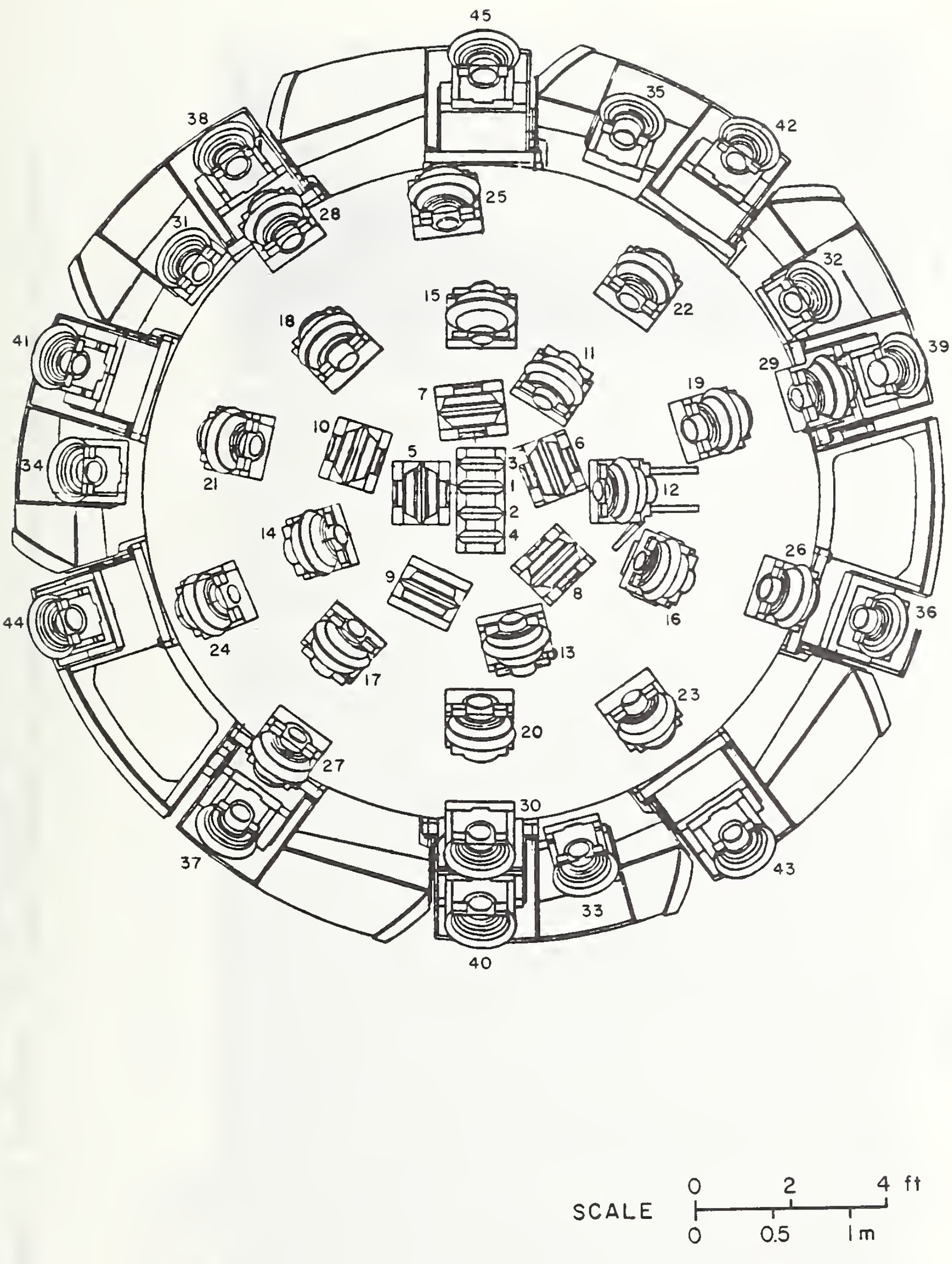


FIGURE 8.10 VIEW OF CUTTERHEAD FACE OF THE CULVER-GOODMAN TBM

Figures 8.11 and 8.12 summarize information regarding the number and location of replaced cutters for the Densmore and Goodman legs, respectively. Cutter changes are referenced according to tunnel stations, and the number of replacements at each position are summarized and shown in histogram form.

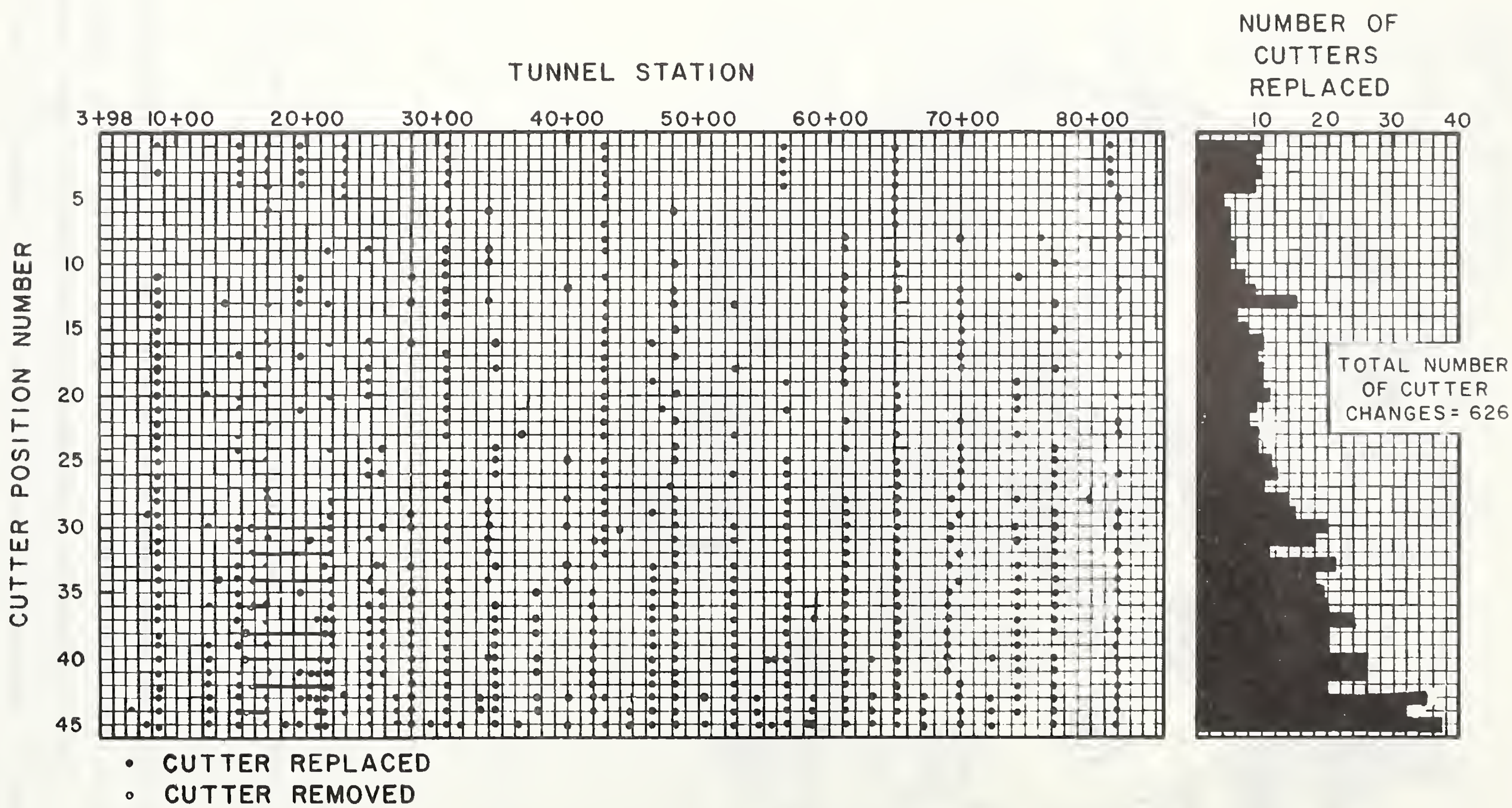


FIGURE 8.11 SUMMARY OF REPLACED CUTTERS, NUMBER OF CHANGES, AND LOCATION ON CUTTERHEAD FACE FOR THE CULVER-GOODMAN TUNNEL, DENSMORE LEG

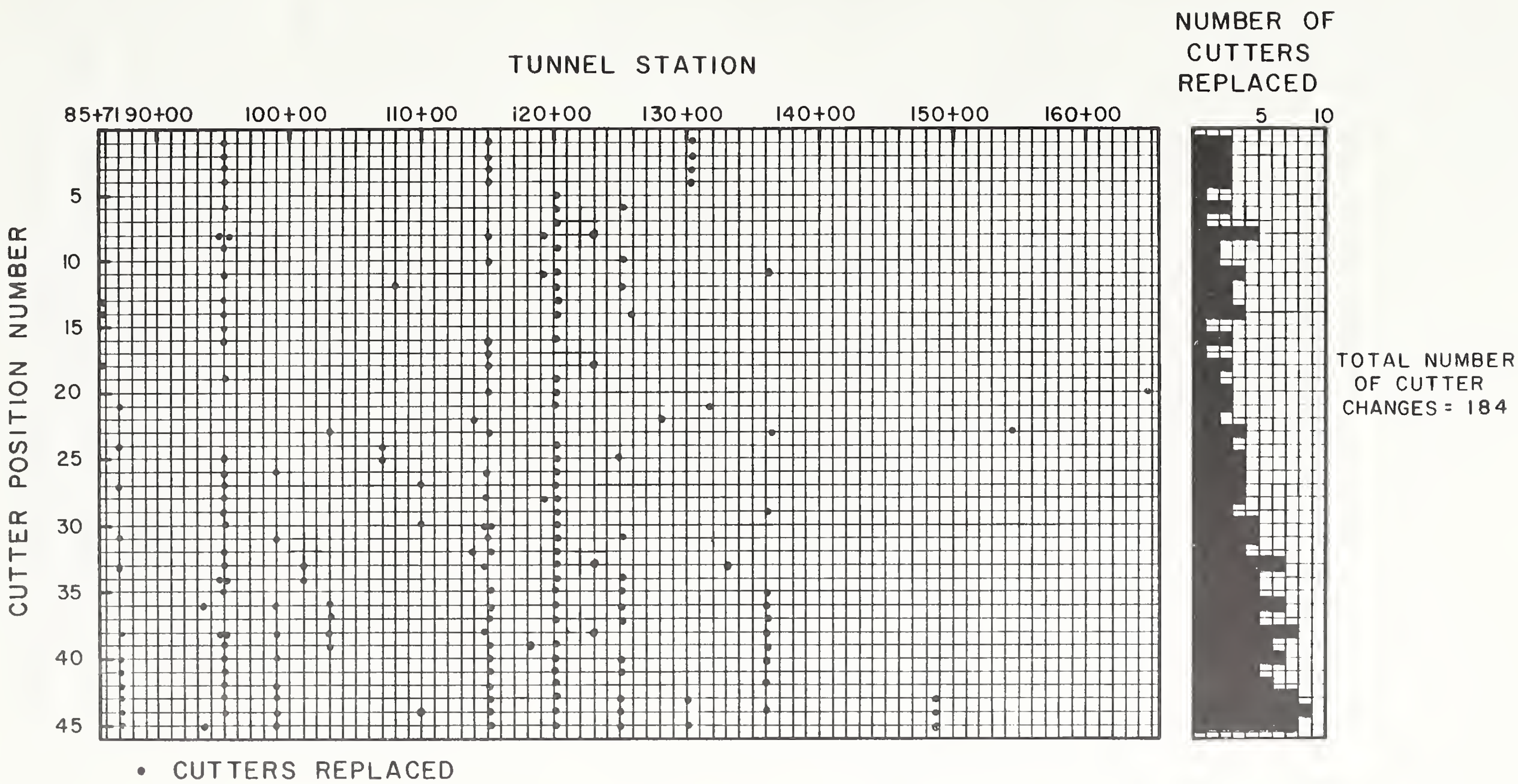


FIGURE 8.12 SUMMARY OF REPLACED CUTTERS, NUMBER OF CHANGES, AND LOCATION ON CUTTERHEAD FACE FOR THE CULVER-GOODMAN TUNNEL, GOODMAN LEG

A total of 626 cutters were changed during the Densmore leg drive, of which 305 changes were made in the gage cutter positions. There were an average of 9.7 changes per face cutter position and an average of 25.4 changes per gage cutter position over this 8,173 ft (2,491 m) section of tunnel. The contractor changed cutters at an average rate of one cutter per 137 yd^3 (105 m^3) of excavated rock. The contractor made two changes aimed at increasing the penetration rate and reducing the high cutter wear, particularly in the gage positions. Between Stations 15+28 and 21+69, the contractor removed the even number gage cutters. In this section, the penetration rate increased by roughly 10 percent, but the number of cutters changed at other gage positions increased. From Station 26+73, the contractor used cutters with 1.125 in. (28.6 mm) wide, constant width rings in gage positions. The contractor used these constant attack area cutters in outer gage positions through the rest of the tunnel.

A total of 184 cutters were changed during the Goodman leg drive, of which 79 changes were made in the gage cutter positions. There were an average of 3.2 changes per face cutter position and an average of 6.6 changes per gage cutter position over this 8,422 ft (2567 m) section of tunnel. The contractor changed cutters at the rate of one cutter per 458 yd^3 (350 yd^3) of excavated rock. Over 70 percent of the cutter changes shown in Figure 8.12 occurred between Stations 95+75 and 140+50, where at least part of the heading was in the Reynales Limestone.

8.8 SUMMARY

From the time the TBM was installed, excavation of the Densmore and Goodman legs of the Culver-Goodman Tunnel required 6,572 hours, of which 1,014 were spent on weekend and Christmas holiday maintenance. Including weekend and holiday shifts, the average advance rate was 2.5 ft/hour (0.77 m/hr) for 16,595 ft (5,058 m) of tunnel. The overall TBM utilization was 36 percent.

Major geologic controls on tunneling performance included the presence of highly abrasive rock and the type of rock present at the heading. The abrasive Grimsby Sandstone affected performance by reducing machine utilization through cutter changes and repairs. Penetration rates were influenced by the amount of shale at the face. Relatively high penetration rates were attained when the face was composed of the Maplewood, Lower Sodus or Williamson Shales. Lower penetration rates were experienced when the face was composed of the Grimsby Sandstone or Reynales Limestone. Steel sets and channel sections were installed in areas of heavily jointed rock and in tunnel sections in shale, where overbreak developed in the crown. Support installation was often accompanied by difficulties with muck jams in the cutterhead buckets, scaling, gripper reaction, and clearance of trailing gear components.

Major mechanical causes of downtime included cutterhead main bearing seal changes, train delays and derailments. Toward the end of the Goodman leg of the tunnel, trailing gear modifications were required to tunnel successfully around a horizontal curve, and these modifications indirectly caused additional time losses due to train delays, derailments, and trailing floor component clearance.

A total of 626 cutters were changed during the Densmore leg drive, of which 305 were in gage cutter positions. A total of 79 of the 184 cutter changes in the Goodman leg were made at the gage cutter positions.

CHAPTER 9

CHICAGO TARP CONTRACT 73-287-2H

9.1 PROJECT OVERVIEW

The Tunnel and Reservoir Plan (TARP) is a regional scheme to intercept, store, and treat combined storm and wastewater flows in the area of Chicago, Illinois. The tunnels of the TARP project are designed to comply with state and federal environmental laws by preventing back-flows into Lake Michigan, eliminating pollution caused by combined sewer overflow, and providing an outlet for flood waters. The system is owned and operated by the Metropolitan Sanitary District of Greater Chicago (MSDGC). Funding for the project is provided by the MSDGC and by grants from the U.S. Environmental Protection Agency.

The TARP project is divided into four systems, and construction is planned for two phases. Phase I consists of tunnels, drop shafts and connecting structures, and is expected to intercept 85 percent of the overflow of the existing combined sewer system (Dalton, 1979). Phase II is designed to control flooding and includes storage reservoirs and additional tunnels.

The Calumet System is the southernmost system of the TARP project. As shown in Figure 9.1, this system includes the construction of 41.2 miles (66.3 km) of tunnel and 103 drop, access, and construction shafts (Keifer & Associates, 1976a). The design of the system was performed by Keifer & Associates, Inc., with the MSDGC acting as the resident engineer. The Calumet System construction was planned in seven stages. The first stage, bid as Contract 73-287-2H, was constructed by the joint venture of Traylor Brothers, Inc., Rocco Ferrera and Company, Inc., and Resco Construction Company. This contract includes the Treatment Plant Trunkline, the Cal-Sag Tunnel, the 130th Street East and West Branch Tunnels, and the 125th Street Branch Tunnel.

In total, Contract 73-287-2H involved the construction of 42,540 ft (12,966 m) of 21.25 ft (6.48 m) diameter tunnel, 5,515 ft (1,681 m) of 9.0 ft (2.74 m) diameter tunnel, and 23 shafts. Excavation of the drop shafts was performed by one of four methods: drill-and-blast, raise boring, blind drilling, and reaming of smaller diameter blind-drill holes. Adits from the shafts to the main tunnel were excavated by

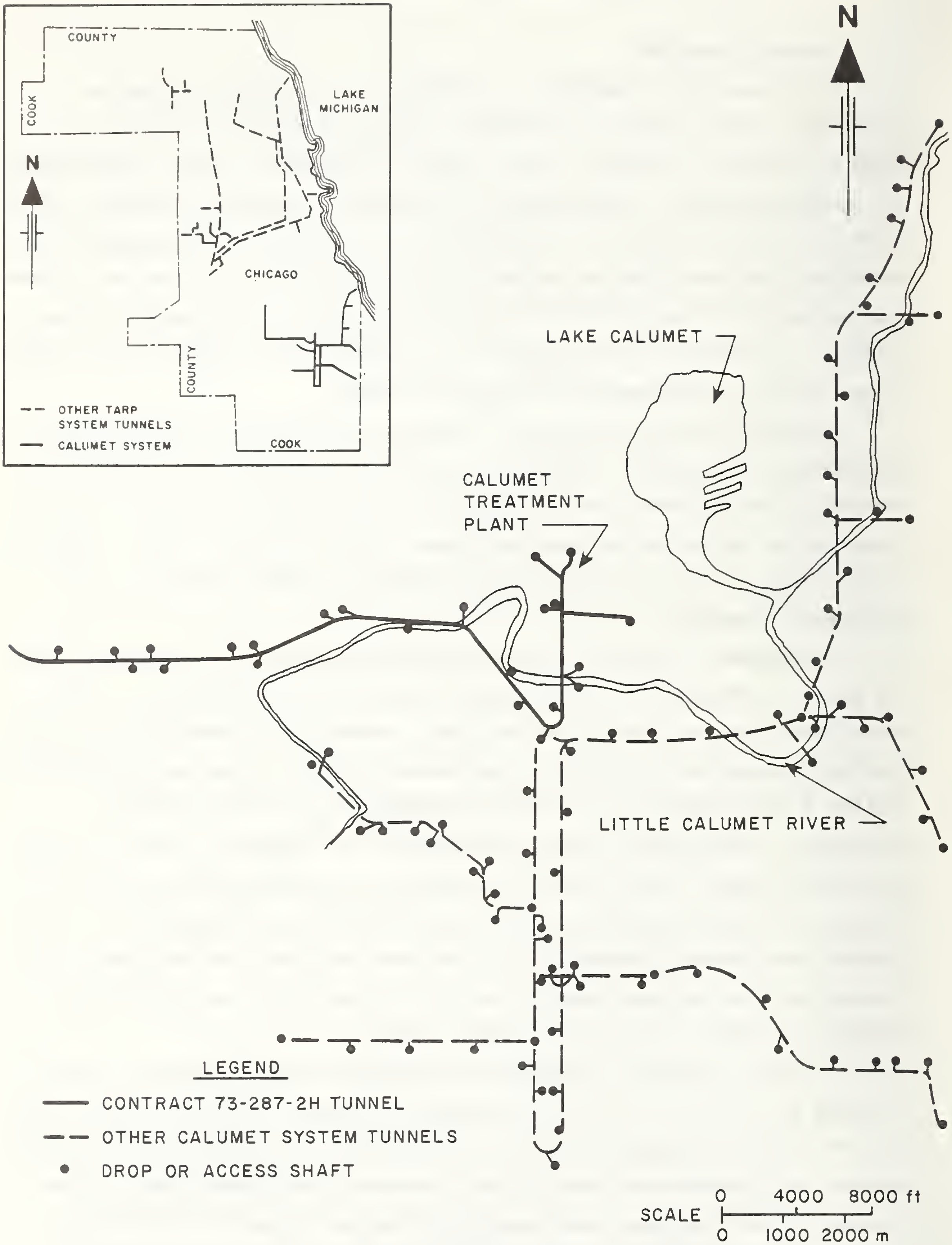


FIGURE 9.1 PLAN VIEW OF THE CALUMET SYSTEM OF THE TUNNEL AND RESERVOIR PLAN, CHICAGO, ILLINOIS

drill-and-blast methods and were generally 9 ft (2.7 m) in diameter. This study focuses on the eastern part of the 21.25 ft (6.48 m) diameter tunnel. Figure 9.2 shows a plan view of this part of the contract that includes 24,159 ft (7,364 m) of main tunnel with connecting drop shafts and adit tunnels. Tunnel construction includes the Treatment Plant Trunkline, the 125th Street Branch Tunnel, and part of the Cal-Sag Tunnel. The tunnel stations, shown in units of feet, are drawn to scale along the alignments of the main and branch tunnels. Drop shafts and adit tunnels are shown at their true locations. The alignment includes four horizontal curves in the main tunnel: a 600 ft (183 m) radius curve between Stations 241+86 and 247+52, a 500 ft (152 m) radius curve between Stations 313+37 and 325+77, and two 450 ft (137 m) radius curves between Stations 404+55 and 408+89.

The contractor began near the middle of the contract, at Drop Shaft 6R, and excavated an access shaft, 23 ft (7 m) in diameter, to depth of 297 ft (91 m). The shaft and a 52 ft (16 m) long starter tunnel for the TBM were excavated by drill-and-blast techniques. The shaft and adit tunnel are shown on the left side of Figure 9.2.

The horizontal alignment for the contract was set by considering the location of existing waste treatment facilities and sewer lines, possible drop shaft locations, and right-of-way limitations. In addition, the logistics of other Phase I and II tunneling were considered in final selection. Access shafts were required at spacings of not more than 3,500 ft (1067 m). The 125th Street Branch Tunnel was initially designed to intersect the main tunnel at a shart, acute angle. The branch tunnel alignment was changed to include a 500 ft (152 m) radius curve at the turn-off from the main tunnel. This realignment added footage to the branch tunnel, and the initial station was changed from 0+00 to -1.34.

The vertical alignment was set to minimize vertical pumping distance while meeting hydraulic grade requirements and locating the tunnel in a geotechnically favorable rock unit. The tunnel grade was set at 0.3 percent from Station 0+00 to 319+00, 0.05 percent from Station 319+00 to 409+68, and 0.08 percent in the branch tunnel.

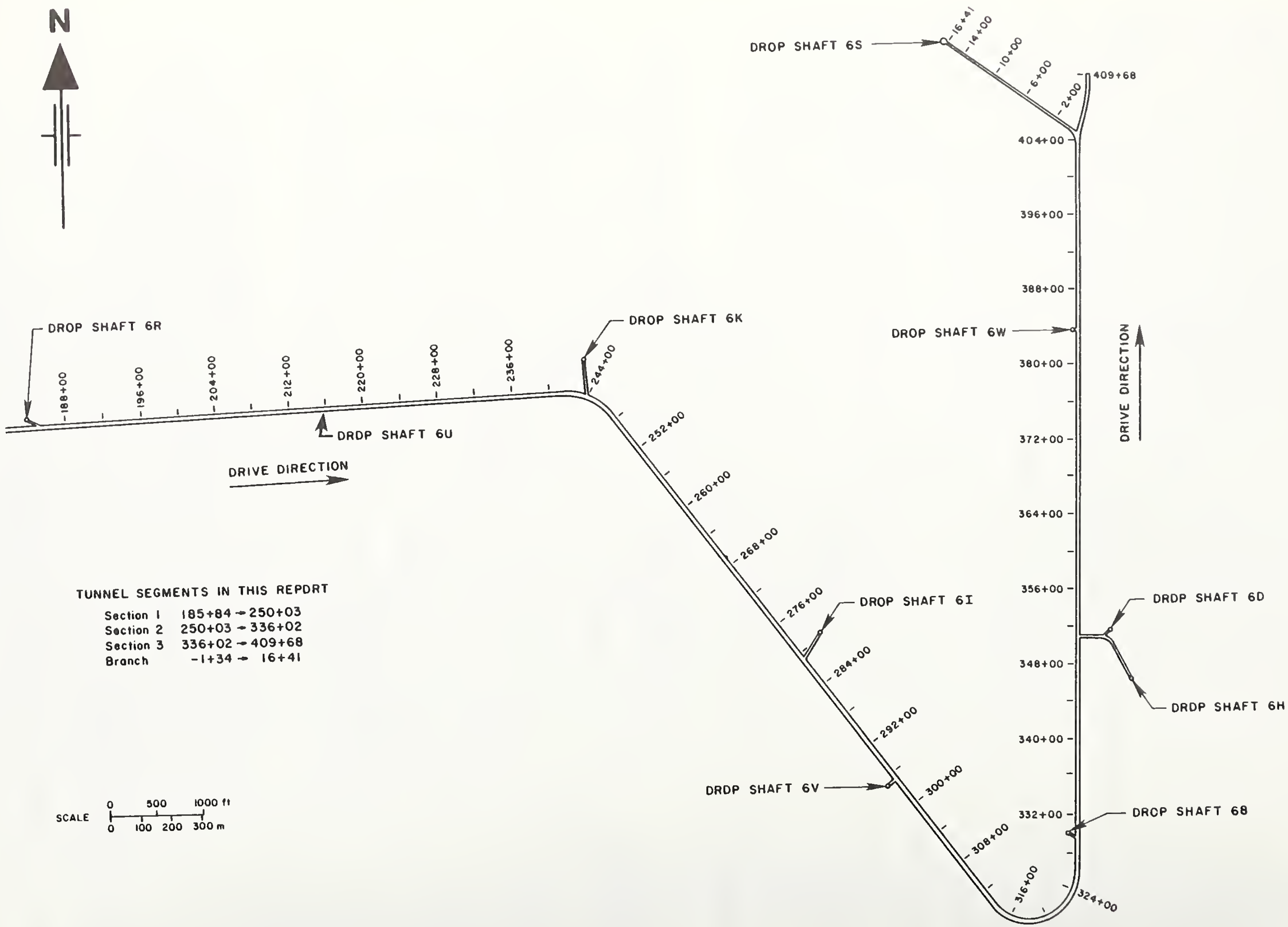


FIGURE 9.2 PLAN VIEW OF TARP CONTRACT 73-287-2H

9.2 GEOLOGIC SETTING

The subsurface geology in the Chicago area consists of a sequence of glacial deposits overlying a sequence of Lower Paleozoic sedimentary rocks. The sedimentary rock units strike approximately north to northeast and dip to the east or southeast at 10 to 15 ft/mile (1.9 to 2.8 m/km).

Glaciation of the area was extensive. Glacially deposited materials include basal and morainal till and outwash sand. Lake clays and beach sands are also found in the area. These surficial deposits vary in thickness from 10 ft (3.0 m) at the west end of Contract 73-287-2H to about 70 ft (21.3 m) at the east end.

The near surface bedrock in the Calumet area consists of dolostones and shales deposited during the Silurian period. A stratigraphic column of Silurian rock in the area is shown in Figure 9.3.

The Racine Formation is usually at the top of rock in the Calumet area, and two facies are present. The younger rock in the Racine belongs to an inter-reef facies, and averages 123 ft (38 m) in thickness in the vicinity of Contract 73-287-2H. The inter-reef unit is a fine-grained, dense, and uniform dolostone. It may be thick to thinly bedded with shaly partings common. The argillaceous content of the rock decreases with depth as the frequency of stylolites increases. The upper 20 ft (6.1 m) of this unit is usually highly weathered and the lowest 20 to 30 ft (6.1 to 9.1 m) is a pure, white, fine-grained dolostone. This pure dolostone is thick bedded, and chert nodules are present in amounts less than 10 percent by volume.

Beneath the inter-reef facies is the reef facies which averages 76 ft (23 m) in thickness. This lithology is fossiliferous dolostone which is porous, vuggy, thick to massively bedded, and medium grained. Stylolites are common and many of the vugs are filled with pyrite or natural asphalt. The lower 10 ft (3.0 m) of the reef facies is less porous and the transition to the underlying Joliet Formation is gradual.

Three members have been identified within the Joliet Formation, but only two are present in the Calumet area. Uppermost is the Romeo Member which is 8 to 15 ft (2.4 to 4.6 m) thick. This unit is a white, fine-grained dolostone of high purity. The rock is thickly bedded and dense, with frequent stylolites. The transition to the underlying Markgraf is

SYSTEM	SERIES	GROUP	FORMATION	MEMBER	LITHOLOGIC DESCRIPTION
SILURIAN	NIAGARAN	HUNTON	RACINE		Inter-reef facies, average 123 ft (38 m) thick, argillaceous, gray, fine-grained DOLOSTONE. Thick to thinly bedded with thin shale partings. Less argillaceous with depth. Stylolites more frequent with depth. Chert nodules in lowest 20-30 ft (6-9 m).
					Reef facies, average 76 ft (23 m) thick, massive to thick bedded, gray, fossiliferous DOLOSTONE. Porous, vuggy, medium-grained with some interbeds of dense rock.
			JOLIET	ROMEO	Average 11 ft (3.4 m) thick, light gray to white, fine-grained, dense, thick bedded, nearly pure DOLOSTONE. Stylolites common.
				MARKGRAF	Average 32 ft (10 m) thick, light to medium and bluish-gray, fine-grained DOLOSTONE, frequently mottled. Moderately argillaceous and silty with shale partings most common in upper and middle parts. Lower part pink, medium to fine-grained and porous.
			MINOR UNCONFORMITY		
	ALEXANDRIAN		KANKAKEE		Average 28 ft (8.5 m) thick, white to gray, fine to medium-grained, thinly bedded DOLOSTONE. Many green shale partings, especially in middle third.
			EDGEWOOD		Average 81 ft (26 m) thick, to 50-76%, slightly argillaceous, gray, fine to medium-grained, thin bedded DOLOSTONE. Approximately 20% of this is bedded and nodular white CHERT. Lower 25-50%, argillaceous to shaley DOLOSTONE thin bedded, medium to dark gray. Bottom 20 ft (6 m), 30 to 40% SHALE.

FIGURE 9.3 STRATIGRAPHIC COLUMN, CALUMET AREA, CHICAGO, ILLINOIS

gradual. The Markgraf Member is a moderately argillaceous and silty, fine-grained dolostone which has a mottled blue and gray appearance. Thin shale partings are numerous, particularly in the middle part of the unit, and calcite-filled vugs are usually present. The Markgraf averages about 32 ft (9.8 m) in thickness.

A minor unconformity separates the Markgraf from the underlying Kankakee Formation. The Kankakee is a fine to medium-grained, slightly argillaceous dolostone. The top 1 to 3 ft (0.3 to 0.9 m) are thickly bedded, pure dolostone. The argillaceous content increases from the top to the middle of the formation, where green shale partings up to 0.3 in. (8 mm) in thickness may occur on an average spacing of less than 1.0 in. (25 mm). The frequency of shale partings decreases from the middle to the bottom of the unit. The thickness of the Kankakee in the Calumet area averages 28 ft (8.5 m).

The oldest Silurian unit in the Calumet area is the Edgewood Formation. The Edgewood is distinguished from the Kankakee by the presence of chert. The upper 50 to 75 percent of the Edgewood is slightly argillaceous, fine to medium-grained, thinly bedded dolostone. Approximately 20 percent of the rock is composed of nodules and beds of white chert, with many beds in the upper 20 ft (6.1 m) up to 6 in. (0.6 m) in thickness. Gray shale partings are numerous and become more frequent with depth. The lower 25 to 50 percent of the Edgewood is a thinly bedded, shaly dolostone, and shale may make up 30 or 40 percent of the rock in the bottom 20 ft (6.1 m). The average thickness of the Edgewood Formation in the Calumet area is 81 ft (25 m).

In terms of regional structure, the bedrock in the Calumet area is on the northeast flank of the Kankakee Arch which separated the Michigan and Illinois depositional basins during the Paleozoic Era. Most joints in the rock are vertical or near vertical and two sets are common, generally striking northeast and northwest. Most of the joints are tight but some are filled with clay and dolostone fragments, pyrite, and infrequent deposits of calcite. Some joints are open and can transmit significant quantities of ground water. Several faults in the area have been identified on the basis of isopach maps and structure contour line offsets (Keifer & Associates, 1976b). These fault locations correlate

TABLE 9.1 SUMMARY OF AVERAGE RQD, NUMBER OF JOINTS IN 100 FEET OF CORE, AND UNCONFINED COMPRESSIVE STRENGTH FOR STRATIGRAPHIC UNITS IN THE VICINITY OF TARP CONTRACT 73-287-2H (Keifer & Associates, 1976 b)

STRATIGRAPHIC UNIT	RQD (%)	NUMBER OF JOINTS IN 100 FT (30 m) OF CORE	UNCONFINED COMPRESSIVE STRENGTH
Racine: Inter-reef	94	4.7	22.2 ksi (153 MPa)
Racine: Reef	91	4.8	18.7 ksi (129 MPa)
Romeo	92	8.2	35.2 ksi (243 MPa)
Markgraf	96	2.0	25.2 ksi (174 MPa)
Kankakee	95	1.6	22.2 ksi (153 MPa)
Edgewood	92	0.5	24.4 ksi (168 MPa)

well with zones of lower rock quality in the exploratory core and with areas of relatively high pumping rates during water pressure tests.

The site exploration program covering the length of Contract 73-287-2H included 31 vertical and two angled NQ wire line core borings, 1.88 in. (48 mm) in diameter. The borings were made on approximately 2,000 ft (610 m) centers along the tunnel alignment, with additional taken at drop shaft locations. Only Silurian age rock was described and sampled. Core recoveries were generally 98 to 100 percent. The Rock Quality Designation (RQD) and the number of joints were determined at the time of exploration. The cores were described, stratigraphic contacts were identified and laboratory tests were performed. Average values of the RQD, number of joints per 100 ft (30 m) of core, and unconfined compressive strength for each rock unit are listed in Table 9.1.

The subsurface geology, as interpreted from the site exploration borings, is shown in Figure 9.4. The main tunnel is superimposed on the cross-section, and the branch tunnel at the northeast end of the project is shown between Stations -1+34 and 16+41. The tunnel is below the

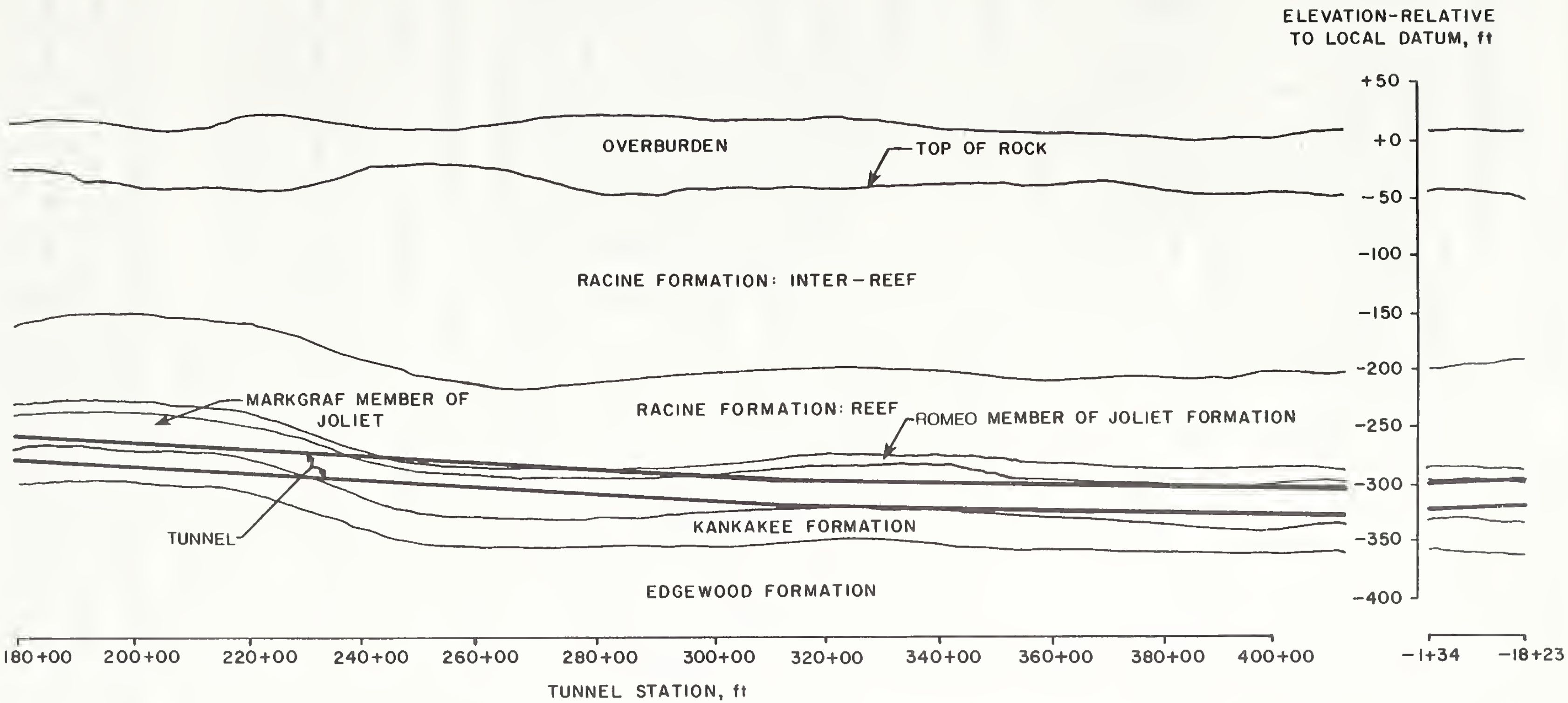


FIGURE 9.4 GEOLOGIC PROFILE FOR THE EAST HEADING AND 125th STREET BRANCH TUNNEL OF TARP CONTRACT 73-287-2H

potentially abrasive chert and weathered rock in the Racine Formation and above the chert in the Edgewood Formation. Because the Romeo Member shows a high unconfined compressive strength, much of the tunnel alignment was set in the lower strength rock of the Markgraf Member of the Joliet Formation and the Kankakee Formation.

Detailed mapping of the tunnel wall geology and of installed support was performed by Keifer & Associates, Inc. Maps and support descriptions are included in Appendix A.

9.3 DESCRIPTION OF MACHINE AND MUCKING SYSTEM

The TBM used on Contract 73-287-2H was manufactured by The Robbins Company of Seattle, Washington, and was designated as Model 213-190. Figure 9.5 shows a profile and two cross-sectional views of the machine. The figures are drawn to scale and prominent components are labelled.

Table 9.2 summarizes machine dimensions, components, and operating characteristics. The machine was 54 ft (16.5 m) long with thrust cylinders retracted, as measured from the front of the cutterhead to the rear of the conveyor assembly. The cutterhead was 21.25 ft (6.5 m) in diameter. The maximum cylinder pressure was 3,540 psi (24.4 MPa) for a maximum forward thrust of 1,880 kips (8.36 MN). During tunneling, the thrust cylinders were operated at an average 3,180 psi (21.9 MPa) pressure. As indicated in Table 9.2, the thrust cylinder pressure required to advance the TBM without face contact was measured as 500 psi (3.5 MPa). This value was determined when the trailing gear was attached to the TBM. The cutterhead was supplied with power from eight 200 hp (149 kW) motors. Two cutterhead speeds were available at 5.66 and 2.83 rpm. The slower speed was used only at the start of the contract when only four of the eight cutterhead motors were operated. The higher speed was used for all other tunneling. The cutterhead was equipped with ten muck buckets and two access doors, spaced at equal distances around the cutterhead periphery. The roof support extensions were removed early in the tunneling when it was found that they interfered with the laser and target system when mining around curves.

The trailing gear and car pass system were similar to those used in the Buffalo C11 tunnels. The trailing floor was 265 ft (81 m) long and was composed of 13 balanced sleds, each 20 ft (6.1 m) long and 11 ft

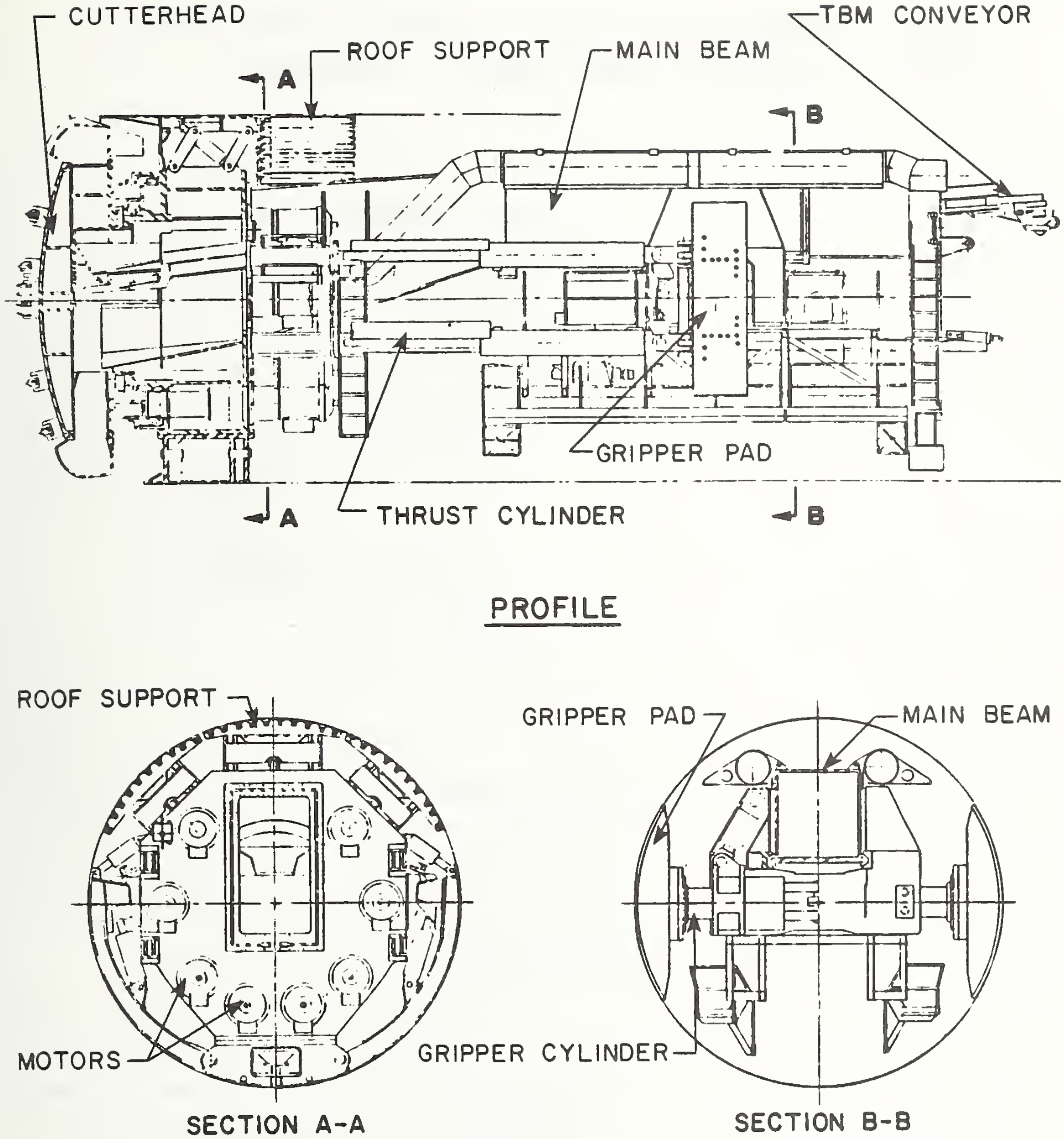


FIGURE 9.5 PROFILE AND CROSS-SECTIONAL VIEWS OF THE TARP CONTRACT 73-287-2H TBM

(3.4 m) wide, and a ramp between the trailing floor and tunnel track. The trailing floor components were manufactured by the Moran Engineering Sales Company of Montebello, California. The sleds supported a bridge conveyor, fan line, high voltage transformer, car pass assembly, and a

TABLE 9.2 SUMMARY OF DIMENSIONS, COMPONENTS, AND OPERATING CHARACTERISTICS FOR THE TARP CONTRACT 73-287-2H TBM

Manufacturer	The Robbins Company, Seattle, Washington
Model Number	213-190
Diameter	21.25 ft (6.5 m)
Length	54.0 ft (16.5 m)
Weight	670 kips (2.98 MN)
Drive Motors	8
Drive Motor Rating	200 hp (149 kW) at 222 amps
Average Operating Amps	not available
Cutterhead Speeds	5.66, 2.83 rpm
Thrust Cylinders	4
Cylinder Diameter	13.0 in. (330 mm)
Stroke Length	6.0 ft (1.8 m)
Maximum Cylinder Pressure	3540 psi (24.4 MPa)
Average Operating Pressure	3180 psi (21.9 MPa)
Cylinder Pressure to Move TBM without Face Contact	500 psi (3.5 MPa)[a]
Number and Types of Cutters	43 single disc cutters, 15.5 in. (394 mm) diameter 2 twin disc center cutters, 12.0 in. (305 mm) diameter
Conveyor Belt Width	36.0 in. (914 mm)
Conveyor Belt Speed	387 ft/min (118 m/min)
Conveyor Capacity[b]	830 yd^3/hr (635 m^3/hr)

[a] measured with trailing gear in tow

[b] based on troughing angle of 25 degrees, surcharge angle of 25 degrees, and muck unit weight of 100 lbs/ft^3 (15.7 kN/m^3)

variety of other mechanical and electrical equipment. Muck was transferred from the bridge conveyor through a fixed-location hopper into 18 yd^3 (14 m^3) muck cars. Assuming a muck unit weight of 100 lbs/ft^3 (15.7 kN/m^3), the capacity of the 36 in. (0.9 m) bridge conveyor was 670 yd^3/hr (512 m^3/hr).

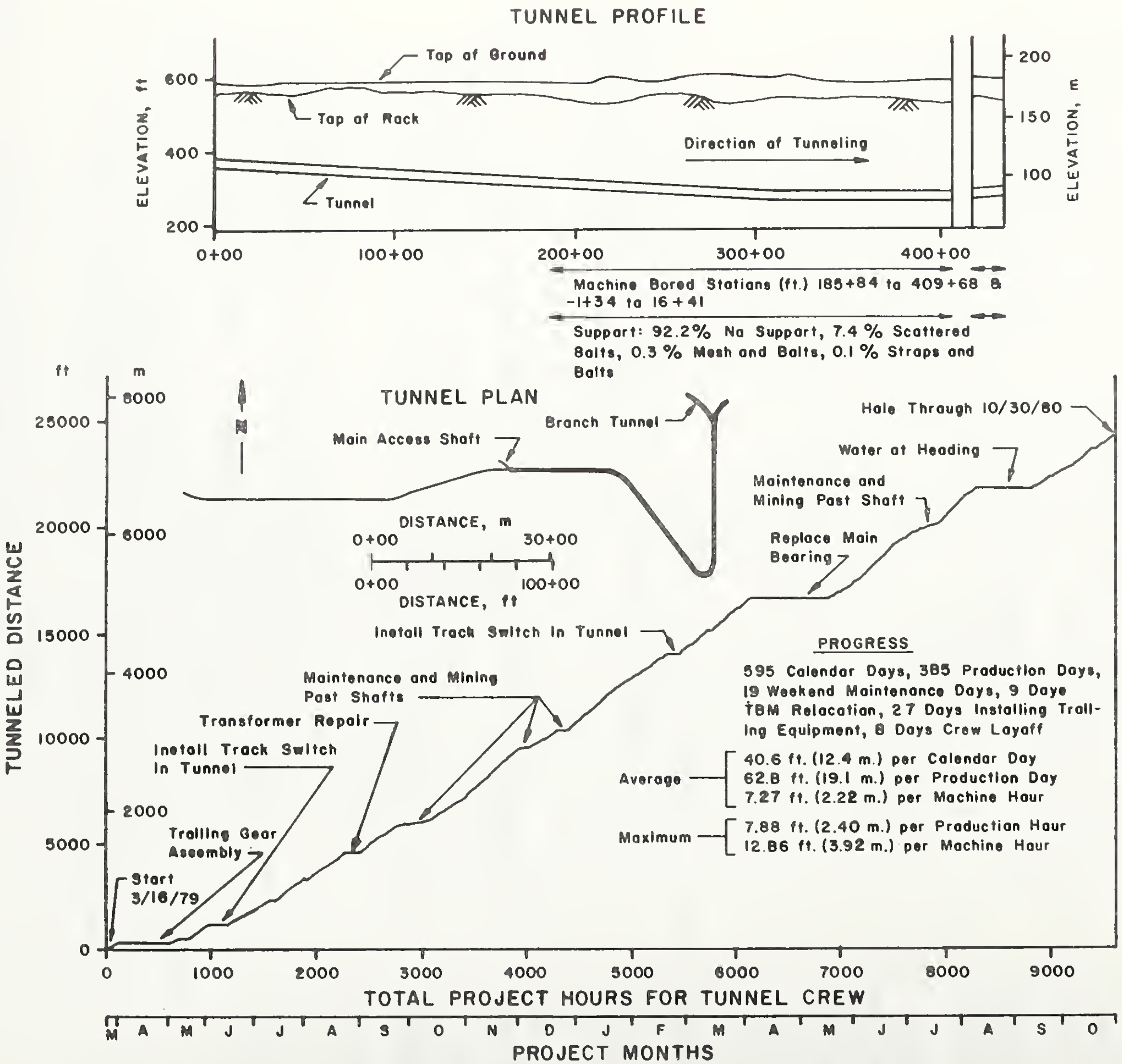
The car pass included a hydraulically operated uncoupling device on the inbound track, a chain-driven sliding floor between tracks, and a hydraulically operated unit on the outbound side which advanced the cars beneath the hopper and reassembled the train. The rail track was laid on wooden wedges fastened directly to the rock in the tunnel invert with bolts. Drill rigs, which installed the bolts, were mounted on the trailing floor beneath the bridge conveyor. A 20 ton (178 kN) locomotive was used to take the six-car muck train to the muck removal shaft.

The shaft mucking system was similar to that used in the Buffalo C31 tunnels. The locomotive positioned the muck cars in the shaft, and the boxes were lifted off the muck car frames with a 150 ton (1.33 MN) crane. The boxes were hoisted 297 ft (91 m) to the surface where they were dumped with a whip line. A 5 yd^3 (3.8 m^3) loader was used to reposition the muck at the surface. The capacity of the overall shaft mucking system was estimated as 300 yd^3/hr (229 m^3/hr).

9.4 CONSTRUCTION EVENTS

Figure 9.6 shows a plot of the tunneled distance versus the total project hours for the tunnel crew. The figure shows a simplified tunnel plan and profile and summarizes information on the machine, project, and lithologies encountered in the bore. The format of this figure is similar to that used by the U.S. Bureau of Reclamation, which serves as a standard reference base for TBM-driven tunnels owned by that agency (U.S. Bureau of Reclamation, 1974).

Figures 9.7, 9.8, and 9.9 summarize the advance rate, utilization, availability, and penetration rate as a function of tunnel station in histogram form. The utilization and penetration rates were calculated on the basis of machine boring times recorded by the contractor and read from the machine clock. The clock was activated when the air clutch for the cutterhead motors was engaged. Each horizontal line segment of the



MACHINE DATA

Robbins Model 213-190

Diameter 21.25 ft. (6.48 m.)

Length 54 ft. (16.5 m.)

Weight 335 tons (2.98 MN)

Max. Thrust 1880 kips (8.36 MN)

Recycle Stroke 72 in. (1.83 m.)

Cutterhead Rotation 5.66 rpm, 2.83rpm

Cutters 43 15.5 in. (394 mm.) Single Disc

4 12 in. (305 mm.) Single Disc Center

Motors 8 200 hp.

PROJECT INFORMATION

24159 ft. (7364 m.) Study Length out of Total 42540 ft. (12966 m.)

Variable Grade: Uphill Max. 0.08 %
Downhill Max 0.3 %

Muck Loading by Carpass

Muck Disposal Through Shaft by Crane Dumping of Muck Cars

Contractor: Traylor Brothers, Inc.

Owner: Metropolitan Sanitary District of Greater Chicago, Chicago, Illinois

LITHOLOGY

Dolostone, Unconfined Compressive Strengths from 12 ksi (80 MPa) to 44 ksi (300 MPa)

FIGURE 9.6 TUNNELED DISTANCE VERSUS CUMULATIVE PROJECT HOURS AND PROJECT INFORMATION FOR TARP CONTRACT 73-287-2H, EAST HEADING

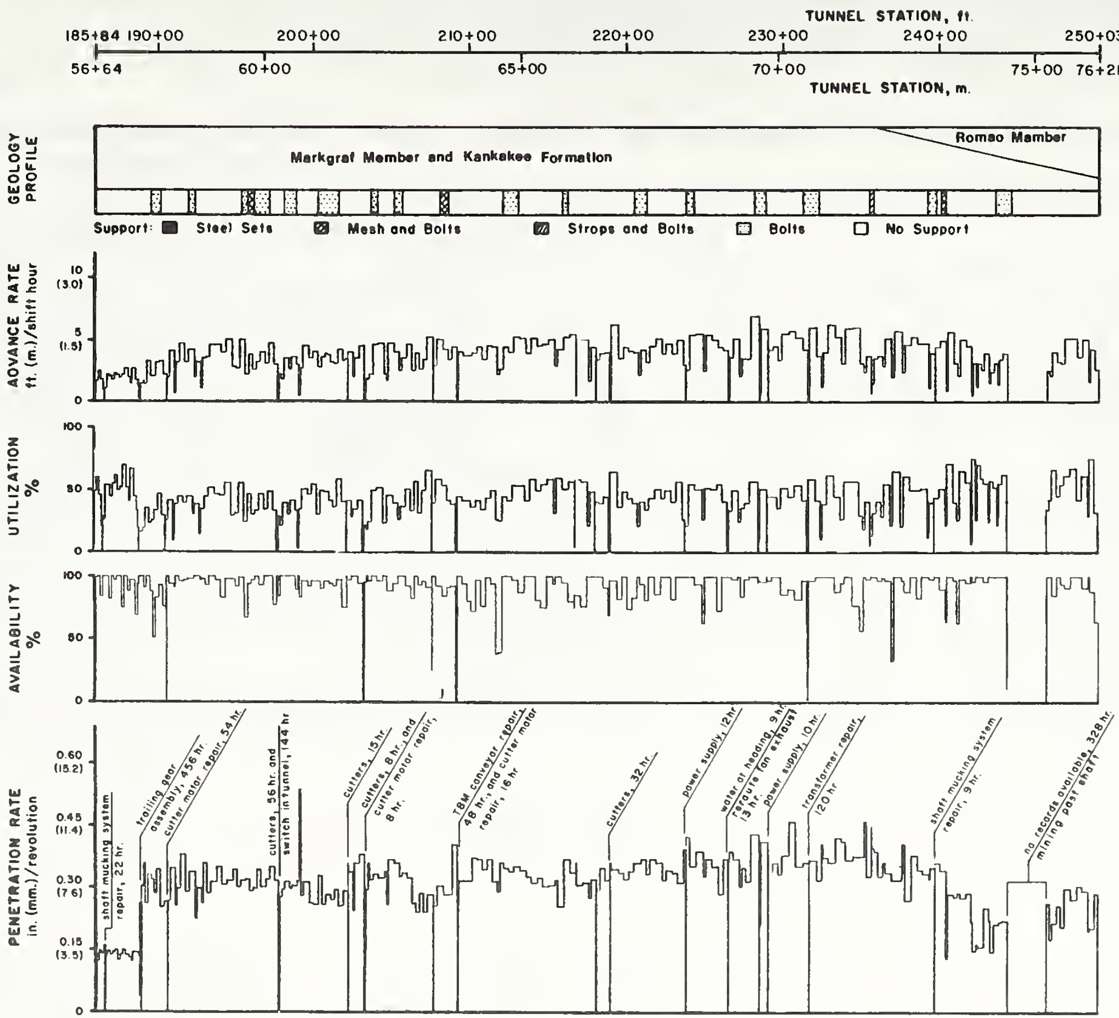


FIGURE 9.7 TBM PERFORMANCE RECORD, TUNNEL GEOLOGY, AND SUPPORT FOR TARP CONTRACT 73-287-2H, STATION 185+84 TO 250+03

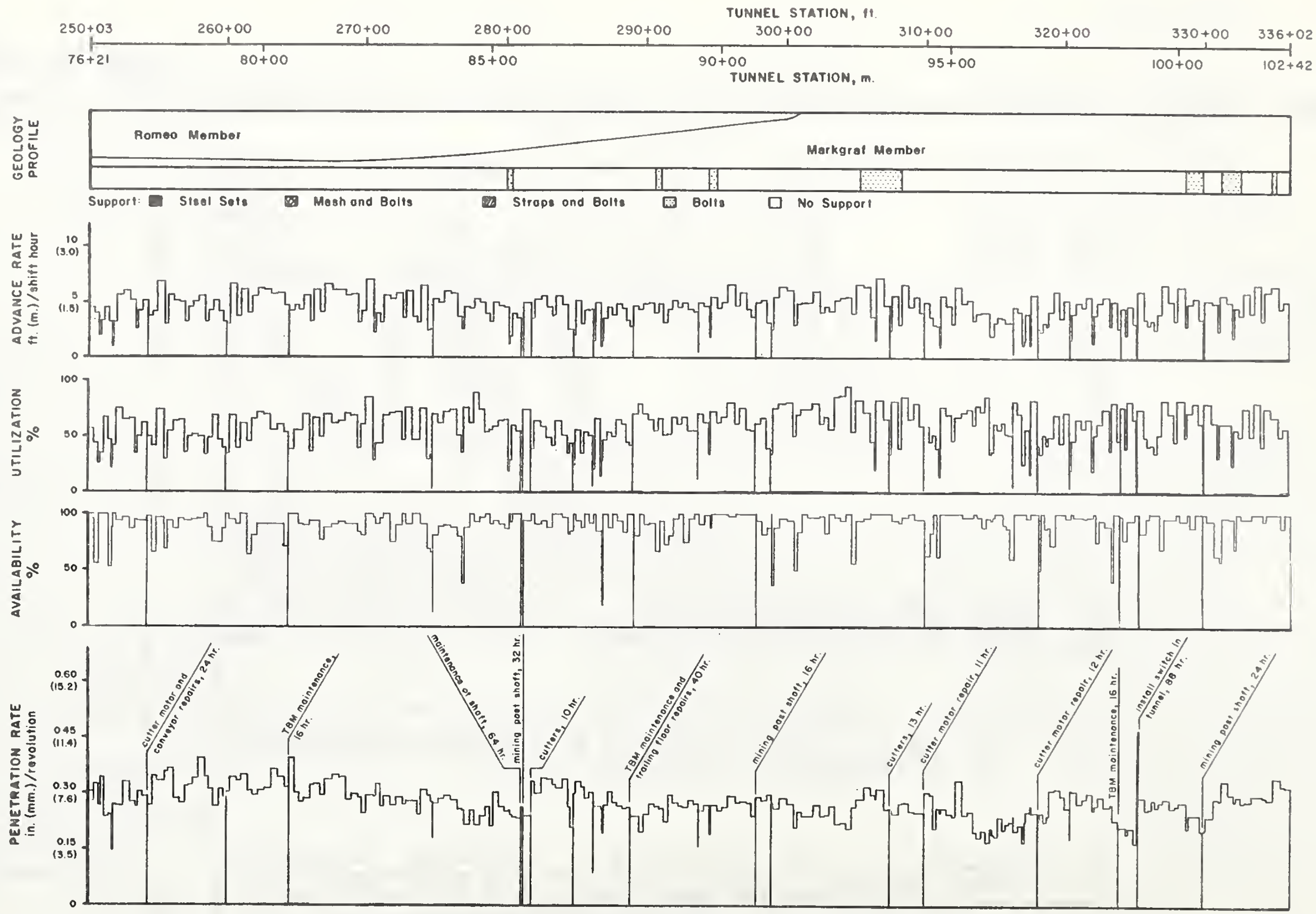


FIGURE 9.8 TBM PERFORMANCE RECORD, TUNNEL GEOLOGY, AND SUPPORT FOR TARP CONTRACT 73-287-2H, STATION 250+03 TO 336+02

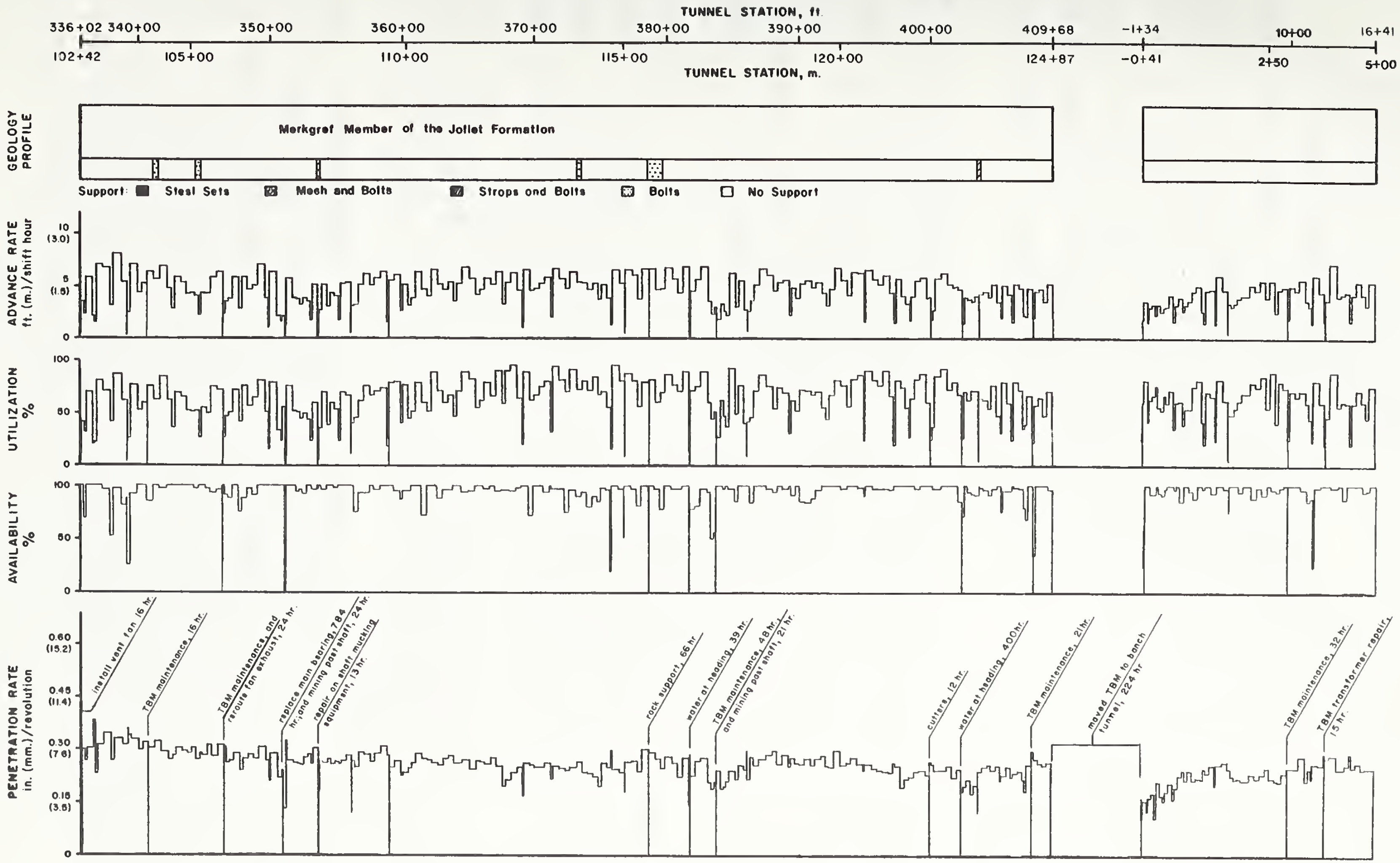


FIGURE 9.9 TBM PERFORMANCE RECORD, TUNNEL GEOLOGY, AND SUPPORT FOR TARP CONTRACT 73-287-2H, STATION 336+02 TO 409+68 AND THE 125TH STREET BRANCH TUNNEL

histogram plots corresponds to one shift. The length of the line segment is proportional to the distance tunneled during the shift. Each line segment is plotted above the horizontal axis at a distance proportional to the value of the performance parameter calculated for the shift. If tunneling delays at a given station were longer than the duration of a shift, the performance parameters at that station are equal to zero and the plot appears as a vertical line intersecting the horizontal axis. Tunnel stations used in this report are in units of feet, conforming with conventional U.S. practice. Figures 9.7 through 9.9 also show a simplified illustration of the geologic profile as mapped in the excavated tunnel and the types of initial support used at various locations in the tunnel. A detailed record of the geology with stratigraphic identifications, joint planes, overbreak, and support may be found in Appendix A.

In combination, Figures 9.6, 9.7, 9.8, and 9.9 provide a summary of the tunneling events and TBM performance referenced by the cumulative hours and the distance tunneled. They index shift time and tunnel station for the discussion of construction events that follows.

The basic work schedule consisted of a five day week. Initially, two 8.0 hour shifts were operated, but beginning 3 April 1979, the contractor ran three 8.0 hour shifts each day.

The TBM was assembled in Drop Shaft 6R near the middle of the contract and was advanced to the east through a drill-and-blast tunnel to Station 185+84. From this location, the TBM excavated 337 ft (103 m) to Station 189+21 where production was halted on 5 April 1979 to allow erection of the trailing sleds and muck handling equipment. While the mucking gear was being assembled, three cutters were changed and break-in maintenance was performed on the TBM. In total, 21 working days were spent on these activities.

On 2 May 1979, boring was started again. At Station 190+58, metal fragments were found in the cutterhead motor reduction gear boxes and production was stopped for 32 shifts to repair the motors. The TBM crew only worked 7 of these shifts. Mining resumed on 23 May 1979, and continued to Station 197+91. In this interval, the primary causes of downtime were utility line installation and lack of empty muck cars at the heading because of slow muck removal in Shaft 6R. At Station 197+91, production was stopped for 25 shifts to install a switch in the rail line near Shaft 6R. Fifteen cutters were changed and TBM maintenance was also performed at this time.

On 16 June 1979, boring was resumed. Between Stations 197+91 and 208+74, train delays, derailments and shaft mucking system repairs were the primary downtime causes. The TBM conveyor in the main beam was jammed with muck several times and excavation was stopped at Station 208+74 to remove the belt and clean out the main beam. At this location, a total of eight shifts were required to repair the belt and to make repairs on the cutterhead motors and the car pass unit.

Between 17 July and 26 September, the TBM mined from Station 208+74 to 244+19. At Station 219+04, excavation was stopped for four shifts to replace 16 cutters and to change the cable on the crane in Shaft 6R. When the TBM was at Station 226+40, excavation was stopped for three shifts to reroute the fan line exhaust through the recently completed Shaft 6U. Near this location, there were two power outages and a pump failure that caused the heading to be flooded. At Station 231+45, a muck car derailed on the trailing floor and damaged the high voltage transformer. Excavation was stopped for 15 shifts to repair the transformer. During this time, one of the cutterhead motors was repaired, the TBM main beam was cleaned, and a crack in the cutterhead was welded. Train delays continued to be a major cause of downtime until about Station 241+90, when the contractor replaced the crane at Shaft 6R.

At Station 244+19, excavation was stopped for 23 shifts to repair the TBM and prepare for mining past the adit from Drop Shaft K. Because the adit had been excavated in advance of machine tunneling, it was necessary to adopt special measures to develop forward thrust at this location. The gripper pad opposite the adit was bolted to the tunnel wall, and thrust was applied through the two cylinders nearest the bolted pad. Thrust pressures approximately 50 percent greater than normal were applied. The gripper pad was sequentially disengaged and rebolted as the machine was advanced through each cycle of forward thrust until it cleared the adit. This method of advancing the machine was used at all subsequent drop shaft locations.

Between Shaft 6K and Shaft 6I, principal causes of downtime were derailments, car pass repairs, and cable changes on the crane at Shaft 6R. At several locations, muck jams in the cutterhead buckets caused the cutterhead motors to overheat. The bridge conveyor was overloaded and stopped 11 times. The conveyor belt was torn twice and the conveyor drive motor was replaced at Station 254+26.

Before mining past the adit to Shaft 6I, excavation was stopped for eight shifts to perform TBM maintenance and replace 17 cutters. Four shifts were required to mine past the adit. At Station 288+83, excavation was stopped for the Christmas holidays. During this time, the contractor ran five shifts to install a new hydraulic pump on the trailing floor conveyor and to repair a motor on the car pass unit. Mining started again on 27 December 1979, and the TBM excavated to Shaft 6V with train delays, car pass, and shaft mucking equipment repairs as the main causes of downtime.

Most of the tunnel between Stations 297+50 and 313+37 was mined with six or fewer operating cutterhead motors. The principal causes of downtime in this interval were cutterhead motor repairs, cutter changes, and derailments. From Station 313+37 to 325+77, the TBM bored around a 500 ft (152 m) radius curve. At Station 320+25, two shifts were required to replace a bearing on the front roller of the bridge conveyor, and the contractor operated three Saturday shifts for TBM maintenance and repair at Station 321+87. At Station 323+92, two shifts were required to replace and tighten bolts on the cutterhead buckets, and excavation was stopped at Station 325+10 for 11 shifts to install a switch and passing track section in the tunnel. At this time, cutterhead bolts and cutter saddles were also repaired and many bolts were tightened or replaced. The tunnel grade changes from 0.3 percent to 0.08 percent at about Station 319+00, and many derailments occurred near this location. At Station 326+34, two of the trailing gear sleds pulled apart and two shifts were required for repairs.

The adit to Drop Shaft 6B was mined past during three shifts on 6 March 1980, and the high voltage cable was rerouted through this shaft. Between 8 March and 5 April 1980, the contractor operated maintenance shifts every weekend. During these Saturday shifts, the fan line was routed through Shaft 6B, muck cars were cleaned, and cutterhead motors were repaired. Bolts in the connections between the four main cutterhead pieces were often loose, and the contractor used several Saturday shifts to weld these connections and to reinforce the cutterhead buckets with steel plate additions.

At Station 351+32, excavation was stopped at the adit to Shafts 6D and 6H to replace the cutterhead main bearing. Between 7 April and 17 May 1980, 91 shifts were required for the bearing replacement and 8 shifts were used to remove and repair the cutterhead motors. The contractor operated 11 weekend shifts during this time. Mining resumed on 19 May, with three shifts required to advance the grippers past the adit.

At Station 354+04, excavation was stopped for two shifts when the crane dropped a muck box in Shaft 6R. Near this location, ground water inflow, entering from joints above spring line, partially flooded the heading and excavation was severely restricted for four shifts. When the TBM was at Station 379+12, eight shifts were required to install rock bolts in a zone of loose crown rock behind the heading. At Station 382+26, water accumulation at the heading again stopped excavation, and five shifts were required to pump the water out.

Before mining past Shaft 6W, excavation was stopped for six shifts to perform maintenance, change seven cutters, and replace the conveyor belt on the trailing gear. Three shifts were required to advance the machine past the adit. From this point to the end of the main tunnel at Station 409+68, the principal causes of downtime included cutter changes, derailments, and repair of the microdyne fan and motor on the trailing floor. Because the tunnel was mined downgrade, water accumulates at the heading continued to be a problem. At Station 402+86, during a thunderstorm on 10 August 1980, a retaining structure at the surface at Drop Shaft 6K failed. The resulting inflow of water and sewage flooded the tunnel heading to depths of 7 ft (2.1 m). More than 5,000 ft (1,524 m) of the tunnel had standing water. Fifty shifts were required for clean up operations. The cutterhead motors were repaired and 17 cutters were replaced. Excavation was started again on 2 September, but the TBM was not operated at full thrust until 5 September 1980. Loose cutterhead bolts also continued to be a problem and at Station 408+18, the cutterhead and bucket connections were repaired during 21 hours of downtime.

The TBM reached the end of the main tunnel on 15 September 1980. The next 28 shifts were used to back up the TBM to Station 402+00, change 11 cutters, and perform maintenance. Excavation of the branch tunnel started on 29 September 1980. The principal causes of downtime in this tunnel were cutter changes, derailments, and TBM maintenance and system repair. At Station -1+05, one of the TBM rear support cylinders was replaced and, at Station 9+95, four shifts were used to repair the cutterhead buckets and to install fans to reduce the dust at the heading. At Station 11+80, a new conveyor belt was installed in the TBM main beam and 15 hours were required to repair the TBM transformer at Station 12+85.

In summary, excavation of the 21.25 ft (6.5 m) diameter tunnel of TARP Contract 73-387-2H started on 16 March 1979. A distance of 337 ft (103 m) was mined before the trailing gear was installed, and 22,046 ft (6,720 m) of the main tunnel and 1,775 ft (541 m) of the branch tunnel were mined with the trailing floor in tow. The tunneling required 595 calendar days, of which 385 were production week days and 19 were week-end production or maintenance days. The main tunnel was completed on 15 September 1980. The branch tunnel was started on 29 September 1980 and the TBM holed through into Drop Shaft 6S on 30 October 1980. The time required to drive the main tunnel was 8,823 hours (1,104 shifts), of which 248 hours (31 shifts) were worked before trailing gear installation and 456 hours (57 shifts) were worked during weekends. An additional 456 hours (57 shifts) were required for trailing gear installation. The time required to move the TBM from the end of the main tunnel to the start of the branch tunnel was 224 hours (28 shifts) and the branch tunnel was driven in 552 hours (69 shifts).

9.5 TUNNELING PERFORMANCE

Table 9.3 summarizes the average advance rate, utilization, availability, and penetration rate for the east heading of the main tunnel and the branch tunnel of TARP Contract 73-287-2H. The average advance rate and utilization were calculated on the basis of the cumulative

TABLE 9.3 AVERAGE ADVANCE RATE, UTILIZATION, AVAILABILITY, AND PENETRATION RATE FOR STATION 189+21 TO 409+68 AND THE 125th STREET BRANCH TUNNEL OF TARP CONTRACT 73-287-2H

PARAMETER	AVERAGE VALUE
Advance Rate	2.5 ft/hr (0.78 m/hr)
Utilization	35.0 percent
Availability	81.6 percent
Penetration Rate	7.3 ft/hr (2.2 m/hr)
	0.26 in./revolution (6.5 mm/revolution)

project hours from the time the trailing gear was assembled to holing through of the TBM at Station 16+41 in the branch tunnel. These averages include the time devoted to maintenance and preparation at the adits to the drop shafts and the time required to move the TBM and trailing floor from the end of the main tunnel to the start of the branch tunnel. The average penetration rate and utilization were calculated in the same manner as the individual shift penetration rates and utilizations by using the elapsed machine clock times as recorded on the contractor's shift reports.

In general, utilization was low in sections where problems with the shaft mucking equipment and derailments resulted in significant train delays, particularly in the first 5,000 ft (1,524 m) of excavation. Utilization was also relatively low as the TBM mined around curves and in areas where water accumulation at the heading was a problem. Sustained high values of utilization were attained in straight tunnel stretches where the mucking system was in good working order.

The penetration rate was primarily influenced by two factors: 1) the number of functioning cutterhead motors and 2) the horizontal tunnel alignment. Between Stations 297+50 and 313+37, the average penetration rate with eight operating cutterhead motors was reduced by 7 to 15 percent with seven operating motors, and by 13 to 21 percent with only six motors on line. While tunneling around the horizontal curves in the alignment, penetration rates were reduced by 10 to 30 percent. In addition to these factors, there was a general decrease in penetration rate from the start to the end of the main tunnel excavation.

Availability of the TBM was limited primarily by two factors: 1) 1) replacement of the main cutterhead bearing and 2) repairs on the cutterhead, cutter saddles, and buckets. Low machine availability at the start of the tunnel was primarily caused by break-in maintenance of the new machine.

9.6 DOWNTIME ANALYSIS

Table 9.4 summarized the delay, or downtime, associated with various components of the TARP Contract 73-287-2H tunneling. As in previous chapters, four general categories have been used to list the individual causes of delay. These categories include: 1) repairs and maintenance of the TBM, 2) backup system repairs and maintenance, 3) delays related to ground conditions, and 4) other sources of delay. A discussion of downtime categories and a detailed description of tunneling delays is given in Appendix B. The downtime percentages were calculated on the basis of total project hours excluding time before and during the assembly of the trailing gear.

Figure 9.10 shows the downtime percentages in the form of a pie chart. Approximately 65 percent of the shift hours were spent on delays resulting in an average machine utilization of 35 percent.

The major cause of downtime under the general category of TBM maintenance and repair was related to repair of TBM components. A total of 13.6 percent of the shift time was spent on TBM repairs, of which 7.8 percent was devoted to the main bearing replacement and 4.0 percent was required for repair of the cutterhead, saddles, and buckets. Delay due to cutter changes was also significant, and amounted to 5.5 percent of the total shift time.

TABLE 9.4 TABULATION OF DOWNTIME AS A PERCENTAGE OF TOTAL SHIFT HOURS FOR STATION 189+21 TO 409+68 AND THE 125th STREET BRANCH TUNNEL OF TARP CONTRACT 73-287-2H

TBM Maintenance and Repair	Percentage Downtime	Backup System	Percentage Downtime	Ground Conditions	Percentage Downtime	Additional Items	Percentage Downtime
Cutter Change	5.5	Power Supply	0.4	Water Inflow	5.2	Restroke	not recorded
General Maintenance and Inspection	13.6	Cable Utilities Fanline	1.9	Steel Sets	0.0	Shaft Mining and Maintenance	5.5
Lube Oil	0.7	Survey	0.3	Bolts/Straps	0.7	Methane Probe	not used
Hydraulics	0.6	Car Pass	1.6	Bolt Drill Repair	0.0	Other (Supplies, Shift Changes, TBM Relocation)	8.9
Motors	2.7	Tripper	not used	Scaling/ Rock Jam	0.4		
TBM Conveyor	0.8	Trailing Gear Conveyor	1.7	Gripper Difficulty	0.0		
Electrical	1.9	Train Delay	3.3	Clearance	0.0		
		Shaft Operations	2.4				
		Laying Rails	3.2				
		Derailment	3.7				
Subtotal	25.8	Subtotal	18.5	Subtotal	6.3	Subtotal	14.4

TOTAL PERCENTAGE DOWNTIME 65.0

Principal causes of backup system delay included repair of mucking system components remote from the TBM. Train delays amounted to 3.3 percent of the total shift time. These delays were in part caused by derailments and repair of shaft mucking system components, which required 3.7 and 2.4 percent of the total shift time, respectively. A total of 3.2 percent of the shift time was required to lay rails, of which 2.5 percent was devoted to the installation of passing track and switches at two locations in the tunnel.

The downtime associated with ground conditions and water infiltration was principally related to accumulation of water at the heading. Of the 5.2 percent of shift time associated with water problems, only 0.9 percent was actually caused by ground water infiltration. The remaining 4.3 percent was required for cleanup and machine repairs

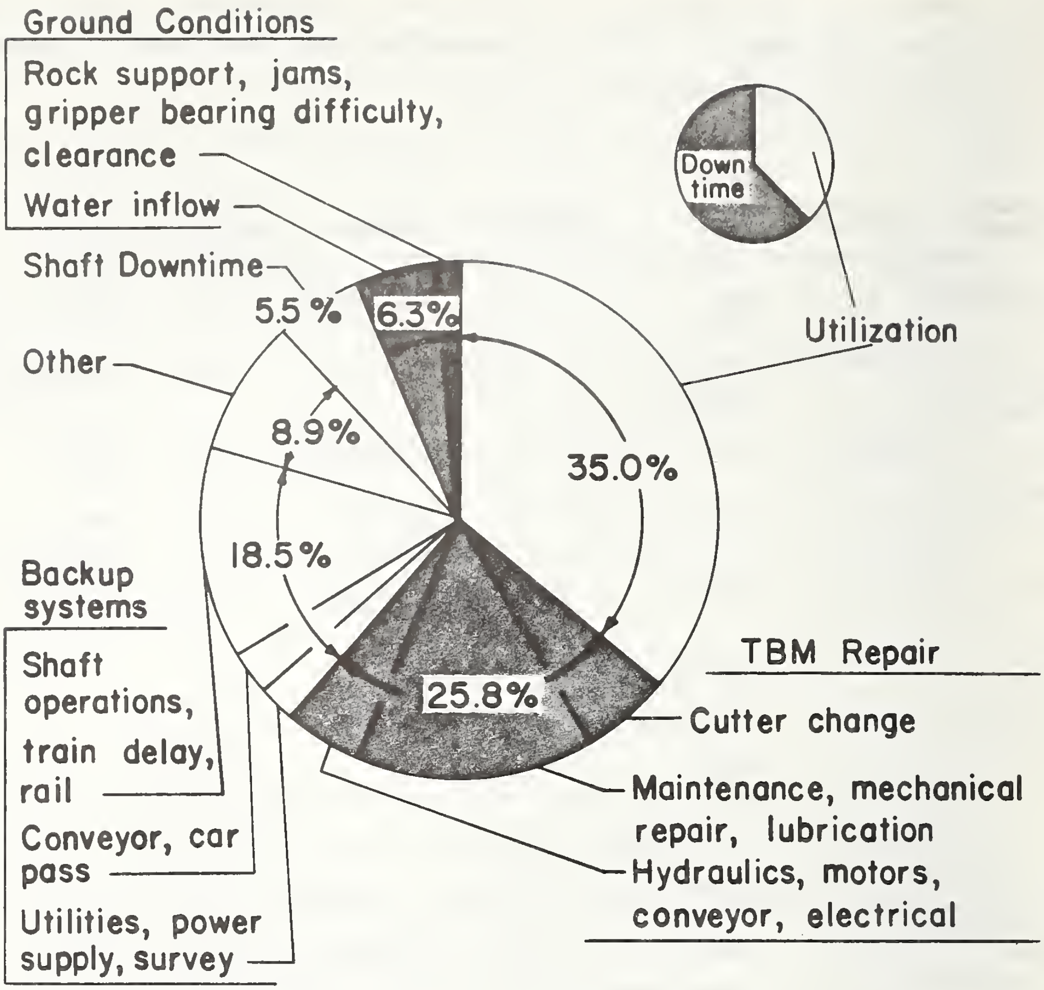


FIGURE 9.10 SUMMARY OF DOWNTIME AS A PERCENTAGE OF TOTAL SHIFT HOURS FOR TARP CONTRACT 73-287-2H, STATION 189+21 TO 409+68 AND THE 125th STREET BRANCH TUNNEL

following the failure of the retaining structure at Shaft 6K. The downtime directly involved with rock support, scaling, rock jam removal, and ground water infiltration was only 2.0 percent of the total shift time.

The category of "shaft mining and maintenance" includes downtime associated with maintenance before and during forward advance past the adits connecting to drop shafts with the main tunnel. Of the total 5.5 percent of shift time in this category, 3.3 percent was accumulated in maintenance delays and 2.2 percent was spent in mining. The category of "other" includes downtime for shift changes, waiting for the dust to clear so that the laser could be read, bringing supplies to the heading, and relocating the TBM after the completion of the main tunnel. Of the 8.9 percent of total shift time in this category, 2.4 percent was associated with moving the TBM to the branch tunnel after the main tunnel was completed.

9.7 CUTTER CONSUMPTION

Figure 9.11 shows a front view of the TBM cutterhead on which each cutter position is designated by a number. Numbers one through 36 refer to face cutters, and 37 through 47 refer to gage cutters. Single disc, 15.5-in. (394 mm) diameter cutters were used at the positions shown by numbers 5 through 47 and twin disc, 12-in. (305 mm) diameter cutters were used at the center positions.

A total of 335 cutters were changed over the 22,384 ft (6,823 m) of main tunnel bore, 11 were changed between the main and branch tunnel excavation, and 54 were changed over the 1,775 ft (541 m) of branch tunnel bore. Figure 9.12 summarizes information regarding the number and position of cutter replacements. Cutter changes are referenced according to tunnel station. The replacements are shown in histogram form for all but 12 cutters.

Cutters needing repair were transported to a shop located on site, where rings were replaced and hubs reconstructed. Records describing the reasons for change were available for all but 30 of the total 400 replacements. Information about the cutter position was recorded for all but 12 of the total replacements. Symbols are used in Figure 9.12 to identify the types of cutter damage. Four principal causes of replacement are identified: 1) worn cutter rings, 2) failure of the roller bearings in the cutter hub, 3) broken cutter rings, and 4) broken retaining rings. The category of "other identified cause" includes cases when the cutter ring was chipped and when contact was lost between the ring and hub, leaving the cutter ring free to turn independently of hub rotation. As shown in Figure 9.12, most of the cutter replacements in the first 10,000 ft (3,048 m) of tunnel bore were attributed to worn rings. Most of the replacements after Station 295+00 were recorded as caused by hub bearing failure.

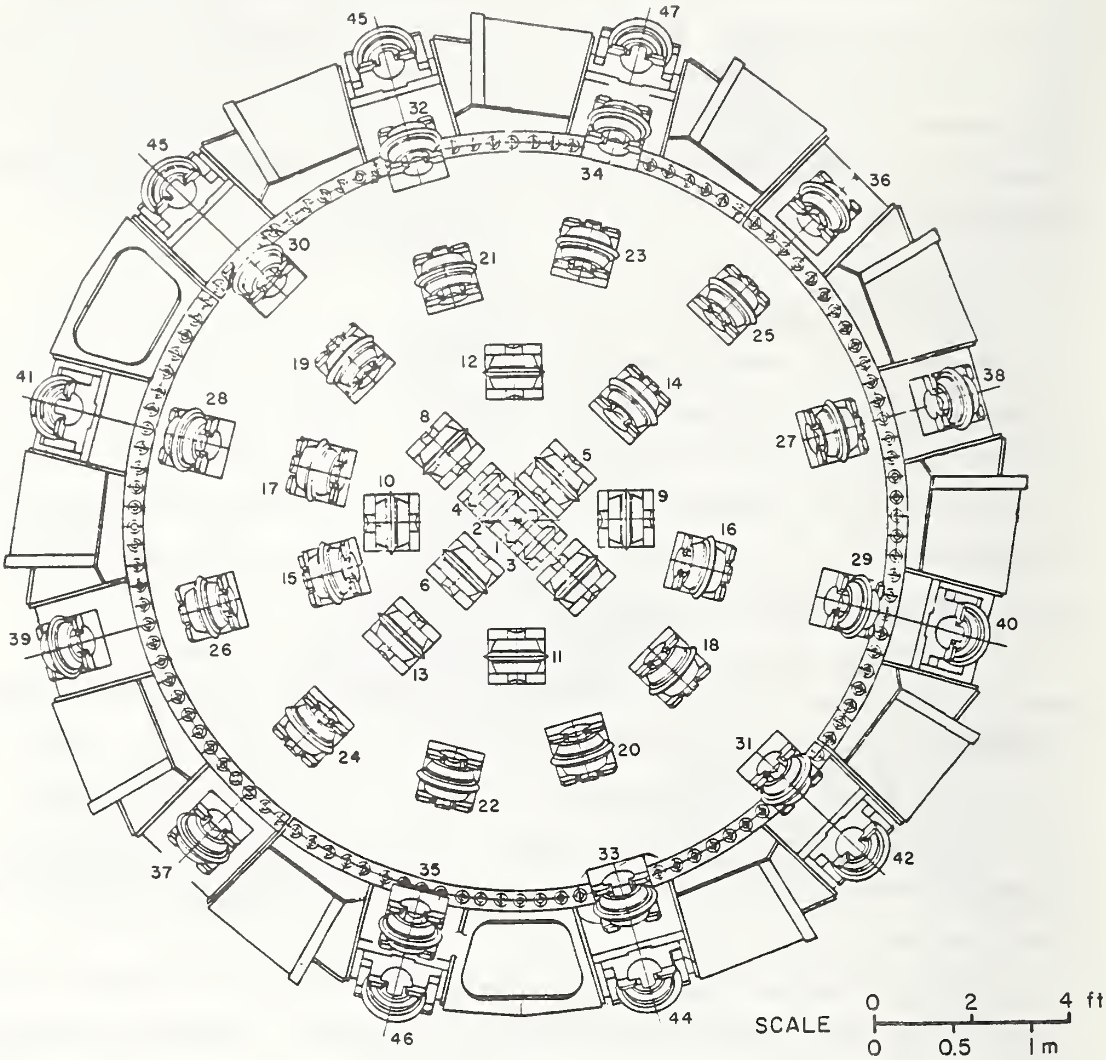


FIGURE 9.11 VIEW OF THE CUTTERHEAD FACE OF THE TARP CONTRACT 73-287-2H TBM

Table 9.5 summarizes the reasons for cutter replacements and the number of cutters replaced for the center, face, and gage positions. Worn cutter rings were the most common reason for gage cutter replacement. For the center and face positions, hub bearing failure was the most frequent cause of replacement.

The contractor changed cutters at an average rate of one cutter per 864 yd^3 (661 m^3) of excavated rock in the main tunnel and at an average

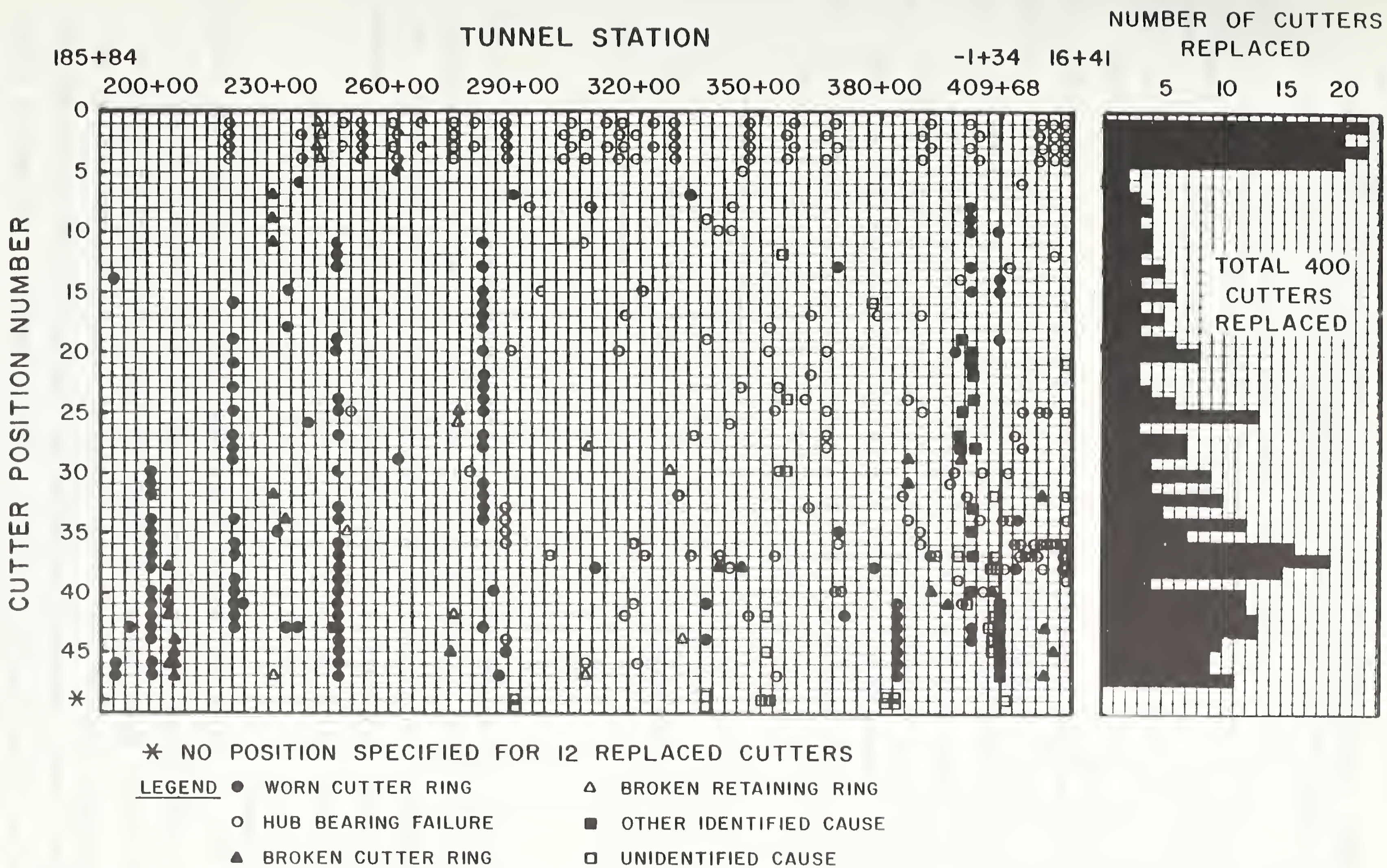


FIGURE 9.12 SUMMARY OF REPLACED CUTTERS, NUMBER OF CHANGES, LOCATION ON CUTTERHEAD FACE, AND TYPE OF DAMAGE FOR STATION 185+84 TO 409+68 AND THE 125th STREET BRANCH TUNNEL OF TARP CONTRACT 73-287-2H

TABLE 9.5 SUMMARY OF CUTTER POSITIONS, NUMBER OF CUTTERS REPLACED, AND REASON FOR REPLACEMENT FOR STATION 185+84 TO 409+68 AND THE 125th STREET BRANCH TUNNEL OF TARP CONTRACT 73-287-2H

CUTTER TYPE	CENTER	FACE	GAGE	TOTAL
Position Numbers	1-4	5-36	37-47	1-47
Number of Positions	4	32	11	47
Number of Cutters Changed for Each Replacement Cause:				
Worn Cutter Ring	0	68	52	120
Hub Bearing Failure	80	81	31	192
Broken Cutter Ring	0	7	18	25
Broken Retaining Ring	4	5	4	13
Other Cause	0	16	22	38
Total Number of Identified Replacements	84	177	127	388

rate of one cutter per 432 yd^3 (330 m^3) of excavated rock in the branch tunnel. Of the total 388 identified changes, 127 replacements were for gage cutters. An average of 21.0 changes were made at each center cutter position, 5.5 changes at each face cutter position, and 11.5 changes at each gage cutter position.

9.8 SUMMARY

From the time the TBM was installed, excavation of the east heading of the main tunnel and the branch tunnel of TARP Contract 73-287-2H required 10,055 shift hours, of which 456 hours were spent on trailing gear assembly and 224 hours were required to move the TBM between the main and branch tunnels. Excluding the time before and during the construction of the trailing gear, the average advance rate was 2.5 ft/hr

(0.78 m/hr) for 23,821 ft (7,261 m) of tunnel. The overall TBM utilization was 35 percent.

Major geologic controls on tunneling performance included stratigraphic units present at the heading and the orientation and frequency of joint sets. Penetration rates appear to have been influenced by the relative amounts of the Kankakee Formation and members of the Joliet Formation at the face. Relatively high penetration rates were achieved when the face was mostly composed of the Kankakee Member.

Major mechanical causes of downtime included the replacement of the cutterhead main bearing and repairs of the cutterhead, saddles, and buckets. Repairs of muck transport system components between the trailing floor and the surface were also major causes of downtime.

A total of 400 cutters were changed. The most common cause of gage cutter failure was worn cutter rings and the most common reason for face and center cutter replacement was failure of the bearings in the cutter hub. The most frequently replaced cutters were the center cutters.

CHAPTER 10

FACTORS AFFECTING UTILIZATION

10.1 INTRODUCTION

The case histories of TBM construction described in the previous chapters include over 75,000 ft (22,860 m) of tunnel, and cover a variety of tunneling procedures and ground conditions. It is of interest to examine these records on a collective basis to look for consistent trends in progress and causes of delay that may be useful in developing realistic estimates of the time required for future construction projects. In addition, a review helps to point out recurrent problems with the machines and backup systems, and to identify difficult tunneling environments.

This chapter focuses on the factors that lead to delay in the construction process, and thereby set limits on the amount of time a TBM is actually used. The chapter begins by summarizing the average utilizations, penetration rates, advance rates, and machine availabilities associated with the projects. Each major category of downtime is discussed in a separate section, including TBM maintenance and repair, difficulties with backup systems, and delays from ground conditions that require special support or interfere with the normal use of the machine. In addition, an example is taken from the case histories to illustrate the impact of closely jointed rock on tunneling progress.

10.2 SUMMARY OF CASE HISTORY OBSERVATIONS

Table 10.1 summarizes the average utilization, penetration rate, advance rate, and availability for each tunnel in the study. The overall averages and standard deviations for these parameters are also included in the table. Individual values of the parameters are generally within 15 percent of the average for all six projects. This limited variation is noteworthy because the tunnels were excavated with both new and reconditioned TBMs, operated in a variety of rock units by four different contractors.

The performance was strongly affected by site specific conditions of geology, construction planning, and contractor practice. Although the data in the table show similar trends, the information must be interpreted in light of the special factors influencing each job. For example,

TABLE 10.1 SUMMARY OF AVERAGE UTILIZATION, PENETRATION RATE, ADVANCE RATE, AND MACHINE AVAILABILITY FOR THE TUNNELS INCLUDED IN THIS STUDY

TUNNEL	UTILIZATION	PENETRATION RATE		ADVANCE RATE	AVAILABILITY
	percent	ft/hr (m/hr)	in./rev. (mm/rev.)	ft/hr (m/hr)	percent
C11 Outbound	32.0	9.2 (2.8)	0.31 (7.9)	2.9 (0.88)	84.9
C11 Inbound	36.2	9.0 (2.8)	0.31 (7.8)	3.3 (1.00)	93.5
C31 Outbound	31.1	7.9 (2.4)	0.31 (7.8)	2.5 (0.75)	86.1
C31 Inbound	28.9	8.6 (2.6)	0.23 (5.8)	2.5 (0.76)	81.6
Culver-Goodman	36.1	7.0 (2.1)	0.30 (7.7)	2.5 (0.77)	92.2
Chicago TARP	35.0	7.3 (2.2)	0.26 (6.5)	2.5 (0.78)	81.6
Average	33.2	8.2 (2.5)	0.29 (7.3)	2.7 (0.82)	86.7
Standard Deviation	3.0	0.9 (0.3)	0.03 (0.9)	0.3 (0.10)	5.1

the relatively low utilization for the C31 inbound tunnel was strongly influenced by the construction plan. A total of 5.3 percent of the total shift time on this project was required to transfer mucking equipment between two work shafts, and this delay was not encountered in other Buffalo tunnels. The Chicago TARP tunnel was similarly affected when 2.4 percent of the total shift time was required to move the TBM to the branch tunnel after the main tunnel excavation had been completed. The flooding of the C11 tunnels was especially severe because a power failure caused the dewatering pumps to stop. If time losses associated with the flooding are not included, average utilization for the C11 tunnels would be approximately 10 percent higher.

The average penetration per revolution is nearly identical for each of the C11, C31 outbound, and Culver-Goodman tunnels. The average penetration per revolution for the Chicago TARP tunnel is relatively low and is related, in part, to difficulties with the cutterhead and main bearing. The lowest penetration per revolution for the C31 inbound tunnel correlates with a cutterhead rotation rate of 7.5 rpm, which was the highest of the machines under study. Because the level of torque per revolution is inversely proportional to the rotation rate, this characteristic may have contributed to the relatively low penetration per revolution. In addition, approximately 65 percent of the tunnel was driven with five or fewer cutterhead motors. Accordingly, the average torque for this machine was significantly lower, overall, than for the other TBMs. In terms of distance per hour, average penetration rates for the Buffalo tunnels varied between 7.9 and 9.2 ft/hr (2.4 and 2.8 m/hr). High penetration rates were achieved in the C11 tunnels which were bored by TBMs equipped with 200 hp (149 kw) motors with typical thrust levels approximately 28 percent higher than those in the C31 tunnels.

The average advance rates for the C31, Culver-Goodman, and Chicago TARP tunnels are nearly identical. The advance rates for the C11 tunnels are nearly identical. The advance rates for the C11 tunnels are relatively high primarily because of the relatively high TBM penetration rates. Since the advance rate depends on the utilization, this parameter is subject to the same site specific conditions that affect the construction delays.

The availabilities listed in Table 10.1 are percentages of shift time during which the TBMs were available for excavation. Downtime affecting the availability is discussed in the next section, which deals with the general category of TBM maintenance and repair.

The time required for thrust cylinder restroke was recorded for three of the projects, and averaged about 3.6 percent of the total shift time. The combination of restroke time and other delays, such as shift changes and stocking the heading with supplies, amounted to an average of 8.5 percent in the Buffalo tunnels, 5.5 percent in the Culver-Goodman Tunnel, and 6.5 percent in the Chicago TARP tunnel. Each project included at least one extended period for maintenance. For the Buffalo tunnels, these maintenance periods occurred at shafts or near Conrail sections, while in the Chicago tunnel, these delays occurred primarily at the adit intersections. An extended maintenance period was scheduled in the Culver-Goodman Tunnel during the Christmas holiday, which accounted for an average of 2.3 percent of the total shift time.

Advance probing for methane was required only on the Culver-Goodman project. Probe hole drilling accounted for 3.6 percent of the total shift time in this tunnel. The contractor performed much of the drilling during Saturday shifts, and probing occurred simultaneously with cutter changes and maintenance.

10.3 TBM MAINTENANCE AND REPAIR

Table 10.2 summarizes the delay, or downtime, associated with various causes under the general category of TBM maintenance and repair. The downtime is expressed as a percentage of the available shift time, and was calculated according to the methods described in the individual case histories and in Appendix B. The table also includes average values for each downtime cause. The average downtime in this combined category was 21.3 percent of the total shift time, and the causes which contributed most to this total were cutter changes and general maintenance and inspection.

The sources of delay often reflect special conditions on a given project. For example, cutter changes on the Culver-Goodman TBM represent the largest, single cause of delay listed in the table. The Culver-Goodman Tunnel is the only project on this study in which standstone was intercepted. Of the 16,595 ft (5,058 m) investigated, approximately 7,500 ft (2,286 m) were driven in the Grimsby Sandstone. The loss of

TABLE 10.2 SUMMARY OF DOWNTIME PERCENTAGES ASSOCIATED WITH TBM MAINTENANCE AND REPAIR

DOWNTIME CATEGORY	DOWNTIME PERCENTAGE						
	C11		C31		Culver-Goodman	Chicago TARP	Average - All Tunnels
	Outbound	Inbound	Outbound	Inbound			
Cutter Change	2.6	1.7	2.2	2.5	16.5	5.5	5.2
General Maintenance and Inspection	4.2	2.0	4.6	7.7	5.8	13.6	6.3
Lube Oil	0.9	0.3	1.7	1.4	0.4	0.7	0.9
Hydraulics	8.2	0.4	2.9	5.3	0.9	0.6	3.1
Motors	0.3	1.3	1.5	3.5	0.6	2.7	1.6
TBM Conveyor	1.5	2.5	3.2	0.4	0.1	0.8	1.4
Electrical	1.6	1.3	4.5	5.7	1.5	1.9	2.8
TOTAL	19.3	9.5	20.6	26.5	25.8	25.8	21.3

time caused by cutter replacements in the Grimsby Sandstone cannot be directly related to problems with the mechanical, electrical, and hydraulic components of the TBM, and the availability of the machine was the second highest determined in this study. The relatively high availability is of interest because the machine had been used to drive over 53,000 ft (16,150 m) of tunnel and had been reconditioned several times before the Culver-Goodman project.

The TBMs used in the C31 tunnels were reconditioned machines with similar causes of downtime. Both machines were affected by significant delays from general maintenance, hydraulics, and electrical components. The downtimes associated with electrical difficulties were from two to three times higher than those for other machines under study.

Significant mechanical difficulties were experienced with the C11 outbound and Chicago TARP TBMs, even though the machines had not been used previously. For the C11 outbound TBM, approximately 7.4 percent of the total shift time was associated with repair of one of the gripper hydraulic cylinders. In the Chicago TARP tunnel, cutterhead repairs and main bearing replacement accounted for about 11.0 percent of the 13.6 percent in the category of general maintenance and repair.

The variation in delays associated with machine components and the lack of a clear pattern in availability do not permit generalizations about the efficiency of new as opposed to old machines. Regardless of machine age, the effective use of the TBM depended closely on the contractor's experience and maintenance program.

10.4 BACKUP SYSTEM MAINTENANCE AND REPAIR

Table 10.3 summarizes the delay, or downtime, associated with various causes under the general category of backup system maintenance and repair. The downtimes are calculated and expressed similarly to those in Section 10.3. The table also includes average values for each downtime cause. The average downtime in this combined category was 20.0 percent of the total shift time, and the causes which contributed most to this total were train delay and shaft or portal operations.

There were many train delays for each of the tunnels. In the C11 tunnels, when the car pass was not in working order, train delays were caused by the necessity of having a locomotive on the trailing floor to

TABLE 10.3 SUMMARY OF DOWNTIME PERCENTAGES ASSOCIATED WITH BACKUP SYSTEMS

DOWNTIME CATEGORY	DOWNTIME PERCENTAGE						
	C11		C31		Culver-Goodman	Chicago TARP	Average - All Tunnels
	Outbound	Inbound	Outbound	Inbound			
Power Supply	0.3	1.0	0.2	0.0	0.2	0.4	0.4
Cables, Utilities, Fanline	1.5	2.1	4.8	5.0	4.6	1.9	3.3
Survey	0.1	0.1	0.5	0.8	0.2	0.3	0.3
Car Pass	3.5	4.1	4.4	NA[1]	NA[1]	1.6	3.4
Tripper	NA[1]	NA[1]	NA[1]	0.4	0.5	NA[1]	0.4
Trailing Conveyor	0.5	0.7	1.8	1.1	1.2	1.7	1.2
Train Delay	5.4	7.3	4.0	5.6	3.9	3.3	4.9
Shaft/Portal Operations	6.7	9.0	0.7	5.7	0.8	2.4	4.2
Laying Rails	0.8	1.7	0.7	0.2	0.3	3.2	1.2
Derailments	1.9	1.2	1.3	2.3	2.3	3.7	2.1
TOTAL	20.7	27.2	18.4	21.1	14.0	18.5	20.0

[1] NA - not applicable because system not used.

maneuver the cars and assemble the train. Excavation was often interrupted after a train was filled and no additional empty cars were present at the heading.

It should be emphasized that lost time attributed to train delay may include any delay remote from the heading. For example, problems with shaft or portal equipment, or derailments in the tunnel may have been recorded as train delays if the TBM operator was not aware of the actual cause.

The shaft mucking system for the C11 tunnels included a rollover pit and bucket elevator. The large downtime percentages associated with shaft operations on this project reflect the vulnerability of the system to groundwater inflow and flooding. Of the 5.7 percent of time associated with shaft operations in the C31 inbound tunnel, 5.3 percent of the downtime was caused by mucking system relocation to an intermediate shaft. If the time required to relocate the C31 inbound mucking system is excluded, the average downtime for shaft operations on the C31 tunnels is 0.6 percent, which is equivalent to that for the Culver-Goodman portal operation, and significantly lower than that for the bucket elevator system used on the C11 project.

The trailing gear in four of the tunnels was equipped with a car pass mechanism for the transfer of muck from the conveyors to the train. In each of these, the downtime caused by repair of the car pass was significantly higher than that required for repair of the tripper mechanism in the other two tunnels. The most commonly noted reasons for car pass problems were: 1) muck accumulations in the mechanism, 2) muck cars which were returned to the heading but still contained muck, making them too heavy to move from one side of the trailing floor to the other, and 3) rails not laid level, so that muck car transfer had to occur in an uphill direction. In addition, several instances were noted when damage was caused by muck trains traveling too fast when they reached the car pass. The tripper is insensitive to most of these problems, with the exception of muck accumulations which occasionally blocked the tripper chute.

In each tunnel, the most frequent derailment location was on the trailing floor, often at the ramp between the tunnel and trailing floor track. Muck accumulations on the trailing floor and misaligned or tilted tunnel track were often noted as causes for derailments. Downtime because of derailments was highest in the Chicago TARP tunnel, for which the rails were supported by rockbolts installed in the rock at the invert.

Installation and extension of electric cable, utility service lines, and fan line were significant sources of downtime in the tunnels excavated by the three reconditioned TBMs. For the C31 inbound and Culver-Goodman tunnels, the majority of downtime in this category was associated with electric cable extension, whereas for the C31 outbound tunnel, most of the downtime was caused by fanline segment installation.

10.5 GROUND CONDITIONS

Table 10.4 summarizes the delay, or downtime, associated with various causes under the general category of ground conditions. The downtimes are calculated and expressed similarly to those in Section 10.3. The table also includes average values for each downtime cause. The average downtime in this combined category was 14.2 percent of the total shift time, and the causes which contributed most to this total were steel set installation and water inflow.

Significant amounts of water inflow occurred in the C11 and Chicago TARP tunnels. In the Chicago TARP tunnel, most of the water problems were caused by water accidentally discharged into the tunnel from the surface.

Steel sets installed manually, were associated with significant amounts of downtime for five of the tunnels under study. In the Buffalo tunnels, steel sets were associated with three general conditions, 1) contract specifications for Conrail crossings, 2) crown overbreak, and 3) springline overbreak which interfered with gripper pad bearing. In general, the downtime per steel set was greatest in sections with springline overbreak. In the Culver-Goodman Tunnel, steel sets were primarily installed because of crown overbreak in shales which developed when mining through a transition from sandstone or limestone.

Tunnel wall scaling and muck jams amounted to significant time losses on the C31 and Culver-Goodman projects, but muck jams were a problem in all the tunnels. For the Buffalo and Chicago projects, the most frequent muck jam location was inside the TBM main beam, usually at the hopper

TABLE 10.4 SUMMARY OF DOWNTIME PERCENTAGES ASSOCIATED WITH TBM GROUND CONDITIONS

DOWNTIME CATEGORY	TUNNELS						
	C11		C31		Culver-Goodman	Chicago TARP	Average - All Tunnels
	Outbound	Inbound	Outbound	Inbound			
Water Inflow	3.4	5.9	0.0	0.0	0.0	5.2	2.4
Steel Sets	11.3	5.5	7.9	5.7	5.1	0.0	5.9
Bolts/Straps/ Channels	1.7	1.4	2.1	1.7	2.3	0.7	1.7
Bolt Drill Repair	0.6	0.7	3.4	3.5	1.4	0.0	1.6
Scaling/Rock Jam	1.1	1.2	5.3	2.3	3.1	0.4	2.2
Gripper Difficulty	0.2	0.5	0.0	0.1	0.3	0.0	0.2
Clearance	0.1	0.0	0.0	0.3	0.5	0.0	0.2
TOTAL	18.4	15.2	19.0	13.6	12.7	6.3	14.2

between the cutterhead and the conveyor. In the Culver-Goodman Tunnel, scaling required more time than muck jam removal, and most of the muck jams occurred while mining in shale because the cutterhead buckets often became packed with water-softened muck. In the C31 tunnels, crown scaling and removing rock slabs which dropped onto the TBM shield caused significant delays.

Gripper difficulties were associated with areas of springline overbreak, as is evidenced by the construction records of the Buffalo tunnels, and with gripper pad slippage in shale, as was observed in the Culver-Goodman Tunnel. Clearance problems most often occurred when ventilation system components jammed into or snagged on steel sets.

Crown instability was influenced by both the joint frequency and geometry of the rock blocks formed by joint intersections. The loosening of rock in the crown and consequent danger of fallout were pronounced in zones with two vertical joint sets as is illustrated in Figure 10.1 for the C31 outbound tunnel. The figure includes a plan view of the joints in the tunnel crown between Stations 12+60 and 15+40, support notation, and histogram plots of the TBM driving rate, utilization, and penetration rate for successive 20 ft (6.1 m) segments in this tunnel section. Rockbolts were 8 ft (2.4 m) steel bars that were epoxy-grouted for their full length, and steel sets were W6x25 sections. Driving rate has been used by McFeat-Smith and Tarkoy (1980) to show the delay times associated with TBM construction in various geologic environments. It is defined as the shift time to mine a unit distance of tunnel.

In the tunnel section shown, the Falkirk Member is present from about 2 ft (0.6 m) above springline to the tunnel crown, and the Oatka Member is present below the Falkirk. Dolostone beds in the Falkirk Member are generally about 1.0 ft (0.3 m) thick, and beds are often separated by 2 to 3 in. (51 to 76 mm) thick shale partings. In the Oatka, bedding plane spacing is 2 to 6 in. (51 to 152 mm). Two nearly vertical joint sets are present, striking approximately N 15 degrees E and N 85 degrees E. In the Falkirk rock, many of the vertical joints were infilled with 1 to 2 in. (25 to 51 mm) of weathered material. The joint surfaces were generally smooth and water inflow was minor. The joint spacings varied from 5 to 30 ft (1.5 to 9.1 m). Joints were often discontinuous at the contact between the Falkirk and Oatka Members, and vertical joint spacings in the Oatka varied from 1 to 5 ft (0.3 to 1.5 m). Tunneling was performed around a horizontal curve so that the orientation of the tunnel's longitudinal axis changed progressively from N 55 degrees E to N 40 degrees E.

The driving rate increased at approximately Station 12+80, where muck jams developed in the main beam, and extra rockbolts were used to stabilize rock wedges in the tunnel crown. The contractor reduced the TBM thrust cylinder pressure, thereby reducing the penetration rate and the amount of material entering the mucking system. At Station 13+40, several unstable rock blocks were intercepted in the right-hand portion of the crown. From this location to Station 14+20, steel sets were installed on about 5 ft (1.5 m) centers. Each cycle of forward thrust was followed by steel set installation, muck jam clearing, tunnel wall scaling, and spot bolting to stabilize rock wedges. The zone of steel set installation corresponds to the zone of closely spaced, intersecting joint sets and low values of machine utilization. Between Stations 14+40 and 15+40 only one vertical joint set was present, and the crown stability was substantially improved.

In Figure 10.1, the area within the histogram outline is equal to the total shift time spent in the tunnel section. A line is drawn in the figure, which corresponds to the driving rate in adjacent, realtively unjointed rock. The area between this line and the histogram outline is equal to the extra time required to mine this section realtive to the adjacent portions of the tunnel. The increased driving rate up to Station 13+40 was associated primarily with the reduction in penetration rate. The large driving rate after this location was caused by low machine utilization. The overall delay time associated with mining between Stations 12+80 and 15+20 was approximately 190 hours.

In general, the direct consequences of tunneling in rock that is closely jointed and/or weathered include cutterhead damage from large blocks that can become wedged either between cutters or the cutterhead and tunnel wall, and the necessity of installing extra rock support. If blocks of rock enter the TBM mucking system, muck jams and conveyor damage can occur. Closely spaced steel sets limit the amount of tunnel wall available for gripper pad bearing, and springline overbreak can make contact between gripper pads and intact rock difficult to achieve.

The frequency and condition of rock mass discontinuities have been

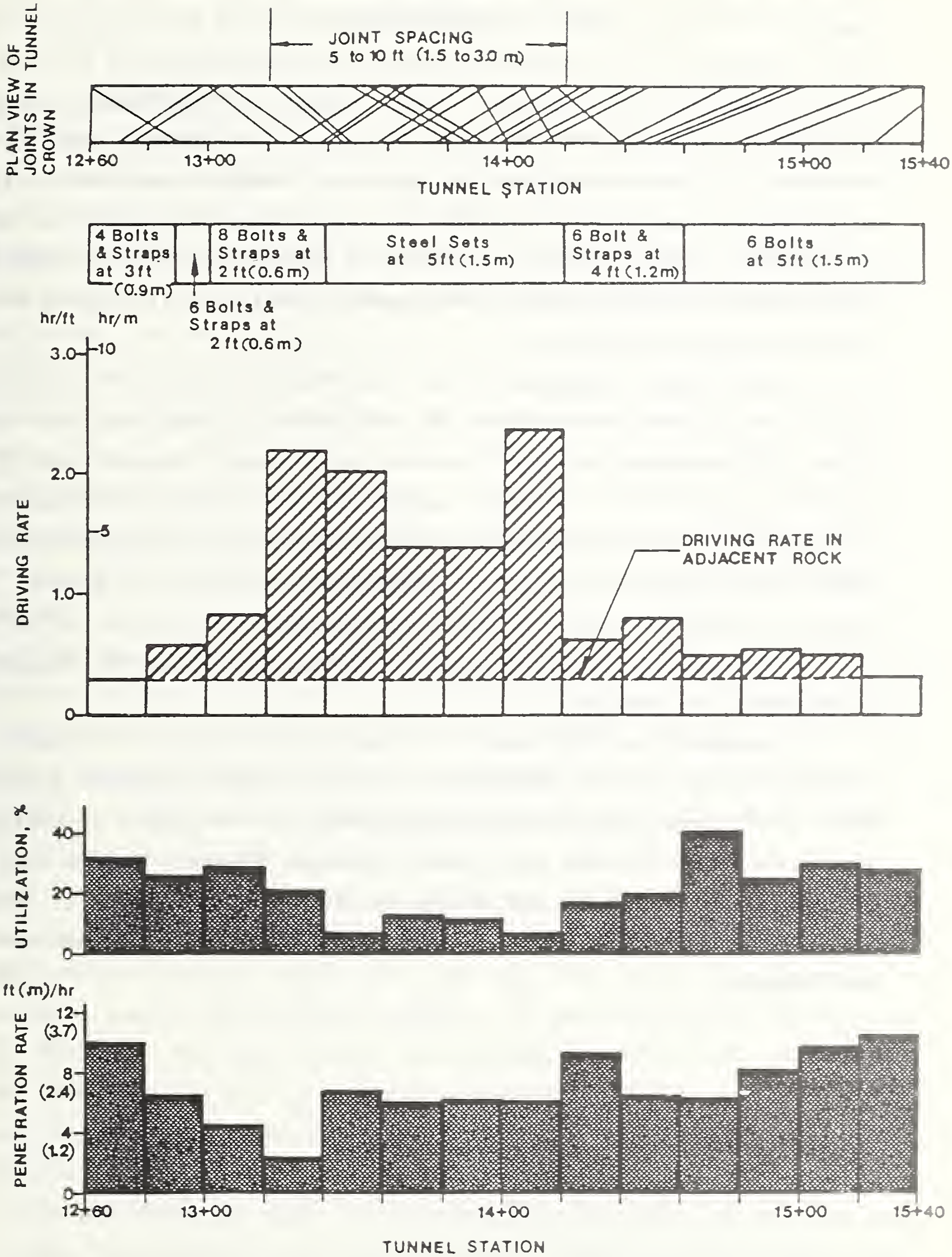


FIGURE 10.1 RECORD OF TUNNELING ON C31 OUTBOUND TUNNEL, STATIONS 12+60 TO 15+40

cited as factors that affect machine penetration rate. Korbin (1979) reported that penetration rate increased threefold when the joint spacing in dolerite at the Kielder Aqueduct decreased from 3.3 ft (1.0 m) to less than 0.4 in. (100 mm). Korbin also noted that joint spacings must be on the order of 2 to 10 in. (50 to 250 mm) before significant increases in penetration rate are observed. Aeberli and Wanner (1978) noted that frequency, orientation, and type of discontinuity can affect penetration, and reported a reduction in penetration rate of nearly 70 percent when the joint spacing decreased from 3.3 ft (1.0 m) to less than 2 in. (50 mm) in limestone.

For the cases investigated in this study, no clear trend can be delineated between penetration rate and joint spacing in a given lithology. Difficulties in tunnel sections with closely spaced vertical and high-angle joints did, however, affect the utilization and operation of the machine. As a consequence of these rock conditions, penetration rates were often low because of intentional reductions in thrust. In highly jointed and weathered rock, the penetration rate was often difficult to determine reliably because of thrust variations and frequent stopping of the machine.

In general, any improvements in penetration rate due to highly jointed rock were more than offset by delays associated with extra support, rock jams, gripper reaction problems, and clearance of trailing gear. Penetration rates are closely related, however, to the rock type and the levels of thrust and torque developed by the machines. These factors, among others, affecting the penetration rate are discussed in the next chapter.

CHAPTER 11

TBM PENETRATION RATE

11.1 INTRODUCTION

Case history studies of TBM projects have generally shown a relationship between penetration rate and rock properties for a given job. For example, Morgan, Barratt, and Hudson (1979) have shown trends between penetration rate and uniaxial compressive strength, point load indices, and the results of the National Coal Board cone indentor test for a TBM used during construction of the Kielder Aqueduct. Tarkoy (1974) and Tarkoy and Hendron (1975) compared rock hardness indices, uniaxial compressive strengths, and penetration rates for a variety of TBM projects and showed that correlations between penetration rates and rock properties were statistically significant for several of the jobs. Some investigators have correlated penetration rate with combinations of rock property indices. Blindheim (1976, 1979) combined brittleness and abrasion test results and a drilling rate index to develop a correlation with machine penetration rate. McFeat-Smith and Tarkoy (1979) recommend the use of total hardness, a combination of abrasion and rebound hardness indices. Jenni and Balissat (1979) suggest that penetration rate can be predicted with the use of a combined index including rebound hardness, point load strength, abrasion hardness, and mineral hardness.

Correlations between penetration rate and rock index properties over a variety of jobs employing different machines have shown substantial scatter. As discussed by Korbin (1979), good correlations could be demonstrated between penetration rate and rock indices for different machines used at the Kielder Aqueduct, but the correlation relationship was different for each machine, even though the rock units excavated by the machines were similar. Tarkoy and Hendron (1975) correlated average hardness indices and penetration rates for 13 TBM projects which used machines with different types of cutters operating at a variety of torque and thrust levels. The resulting correlations indicate general trends, but accurate predictions were not possible without taking into account the variations in machine design, operating levels, and rock mass properties. Wanner (1975), Aeberli and Wanner (1978), and Wanner and Aeberli (1979) used an index called specific penetration, which is the ratio of penetration per cutterhead revolution and the average thust per cutter, to normalize TBM performance with respect to cutterhead rotation rate and operating thrust levels. They found that, while correlations could be demonstrated between specific penetration and the results of indentation testing, the effects of discontinuity frequency and rock texture varied with each rock type considered. Hamilton and Dollinger (1979) introduced the field penetration index, R_f, as a parameter useful in TBM performance studies. This index is calculated as the average thrust per cutter divided by the penetration per cutterhead revolution, and is thus the inverse of specific penetration. Dollinger (1982) has indicated that R_f may be more useful in developing correlations than penetration rate alone.

Korbin (1979) summarized various approaches that have been taken for TBM performance prediction and discussed the limitations of the methods. He pointed out that rock property indices do not account for variations in machine design, operating levels, the condition of cutters and rock mass characteristics.

Table 11.1 summarizes the factors affecting TBM performance and emphasizes the variety of conditions that can change from site to site and within a given job. Contractor practices can vary significantly among tunneling projects, and the selection of mucking, support, supply, and maintenance systems can strongly affect TBM performance principally by limiting the time available for machine boring. The penetration rate can also be influenced when thrust, torque, or mucking capacities are reached and when normal operating levels of thrust are restricted because of mechanical difficulty or erection of support.

The six tunnels included in this study were excavated with TBMs of similar design. Single disc cutters were used on each machine, and the cutter array and spacings were comparable. The tunnel diameters varied over a narrow range from 18.5 to 21.3 ft (5.6 to 6.5 m). Of the seven principal factors affecting TBM performance listed in Table 11.1, only the last four show significant variation for the tunneling projects studied.

To judge how factors related to machine operation, mechanical repair, and support requirements affect penetration rates in different rock types, this chapter begins with an examination of the boring

TABLE 11.1 FACTORS AFFECTING TBM PERFORMANCE

Principal Factors Affecting TBM Performance	Elements Contributing To Machine Use And Rock Excavation
Overall Machine Configuration	Thrust, torque, and gripper reaction capacities, gripper configurations, mechanism for steering, machine stiffness.
Cutterhead Design	Cutterhead profile, spatial array of cutters, cutter spacing, muck removal components.
Cutter Design	Type of cutter, cutter composition, cutter geometry, capacity of roller bearing.
Contractor Practices	Material and utility supply systems, maintenance schedule, muck removal, operator technique, coordination of machine excavation with erection of support, experience of tunneling crew.
Contract Restrictions	Tunnel alignment, line, and grade; access to tunnel, length of tunnel.
Ground Conditions	Lithology, discontinuities, weathering, ground water, in-situ state of stress.
Intact Rock Properties	Material properties and index parameters reflecting strength, deformability, abrasivity, and resistance to fracture.

records of the Culver-Goodman Tunnel. The quality of the records for this tunnel and the detail with which shift events were recorded permits a comprehensive investigation of contractor practices, mechanical difficulties, and rock property variation. In Sections 11.2, 11.3, and 11.4, the records of the Culver-Goodman Tunnel are used to show how penetration rate is related to various excavation and support practices, different levels of thrust and torque, and cutter wear. In Section 11.5, the rock index properties pertaining to the principal rock units in all the tunnels under study are summarized. In Section 11.6, correlations between penetration rate and various rock index properties are examined. A general model for the relationship between penetration rate, thrust, and torque in different rock types is introduced and discussed in Section 11.7.

11.2 MACHINE OPERATION

Figure 11.1 shows the variation in penetration rate and average thrust per cutter for the Culver-Goodman TBM between Stations 30+00 and 160+00. The penetration rate is the average penetration per cutterhead revolution for each shift and is calculated by dividing the shift advance by the product of the elapsed clock time and the cutterhead rotation rate. The average thrust per cutter is calculated by dividing the net machine thrust by the number of cutters. The average thrust was determined from the recorded thrust cylinder pressure according to Equation 2.1, in which the pressure required to advance the cutterhead without face contact is recorded in Table 7.3. Also shown in the figure are a profile view of the tunnel geology and the average amperage recorded for the cutterhead motors in various sections of the tunnel. The motors were operated consistently above their maximum rated amperage in an effort to deliver as much torque to the tunnel face as possible.

Although the penetration rates and cutter thrusts show clear trends, there are considerable variations in the data. It is of interest to determine if these variations are systematic and can be linked to specific aspects of the contractor's operation and tunneling practice. The sources of variation are important from the perspective of both interpreting and applying the data. Penetration rates that are indirectly affected by mechanical and electrical difficulties should not be

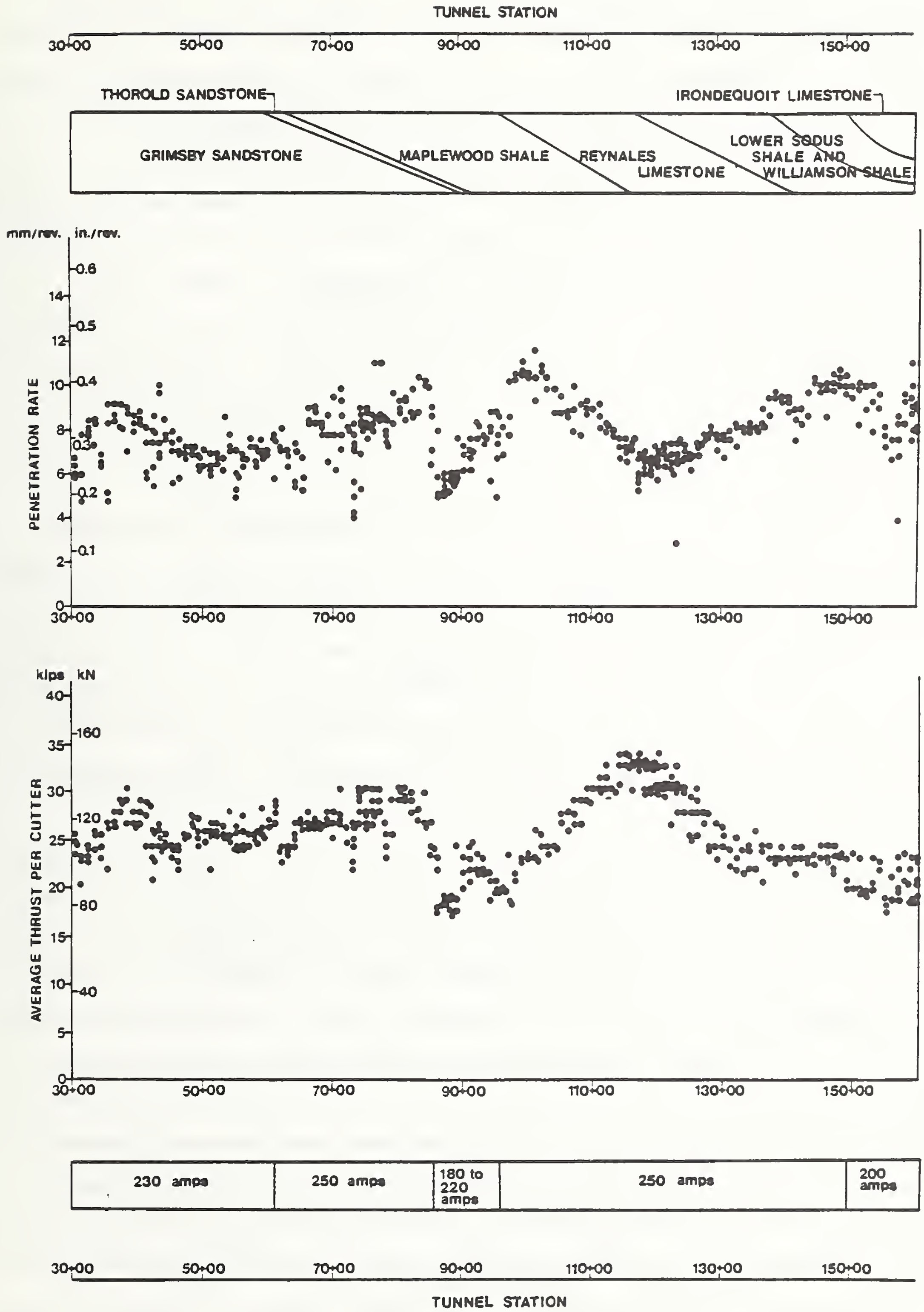


FIGURE 11.1 PLOTS OF PENETRATION RATE AND AVERAGE THRUST PER CUTTER, CUTTERHEAD MOTOR AMPERAGE, AND TUNNEL GEOLOGY FOR THE COMPLETE DATA SET, STATION 30+00 TO 160+00, CULVER-GOODMAN TUNNEL

used to develop correlations with rock index properties. When empirical correlations are used to forecast machine performance, one should understand how muck deviation from predicted trends can result from different operators or changes in routine brought about by mechanical difficulty and rock mass conditions leading to support difficulties.

To judge the importance of the variations in penetration rate and thrust, the data pertaining to a single operator and crew were isolated from the general set of observations. These data, in turn, were screened to remove shifts in which less than six motors were functioning, cutters were changed, steel sets were installed, and obvious mechanical or support problems were encountered. In addition, shifts during which there were many intermittent stops were discounted. These shifts often had elapsed clock times of less than one hour and, with each stop, clock time was recorded when the machine was not actually boring with full thrust and torque power. Ozdemir and Wang (1979) noted that even with full stroke excavation, several minutes may be required to bring the TBM systems to an optimum operating level. This start-up time is of less importance when each stroke requires 40 to 60 minutes to complete, but with many start-ups and short strokes, the real boring time may differ significantly from the recorded clock time, and the calculated penetration rate may be seriously in error.

The screened data are plotted in Figure 11.2. Lines are superimposed on the figure to show the full range in variation for the complete record. Between Stations 85+71 and 95+11, all the data have been removed because problems with the main bearing seal forced the contractor to operate at low levels of thrust and torque. Other intervals for which data were removed because of motor difficulties and the erection of steel sets are shown by vertical lines in the figure. By comparing Figure 11.2 with Figure 11.1, it is clear that the amount of variability in the data has been reduced by the screening process. This effect is pronounced in the Grimsby Sandstone. Several sections of tunnel in the Grimsby were mined with five functioning motors, multiple stops for cutter replacement, and the installation of steel sets. At other sections of the tunnel, the differences between the screened data and full set of observations are less obvious. In the Reynales Limestore and Lower Sodus and Williamson Shales, the screened data points are distributed

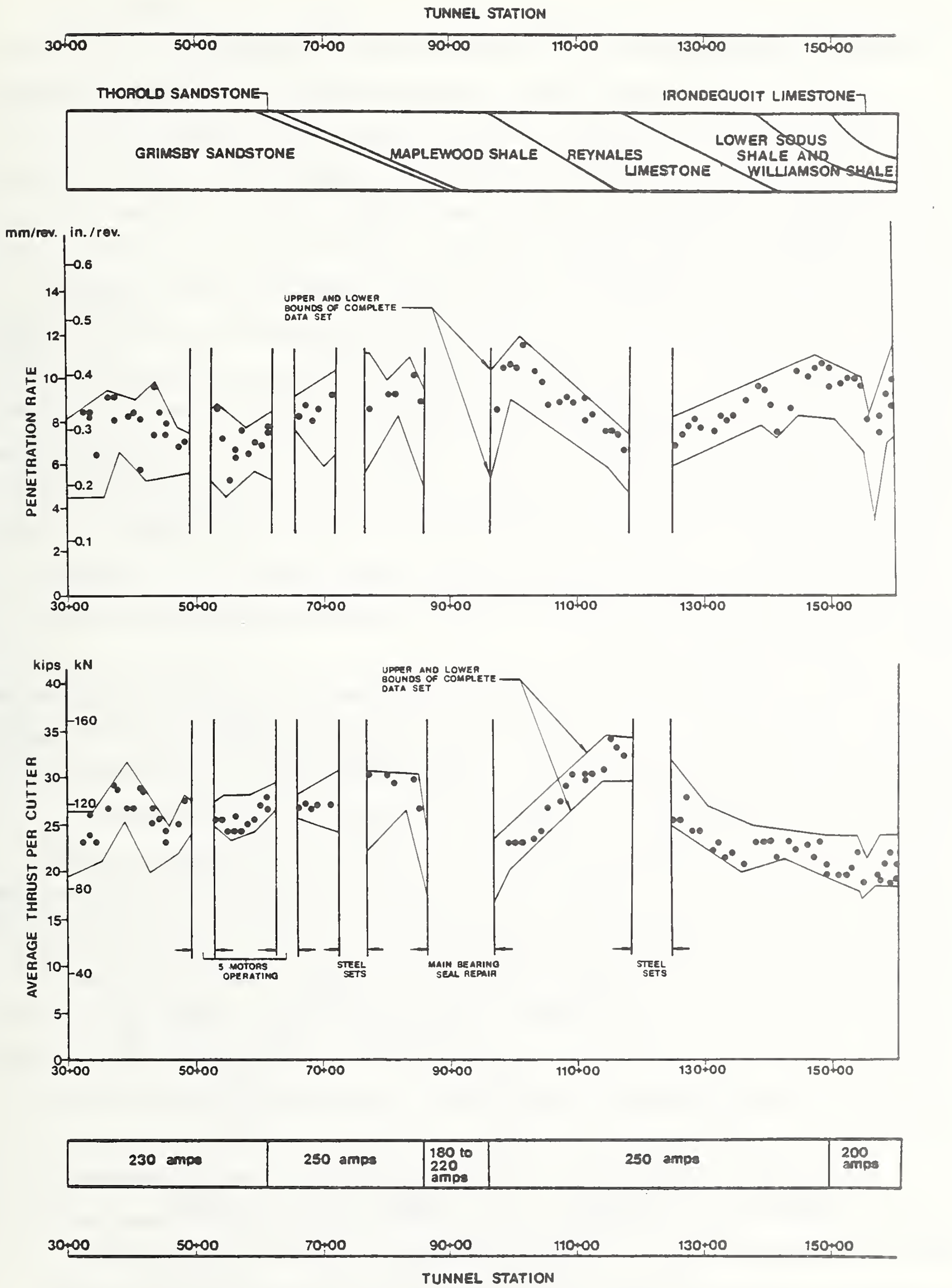


FIGURE 11.2 PLOTS OF PENETRATION RATE AND AVERAGE THRUST PER CUTTER, CUTTERHEAD MOTOR AMPERAGE, AND TUNNEL GEOLOGY FOR THE SCREENED DATA SET, STATION 30+00 TO 160+00, CULVER-GOODMAN TUNNEL

throughout the full range of variation with only a small amount of clustering near the upper bound for the entire data set.

In Table 11.2, the average penetration rates for TBM tunneling in four rock units are summarized. Average penetration rates are shown for both the complete and screened data set associated with a single operator and crew. In each case, the screened data result in higher rates when compared with the overall averages. The difference is largest for tunneling in the Maplewood Shale where the screening process removed shifts of intentionally low torque and thrust before and after the main bearing seal repairs. The average penetration rate calculated from the screened data set in the Grimsby Sandstone is roughly 14 percent larger than that based on all observations, chiefly as a result of slower rates related to both steel set installation and operation with less than six cutterhead motors. Average penetration rates from the screened data set are approximately 10 percent higher than those based on the complete set of observations for tunneling in the Reynales Limestone and Lower Sodus and Williamson Shales.

For the Culver-Goodman Tunnel, it is impossible to distinguish shift-by-shift penetration rates on the basis of the different operators and crews that made up the work force. Figure 11.3 shows the penetration rate per shift plotted as a function of station for the section of tunnel from the Reynales Limestone to the Lower Sodus and Williamson Shales. The penetration rates for two different operators and crews are plotted in this figure using the screened data sets. The variations in rates achieved by the different operators and crews are representative of the largest variations between work forces in other sections of the tunnel. Although a particular operator and crew were consistently able to attain higher penetration rates, the average rates for the two only differ by five percent over the length of tunnel shown.

In summary, penetration rates calculated as overall averages for a given rock unit will be lower than those representing optimum performance at maximum levels of thrust and torque if the data are not screened to discount shifts with mechanical and support difficulties. Nevertheless, average rates determined from screened data sets for the Culver-Goodman Tunnel were only 10 to 14 percent higher than those calculated on the basis of all observations within a given rock unit. The

TABLE 11.2 AVERAGE PENETRATION RATES FOR COMPLETE AND ONE OPERATOR SCREENED, DATA SETS IN FOUR ROCK UNITS FOR THE CULVER-GOODMAN TUNNEL.

ROCK UNIT	TUNNEL STATIONS ft	AVERAGE PENETRATION RATE Complete Data Set in./rev. (mm/rev.)	One Operator, Screened Data Set
Grimsby Sandstone	30+00 to 59+40	0.28 (7.1)	0.32 (8.1)
Maplewood Shale	90+00 to 100+00	0.33 (8.4)	0.42 (10.7)
Reynales Limestone	113+00 to 120+50	0.26 (6.6)	0.29 (7.4)
Lower Sodus and Williamson Shales	141+00 to 149+00	0.37 (9.4)	0.41 (10.4)

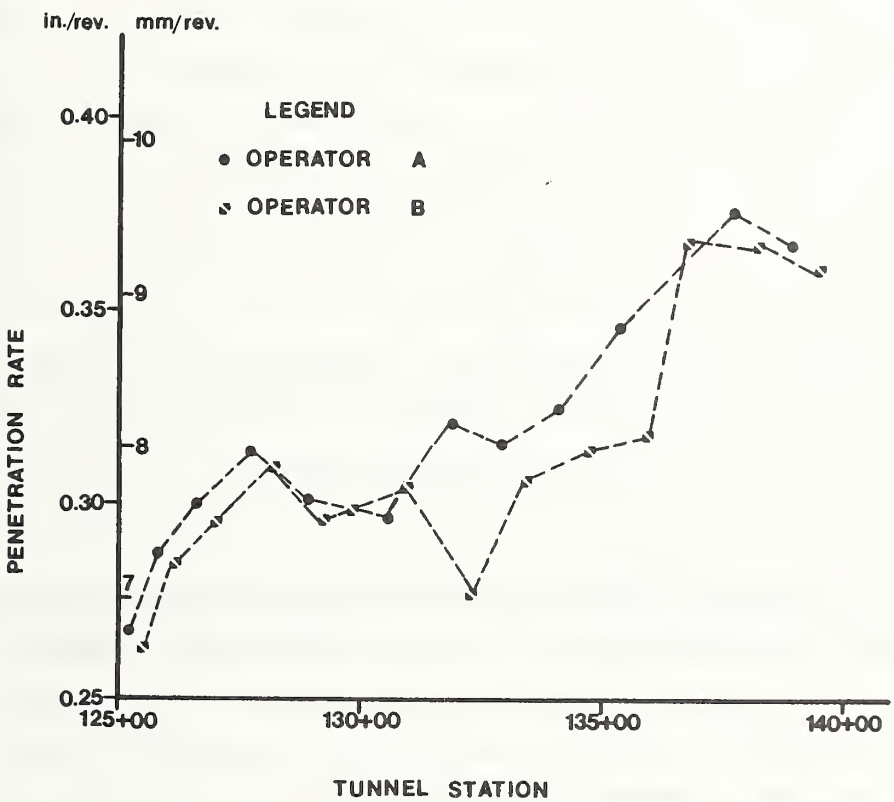


FIGURE 11.3 PLOT OF PENETRATION RATE VERSUS TUNNEL STATION FOR TWO DIFFERENT OPERATIONS AND CREWS, STATION 125+00 TO 140+00, CULVER-GOODMAN TUNNEL

most prominent exception occurred when tunneling was affected by difficulties with the main bearing seal. Although penetration rates were consistently higher for a particular operator and crew, the differences among operators and crews were not significant, being on the average within five percent of the highest rates.

11.3 PENETRATION RATE, THRUST, AND TORQUE

Figures 11.1 and 11.2 show that penetration rate and thrust varied with rock type. The highest penetration rates occurred at relatively low thrust levels in the Maplewood, Lower Sodus, and Williamson Shales, whereas the lowest penetration rates occurred at the highest levels of thrust in the Reynales Limestone. In all sections of the tunnel, the cutterhead motors were operated at levels exceeding their maximum ratings. Accordingly, the torque generated during tunneling was generally at a level consistent with the capacity of the machine.

Figure 11.4 is a plot of the penetration rate versus average thrust per cutter for TBM operation between Stations 96+89 and 117+17. The penetration rates and thrusts are calculated in the same was as described for Figure 11.1, and the data were not screened since all shifts had more than one hour operating time, all six motors were functioning, and steel sets were not installed. In this section of the tunnel, boring was performed from a condition of full-face Maplewood Shale to one of full-face Reynales Limestone. The Maplewood Shale was one of the weakest rocks and the Reynales Limestone was one of the strongest rocks penetrated by the machine. The maplewood Shale has an average uniaxial compressive strength of 9.8 ksi (68 MPa), and the Reynales Limestone has an average uniaxial compressive strength of 18.9 ksi (130 MPa). Accordingly, the transition from full-face shale to limestone represents a condition of continuous change through a significant variation in rock type. The percentage of Reynales Limestone at the face is shown by the use of four different symbols representing successively larger amounts of the limestone. Because the machine was operated in this section at a nearly constant amperage of approximately 250 amps, the plot shows a trend between penetration rate and thrust that depends almost exclusively on the relative amounts of rock type at the face.

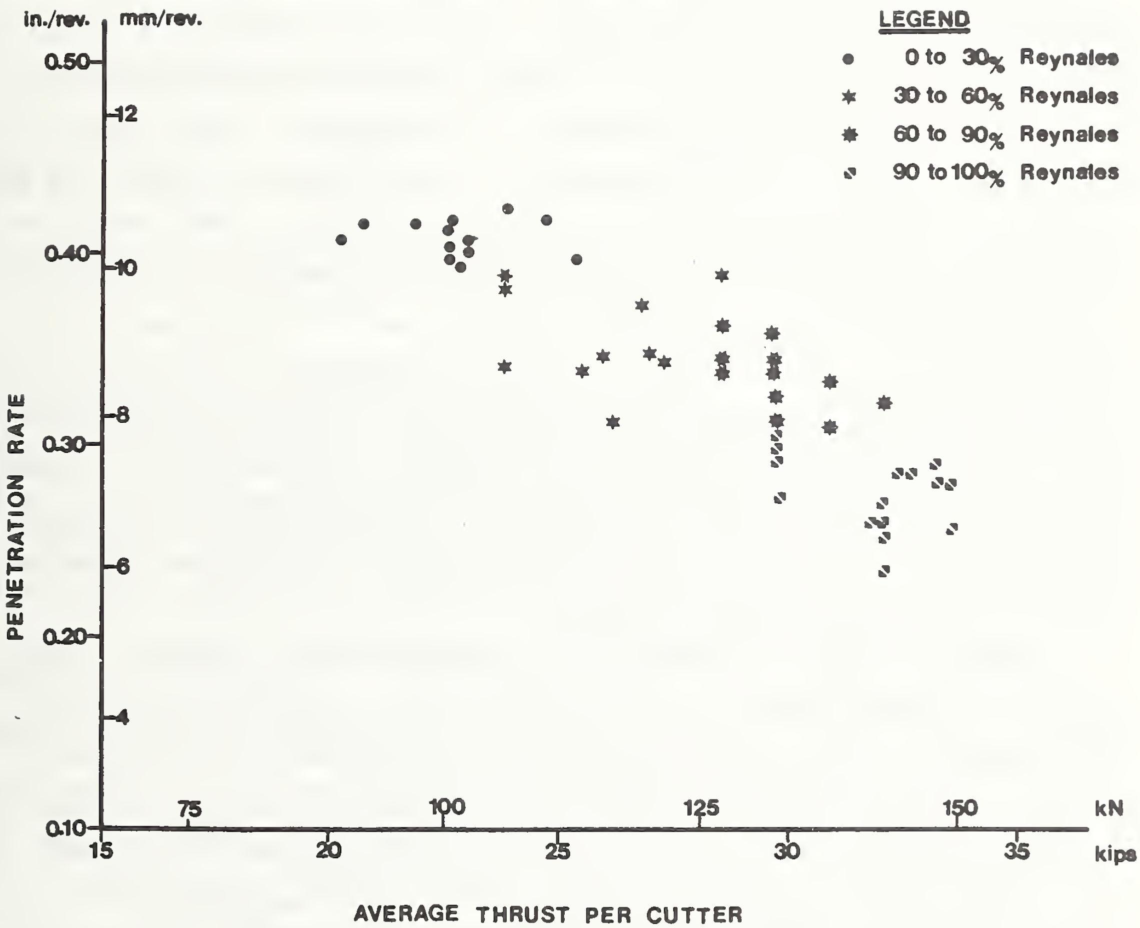


FIGURE 11.4 PLOT OF PENETRATION RATE VERSUS AVERAGE THRUST PER CUTTER FOR EXCAVATION BETWEEN STATIONS 96+89 AND 117+17, CULVER-GOODMAN TUNNEL

As the machine was advanced from a full face of Maplewood Shale to Reynales Limestone, the penetration rate decreased from approximately 0.41 in./rev. (10.4 mm/rev.) to 0.27 in./rev. (6.9 mm/rev.) or a decline of roughly 34 percent. At the same time, the average thrust per cutter increased from approximately 22 kips (98 kN) to 33 kips (147 kN), or an increase of roughly 50 percent. The relationship between penetration rate in the Reynales Limestone, the TBM was operated at a thrust cylinder pressure of 3,300 psi (22.7 MPa), which is approximately 94 percent of the maximum rated pressure for the machine. Hence, the machine was operated in the limestone at a near maximum level of thrust and torque. With larger amounts of shale at the face, lower levels of thrust were used to maintain a constant level of amperage. Accordingly, the TBM performance was constantly dependent on the torque capacity of the equipment. In the extreme, the TBM was operated in a full face of Maplewood Shale at a thrust cylinder pressure of 2,300 psi (15.9 MPa) which is only 66 percent of the rated capacity of the machine. Clearly, the penetration under these conditions was torque-limited, and higher penetration rates would only have been possible if additional power to rotate the cutterhead were available.

The resistance to cutterhead rotation not only relates to the rolling force mobilized by the cutters, but also depends on the frictional forces and obstructions that occur during the removal of muck from the face. This aspect of the torque resistance can be illustrated from the records of machine excavation in the Maplewood Shale. When mining started after the second repair of the main bearing seal at Station 95+09, the motors reached their maximum amperage at thrust levels lower than the TBM operator had previously applied. At Station 96+89, excavation was stopped and, on inspection, the muck buckets at the cutterhead were found to be completely packed with pieces of water-softened shale muck. Since the muck was not being removed, it accumulated at the face, increasing the torque required to rotate the cutterhead as the cutters were dragged through the muck in the tunnel invert. When the buckets were cleaned and the dust abatement spray at the face was turned off, the muck no longer accumulated at disproportionately high rate relative to its removal, and more of the available

TABLE 11.3 AVERAGE AMPERAGE, THRUST PER CUTTER, AND PENETRATION RATE, STATIONS 95+09 TO 99+80, CULVER-GOODMAN TUNNEL

Tunnel Stations	Average Amperage	Average Thrust Per Cutter		Average Penetration Rate	
		kips	(kN)	in./rev.	(mm/rev.)
95+09 to 96+89	230	18.6	(82.7)	0.31	(8.0)
96+89 to 99+80	240	21.6	(96.1)	0.41	(10.5)

torque could be used in the rock cutting process. Details of the TBM operating parameters before and after Station 96+89 are summarized in Table 11.3. At a relatively constant amperage, the bucket clean-out led to an average thrust per cutter increase of 16 percent and the corresponding increase in penetration was more than 30 percent.

The penetration rate depends on the levels of thrust and torque delivered to the face for a given rock type. As a minimum, the penetration rate should be considered in terms of thrust. This usually is done in an implicit way when correlations are developed between penetration rate and rock index properties by selecting data that represent broadly similar conditions of cutter type and machine design. Hamilton and Dollinger (1979), Aeberli and Wanner (1978), and Wanner and Aeberli (1979) have recommended explicit measures for normalizing penetration rate with respect to cutter thrust. Because the field penetration index, R_f, has been used for examining TBM performance on other U.S. jobs, this measure is used in Section 10.6 to develop correlations with rock index properties.

11.4 INFLUENCE OF CUTTER WEAR ON PENETRATION RATE

Several investigators have studied the influence of cutter wear on penetration rate. In these studies, the wear has been regarded as a material loss and change of shape at the abraded disc surface. Ozdemir and Wang (1979) conclude that performance is influenced by wear, but the effects of wear are relatively small for the disc cutter spacings of 3 in. (75 mm) typically used in practice. Kutter and Sanio (1982) show that wear has a significant effect on penetration rate for a given level of thrust, although their study was based on an investigation of cutters with substantially different wear profiles, tested at thrusts lower than those normally attained in practice. Both groups of researchers show that, for a given amount of penetration, thrust forces increase with increasing amounts of wear.

To investigate the effects of wear on the penetration rate of the Culver-Goodman TBM, the boring records for a tunnel section between Stations 30+87 and 41+62 were studied. In this section, the cutters mounted in the outer 11 gage positions were fitted with constant attack area discs. At other cutter positions, 90 degree included angle discs were used. The two types of disc are illustrated in Figure 11.5. The edge of the constant attack area disc was nearly flat when new, but after a short time in use, the edge became rounded. When either type of cutter was replaced, most of the disc material had been worn off, and often the cutter hub had been abraded. The contractor measured the diameters of the outer gage cutters at several locations in this tunnel section, so that an explicit relationship between wear and penetration rate can be evaluated.

Figure 11.6 shows the actual distance travelled by each cutter plotted as a function of the decrease in disc diameter. The travel, or rolling distance, is equal to the circumference of the cutter travel path multiplied by the number of times the cutterhead was rotated after the cutter was installed. The number of rotations is determined as the rotation rate of the cutterhead multiplied by the machine clock time elapsed after cutter installation. The line plotted in Figure 11.6 is the best linear fit of the data, and was determined by regression analysis. A decrease in diameter of approximately 1.0 in. (25.4 mm) occurred after the cutters had rolled 3×10^5 ft (9.1×10^4 m). For the outermost gage cutter, this means that 1.0 in. (25.4 mm) of the disc diameter was worn off in about 18 hours of machine operation.

For each shift between Stations 30+87 and 41+62, the average gage cutter rolling distance was calculated for the machine clock time

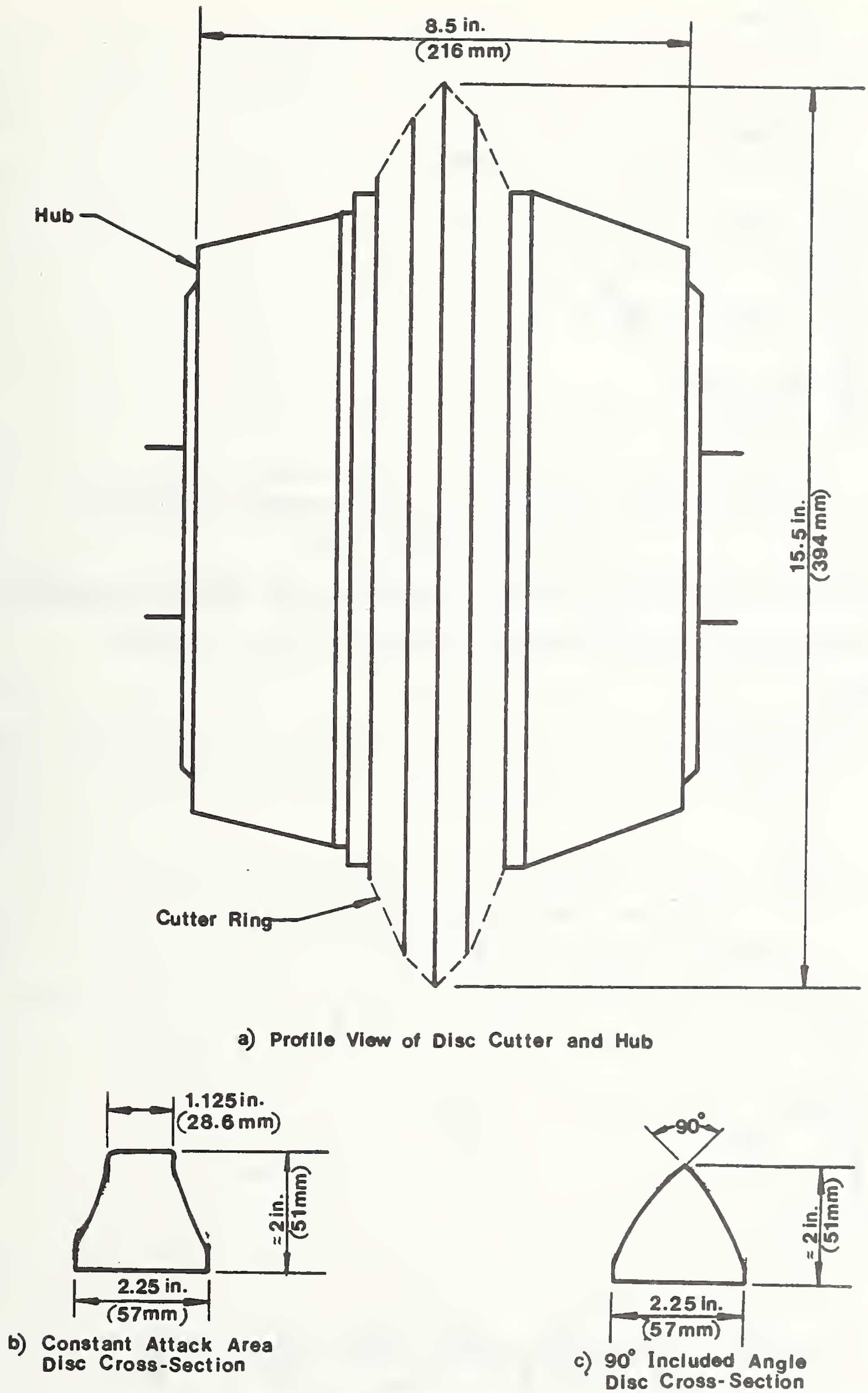


FIGURE 11.5 DISC CUTTER AND CUTTER DISC CROSS-SECTIONS USED ON THE CULVER-GOODMAN TBM

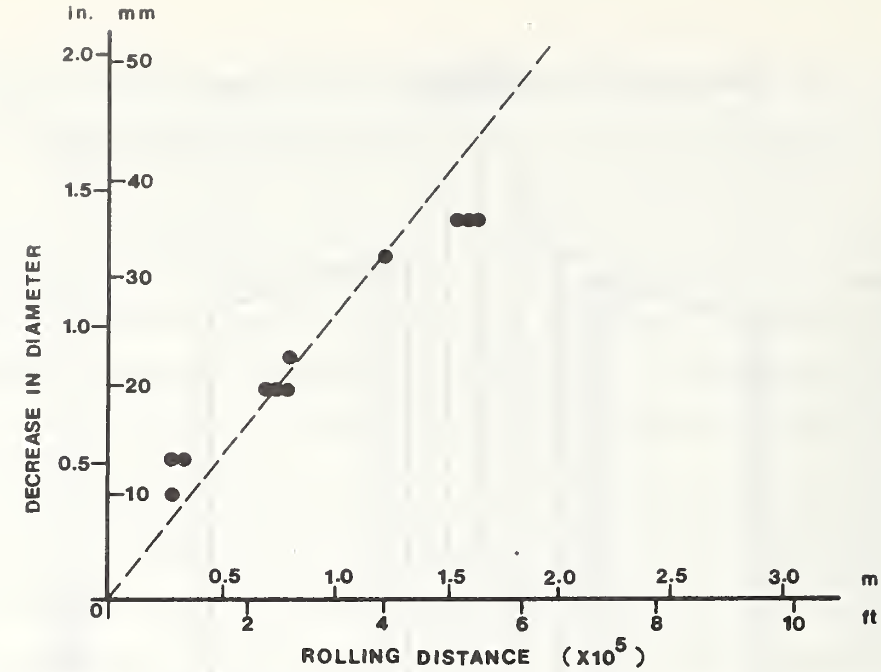


FIGURE 11.6 PLOT OF DECREASE IN CUTTER DIAMETER VERSUS ROLLING DISTANCE FOR OUTER GAGE CUTTERS BETWEEN STATIONS 30+87 AND 41+62, CULVER-GOODMAN TUNNEL

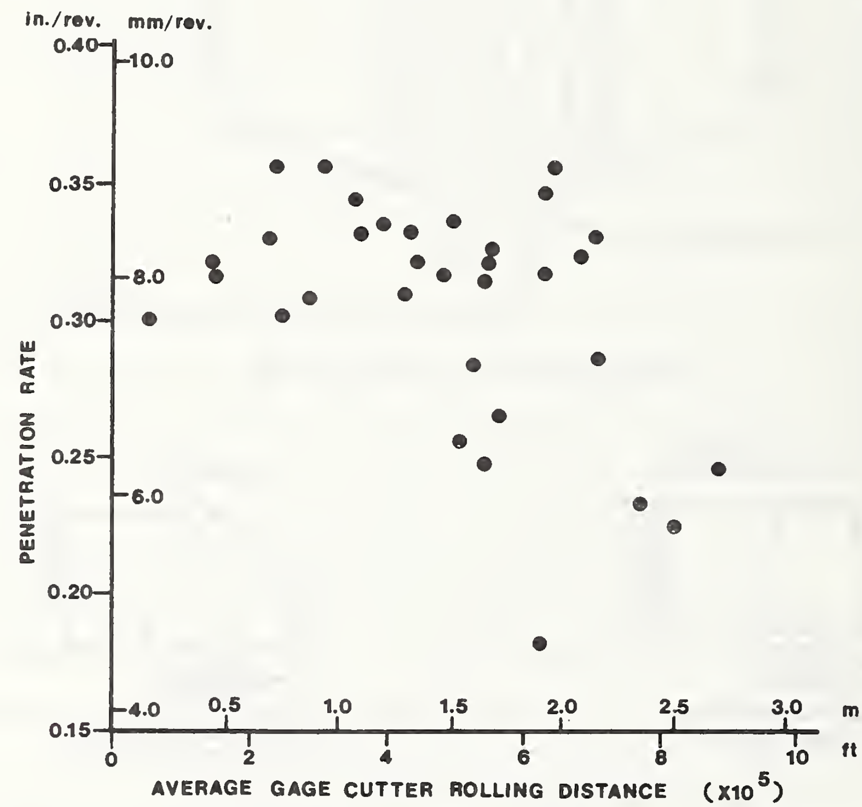


FIGURE 11.7 PLOT OF PENETRATION RATE VERSUS AVERAGE GAGE CUTTER ROLLING DISTANCE FOR SHIFTS OPERATED BETWEEN STATIONS 30+87 AND 41+62, CULVER-GOODMAN TUNNEL

corresponding to the middle of the shift. Cutter wear in the gage positions generally reflects the extent of wear in all cutter positions, because many other worn cutters were replaced at the same time the gage positions were serviced. In Figure 11.7, the shift penetration rates are plotted against the average cutter rolling distance. The data plotted in this figure have been screened as discussed in Section 11.2, so that shifts affected by obvious mechanical problems and excessive delays have been excluded.

The penetration rates associated with travel distances less than 5×10^5 ft (1.5×10^5 m) varied between 0.30 and 0.36 in./rev. (7.6 and 9.1 mm/rev.). With greater travel distances, similar penetration rates were achieved only when the average thrust per cutter was increased by 10 percent. Penetration rates less than 0.30 in./rev. (7.6 mm/rev.) were associated both with travel distances greater than 5×10^5 ft (1.5×10^5 m) and thrust levels similar to those applied when the cutters were first installed. Therefore, with increased rolling distance, either the penetration rate was reduced or higher levels of thrust were required to maintain rates of penetration similar to those achieved with new cutters.

Gage cutters were changed after an average travel distance of 7.8×10^5 ft (2.4×10^5 m), a distance which correlates with a disc diameter decrease of approximately 2.5 in. (64 mm). Comparing this change in diameter with the disc dimensions shown in Figure 11.5, it is clear that very little disc material remained on the cutter hub when the cutters were replaced. This amount of wear is two to three times greater than that considered in the laboratory studies of Ozdemir, Miller and Wang (1977) and Kutter and Sanio (1982).

In the Buffalo and Chicago tunnels, locations were identified where most cutters were changed at the same time. After these major changes, no significant increase in penetration rate occurred. There is no clear evidence that cutter wear had a significant effect on penetration rate for the Buffalo and Chicago tunnels. In the Culver-Goodman Tunnel, the effects of wear on penetration rate could only be discerned in the Grimsby Sandstone at exceptionally high levels of wear.

11.5 ROCK INDEX PROPERTIES

A large number of index tests have been shown to correlate to some degree with TBM penetration rates (Tarkoy, 1973, 1974, 1979; Descoeudres and Rechsteiner, 1973; Tarkoy and Hendron, 1975; Barendsen and Cadden, 1976; McFeat-Smith and Tarkoy, 1979; Cassinelli, et al., 1982) and part of this study was developed to evaluate how well various measures of TBM penetration correlate with different rock index properties for the tunneling projects under review. Index tests were performed by Cornell personnel (Gunsallus, 1983) for each of the major rock units in which tunneling was undertaken and studied. In some cases, lithologic variations were observed within a given rock unit and, where possible, tests were performed on specimens representing each of the lithologically distinct zones. The index tests included Schmidt Hammer (L-type) rebound hardness, modified Taber abrasion hardness, uniaxial compression, diametral point load, and Brazilian tensile strength tests. The procedures for the uniaxial compression, point load, and Brazilian tensile strength tests were preformed according to the recommendations of the International Society of Rock Mechanics (ISRM, 1982). The modified Taber abrasion hardness was determined according to the procedures outlined by Tarkoy and Hendron (1975).

The Schmidt Hammer rebound hardness was measured according to the recommendations of ISRM (1982) with two exceptions: 1) the rebound hardness, H_R, was calculated as the average of the five highest of 10 readings taken with the schmidt Hammer device, and 2) test results were obtained using two core cradles one with a circular and one with a V-notch machined slot. Most of the tests were performed in a core cradle with a circular slot, as recommended by Tarkoy and Hendron (1976) and Tarkoy (1981b), but the core available from Rochester was too large in diameter for the available cradle, and most of the tests on these rock units were performed in a V-notch steel block. Some difficulty was experienced in obtaining the ISRM suggested number of 20 rebound readings on each sample because the core often broke or split before the requisite number of readings. Because only limited amounts of core were available, the test procedure was modified to include 10 readings, of which the highest five were averaged. Procedures of this type are not without precedent. Haley and Aldrich (1978) and Tarkoy (1973) calculate the rebound hardness in the same manner.

The test results obtained at Cornell were supplemented with test results obtained by the geotechnical consultants to the tunneling projects under study. Table 11.4 summarizes the index property tests, referenced procedures, and additional sources of test results. The additional measurements were included to increase the test population and to allow a more comprehinsive picture of the natural rock variability. In general, tests performed by other ogranizations were consistent with ISRM recommendations so that all the test results are derived from a relatively uniform set of testing procedures. All rebound hardness, point load, and Brazilian tensile tests were performed on core samples loaded perpendicularly to the longitudinal axis of the core. The uniaxial compressive strength was determined with load applied parallel with the axis of the core. The rock discs used in abrasion testing were prepared so that the center of the disc corresponded to the core axis.

The results of the index property testing are presented in Table 11.5. The average, standard deviation, and number of tests used to evaluate the indices are included. In addition to the index properties previously discussed, the total hardness index was calculated for most of the rock units. This index was originally defined by Deere (1968) and has been shown by Tarkoy and Hendron (1975) to be useful in TBM performance prediction. The total hardness is determined as the product of the rebound hardness and the square root of the abrasion hardness.

Most of the tests included in Table 11.5 were performed on air-dry rock which had been stored in core boxes sheltered from temperature and moisture extremes. This is consistent with typical engineering practice. The Grimsby Sandstone is, however, a relatively porous rock that was saturated in its in-situ state. To investigage the effect of saturation on index properties, some of the rock samples were prepared by immersing them in water under a 0.30 psi (2.0 kPa) vacuum for at least 48 hours. As shown in Table 10.5, the value of each index property of the Grimsby Sandstone was reduced when the rock was in a saturated as opposed to an air-dry condition.

TABLE 11.4 SUMMARY OF INDEX PROPERTY TESTS, PROCEDURES, AND ADDITIONAL SOURCES OF TEST RESULTS

Index Property Test	Referenced Procedure	Additional Sources Of Test Results		
		Buffalo	Rochester	Chicago
Schmidt Hammer Rebound Hardness	ISRM[1]		B,D	
Modified Taber	Tarkoy and Hendron (1975)		B,D	
Total Hardness	Tarkoy and Hendron (1975)		B,D	
Uniaxial Compression	ISRM	A	B,D,E	
Point Load Index	ISRM	A	B,C,D	
Brazilian Tensile Strength	ISRM			

Additional Data Sources:

A Goldberg-Zoino, 1978

B Haley and Aldrich, 1976

C Critchfield, 1982

D Haley and Aldrich, 1978

E Keifer and Associates, 1976

[1]Note: ISRM and Tarkoy (1973) procedures differ as discussed in text.

11.6 CORRELATIONS OF PENETRATION RATE WITH INDEX PROPERTIES

Correlations between penetration rates and the average index properties summarized in Table 11.5 were investigated. The selection of penetration rates was confined to tunnel sections where excavation was performed in a single rock unit that was relatively unweathered and unjointed. The data for each tunnel section were screened to remove shifts in which less than the full number of motors were operating, cutters were changed, steel sets were erected, or obvious mechanical problems were encountered. Shifts with less than one hour of clock time were discounted to reduce the likelihood of erroneous time measurements. Shifts during tunneling in the Grimsby Sandstone were discounted if the

TABLE 11.5 SUMMARY OF INDEX PROPERTY TEST RESULTS

LOCATION	ROCK UNIT	SCHMIDT HAMMER REBOUND H_R			TABER ABRASION HARDNESS H_A			TOTAL HARDNESS H_T		
		Average	Standard Deviation	Number of Tests	Average	Standard Deviation	Number of Tests	Average	Standard Deviation	Number of Tests
Buffalo	Bertie Formation -									
	Falkirk Member	45.5	4.7	10	1.53	0.71	7	55.1	18.6	7
	Oatka Member	39.4	4.5	10	0.66	0.13	4	34.7	9.4	4
Rochester	Williamson Shale	33.7	5.2	4	0.64	0.15	5	27.7	6.7	4
	Lower Sodus Shale	27.8	8.2	5	0.51	0.09	7	21.5	1.3	3
	Reynales Limestone	46.8	6.0	13	3.27	2.47	10	82.5	30.0	10
	Maplewood Shale	23.5	—	1	0.58	0.06	4	19.3	—	1
	Grimsby Sandstone - air dry									
	All Tests	38.1	7.4	24	2.07	2.72	18	43.7	34.5	15
	Middle Grimsby	39.9	2.7	6	0.36	0.01	2	23.8	—	1
	Grimsby Sandstone - saturated									
	All Tests	29.7	6.7	5	—	—	—	—	—	—
	Middle Grimsby	33.7	4.1	3	—	—	—	—	—	—
Chicago	Joilet Formation									
	Romeo Member	49.0	—	1	2.06	—	1	70.3	—	1
	Markgraf Member	43.1	—	1	0.82	—	1	49.1	—	1

TABLE 11.5 SUMMARY OF INDEX PROPERTY TEST RESULTS (CONTINUED)

LOCATION	ROCK UNIT	UNIAXIAL COMPRESSIVE STRENGTH q_u, Ksi (MPa) Average	Standard Deviation	Number of Tests	POINT LOAD INDEX $I_{s(50)}$, Ksi (MPa) Average	Standard Deviation	Number of Tests	BRAZIL TENSILE STRENGTH σ_T, Ksi (MPa) Average	Standard Deviation	Number of Tests
Buffalo	Bertie Formation -									
	Falkirk Member	27.3 (188)	7.5 (52)	34	1.06 (7.3)	0.22 (2.5)	17	1.93 (13.3)	0.55 (3,8)	19
	Oatka Member	20.2 (139)	4.1 (28)	17	0.37 (2.6)	0.19 (1.3)	15	1.89 (13.0)	0.48 (3.3)	19
Rochester	Williamson Shale	11.9 (82)	0.6 (4)	3	0.09 (0.6)	0.03 (0.2)	9	—	—	—
	Lower Sodus Shale	11.2 (77)	1.4 (10)	6	0.12 (0.8)	0.04 (0.3)	10	—	—	—
	Reynales Limestone	18.6 (128)	6.2 (43)	13	0.64 (4.4)	0.36 (2.5)	16	2.17 (15.0)	0.34 (2.3)	3
	Maplewood Shale	9.8 (68)	2.2 (15)	3	0.13 (0.9)	0.03 (0.2)	9	—	—	—
	Grimsby Sandstone - air dry									
	All Tests	18.9 (130)	11.3 (78)	8	0.52 (3.6)	0.29 (2.0)	50	1.47 (10.1)	0.69 (4.8)	6
	Middle Grimsby	13.5 (93)	2.3 (16)	3	0.99 (6.8)	0.14 (1.0)	3	1.15 (7.9)	0.25 (1.7)	3
	Grimsby Sandstone - saturated									
	All Tests	15.7 (108)	13.1 (90)	9	0.42 (2.9)	0.30 (2.1)	25	0.88 (6.1)	0.88 (6.1)	10
	Middle Grimsby	6.6 (46)	3.4 (23)	3	0.30 (2.1)	0.25 (1.7)	3	0.47 (3.2)	0.23 (1.6)	3
Chicago	Joilet Formation									
	Romeo Member	34.4 (237)	9.6 (66)	17	1.33 (9.2)	0.43 (3.0)	3	2.47 (17.0)	0.39 (2.7)	3
	Markgraf Member	24.4 (168)	5.3 (37)	38	1.32 (9.1)	0.11 (0.8)	3	1.75 (12.1)	0.09 (0.6)	3

average cutter rolling distance was greater than 5×10^5 ft (1.5×10^5 m) so that the penetration rates would not reflect the influence of extreme cutter wear. The shifts remaining after this screening process represented optimal conditions of thrust and torque for a given machine and rock unit.

Table 11.6 summarized the average penetration rates, thrust per cutter, and field penetration indices determined from the screened data. The tunnel stations and full-face rock units associated with the penetration rates and thrusts were also listed. Standard deviations were given for each of the average values. In general, the standard deviations for the penetration rates and thrusts varied between 5 and 15 percent of the mean values, indicating a relatively narrow range of variation. The performance of the Buffalo C31 TBMs was not included in this table because these machines never excavated a full face of either the Oatka or Falkirk Member. Since the index test results for the Lower Sodus and Williamson Shales were similar, the average penetration rates and index properties were calculated by considering the Lower Sodus and Williamson Shales as one rock unit.

The average index properties in Table 11.5 and the average penetration rates in Table 11.6 were used to formulate predictive equations by linear regression techniques. Because index properties for saturated rock were available only for the Grimsby Sandstone, regression equations were developed using test results from air-dry core only. The resulting equations are summarized in Table 11.7. The value of the coefficient of determination, r^2, is listed for each predictive equation. Values of r^2 have been determined according to the number of degrees of freedon in each data set. The magnitude of r^2 can be interpreted as the percentage of the variation in penetration rate that can be anticipated by means of a single parameter linear equation. Correlations based on the abrasion hardness or the combination of abrasion and rebound hardness show the highest statistical significance. The highest degree of correlation is shown by the relationship between penetration rate and a linear combination of abrasion and rebound hardness.

Figure 11.8 shows plots of the average penetration rate as a function of the rebound hardness, abrasion hardness, and uniaxial compressive strength. Each plot is developed for eight different rock units

TABLE 11.6 SUMMARY OF AVERAGE PENETRATION RATE, THRUST PER CUTTER, AND FIELD PENETRATION INDEX R_f

LOCATION	ROCK UNIT	TUNNEL	TUNNEL STATIONS	PENETRATION RATE		AVERAGE CUTTER THRUST LOAD kips (kN)		R_f kips/in. (kN/mm)	
				Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Buffalo	Bertie Formation								
	Falkirk Member	C11 outbound	46+43 to 53+02	0.299 (7.60)	0.037 (0.94)	30.2 (134)	1.3 (6)	100.4 (17.6)	14.9 (2.6)
	Oatka Member	C11 outbound	26+76 to 32+59	.411 (10.44)	0.069 (1.76)	24.2 (108)	1.9 (8)	58.8 (10.3)	9.5 (1.7)
		C11 inbound	28+18 to 32+81	.423 (10.74)	0.075 (1.91)	24.9 (111)	0.8 (4)	58.8 (10.3	10.5 (1.8)
Rochester	Williamson and Lower Sodus Shales		142+77 to 148+68	0.395 (10.03)	0.012 (0.31)	22.2 (99)	1.0 (4)	56.0 (9.8)	3.6 (0.6)
	Renales Limestone		115+17 to 117+17	0.267 (6.78)	0.016 (0.41)	31.8 (141)	1.2 (5)	119.2 (20.9)	9.3 (1.6)
	Maplewood Shale		96+89 to 100+27	0.411 (10.44)	0.007 (0.18)	22.0 (98)	1.0 (4)	53.2 (9.3)	2.8 (0.5)
	Grimsby Sandstone -								
	All Tests		27+55 to 59+40	0.310 (7.87)	0.033 (0.84)	25.1 (112)	1.8 (8)	82.4 (14.4)	11.0 (1.9)
	Middle Grimsby		30+87 to 41+62	0.325 (8.26)	0.016 (0.41)	25.3 (113)	2.6 (12)	74.5 (13.0)	12.8 (2.2)
Chicago	Joliet Formation								
	Romeo Member		260+07 to 267+41	.316 (8.03)	0.028 (0.71)	32.6 (145)	0.8 (4)	103.0 (18.0)	9.9 (1.7)
	Markgraf Member		231+45 to 235+24	.366 (9.30)	0.033 (0.84)	30.9 (137)	1.0 (4)	84.6 (14.8)	7.5 (1.3)

TABLE 11.7 PENETRATION RATE PREDICTION EQUATIONS

ROCK INDEX PROPERTY	UNITS	EQUATION[a]	r^2
Rebound Hardness		$PR = 0.5412 - 0.0048\ H_R$	35.9
Abrasion Hardness		$PR = 0.4112 - 0.0468\ H_A$	58.8
Total Hardness		$PR = 0.4383 - 0.00196\ H_T$	48.5
Uniaxial Compressive Strength	ksi	$PR = 0.4093 - 0.00287\ q_u$	4.1
Point Load Index	ksi	$PR = 0.4001 - 0.0715\ I_{s(50)}$	17.9
Brazilian Tensile Strength	ksi	$PR = 0.3656 - 0.0141\ \sigma_t$	0.0
Rebound Hardness and Abrasion Hardness		$PR = 0.4831 - 0.00214\ H_R - 0.0368\ H_A$	60.3

[a] Penetration rate, PR, predicted by these equations is in units of in./rev.

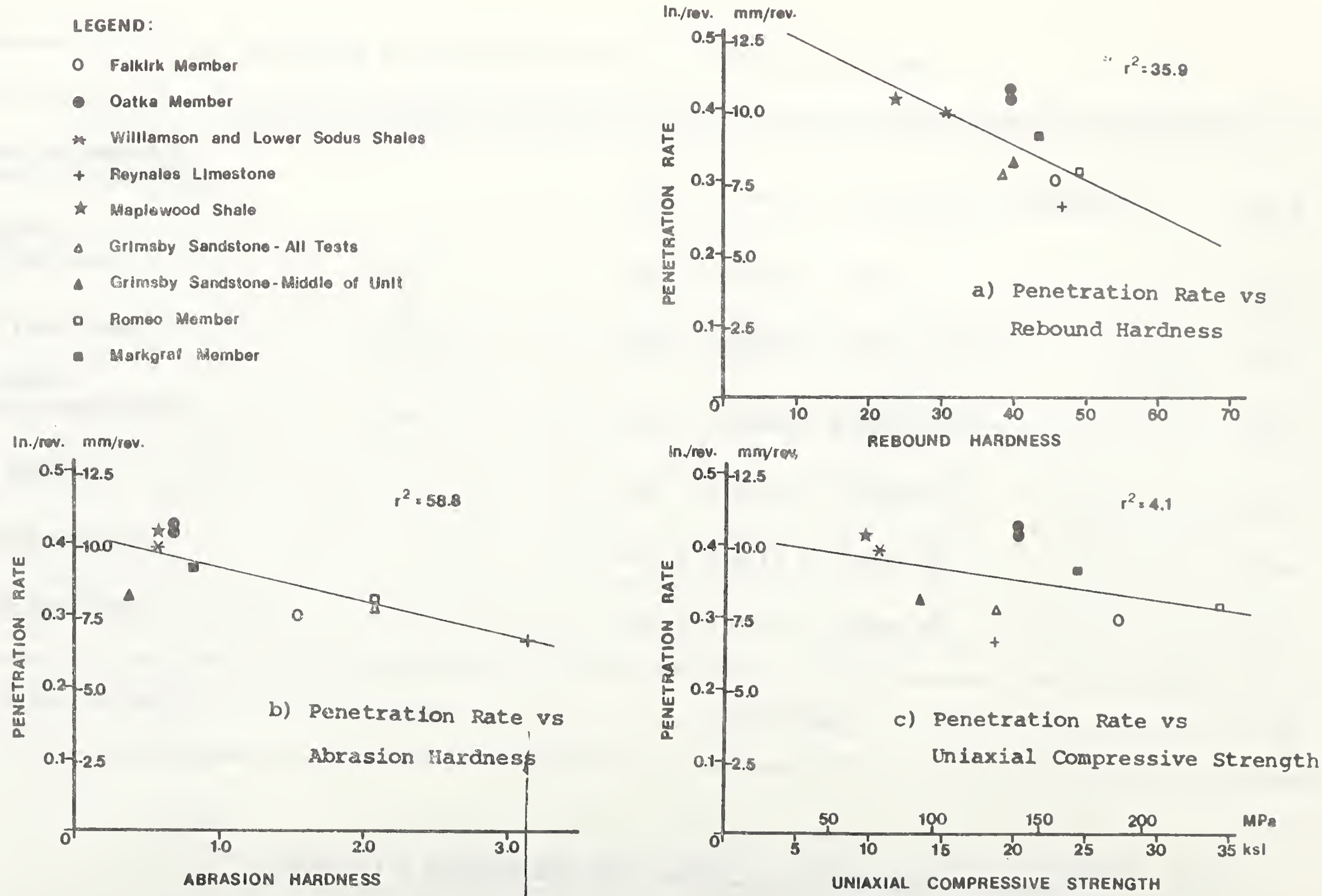


FIGURE 11.8 PLOTS OF PENETRATION RATE VERSUS REBOUND HARDNESS, ABRASION HARDNESS, AND UNIAXIAL COMPRESSIVE STRENGTH

and the data points associated with each rock unit are identified by the symbols listed in the figure. Data for the Grimsby Sandstone include the average penetration rate and index properties for the entire unit and for a specific zone near the center of the deposit which was characterized by more thinly bedded, fine-grained sandstone. Approximately 1,000 ft (300 m) of tunneling were performed under full-face conditions in this zone. The plots of the linear regression equations and values of r^2 are shown. The data for the penetration rate versus abrasion hardness show the least variation relative to the plot of the regressed equation. In contrast, the data for the penetration rate versus uniaxial compressive strength show substantial scatter and indicate that the penetration rate does not correlate well with this parameter.

Figure 11.9 shows the penetration rate plotted as a function of the total hardness, H_T, which is the product of the rebound hardness and square root of the abrasion hardness. The best linear fit of the data is shown as a solid line. As an inset in this figure, the total hardness equation is replotted together with two pairs of curves. The solid pair define the 95 percent confidence interval for the estimation of the mean of all penetration rates in rock of a given total hardness. The dashed pair of curves define the 95 percent prediction interval. These dashed lines define the expected limits for prediction of future penetration rates based on values of H_T and this predictive equation. With the H_T equation, future predictions could be as much as 40 percent in error, and the error could be expected to exceed 40 percent, 5 percent of the time.

To account for the dependency of penetration rate on thrust, the field penetration index, R_f, was also investigated as a function of several different index properties. This parameter provides a measure of the average penetration rate normalized with respect to average thrust per cutter. Predictive equations relating R_f with various index properties were formulated by linear regression techniques. The resulting equations are summarized in Table 11.8 according to the general format of Table 11.7. Correlations based on the abrasion hardness and a combination of abrasion and rebound hardness show the highest statistical significance. On a comparative basis, the r^2 values for correlations related to R_f are substantially larger than those for correlations

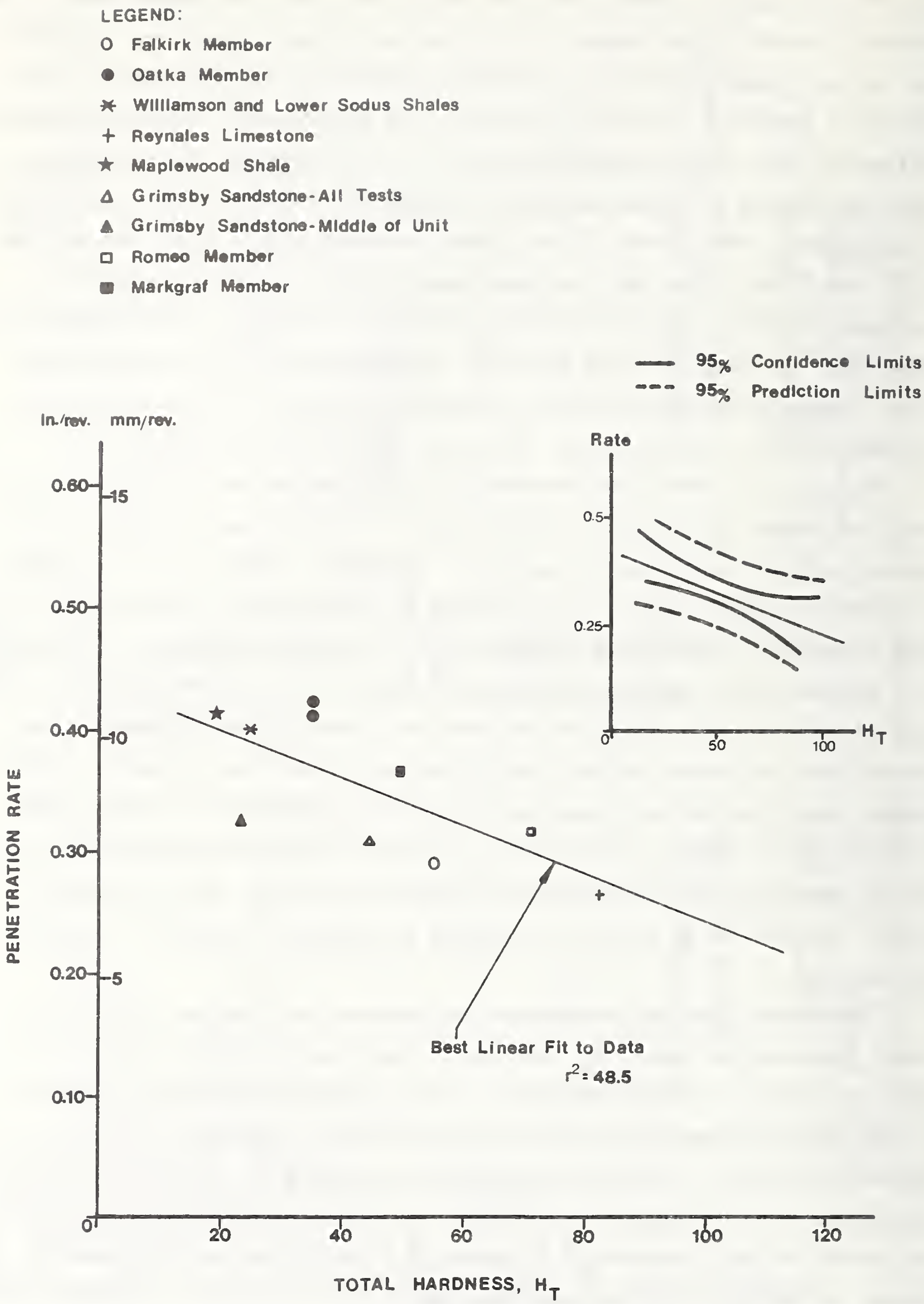


FIGURE 11.9 PLOT OF PENETRATION RATE VERSUS TOTAL HARDNESS

TABLE 11.8 FIELD PENETRATION INDEX PREDICTION EQUATIONS

ROCK INDEX PROPERTY	UNITS	EQUATION[a]	r^2
Rebound Hardness		$R_f = 2.4327\ H_R - 17.12$	61.7
Abrasion Hardness		$R_f = 20.79\ H_A + 52.92$	70.5
Total Hardness		$R_f = 1.021\ H_T + 34.32$	85.1
Uniaxial Compressive Strength	ksi	$R_f = 1.884\ C_o + 41.64$	29.8
Point Load Index	ksi	$R_f = 31.89\ I_{s(50)} + 56.91$	27.1
Brazilian Tensile Strength	ksi	$R_f = 26.00\ \sigma_T + 37.38$	11.3
Rebound Hardness and Abrasion Hardness		$R_f = 1.415\ (H_A + 0.1\ H_R) + 5.18$	85.4

[a] R_f predicted by these equations is in units of kips/in.

related to penetration rate. The highest degree of correlation is shown by relationship between penetration rate and either the total hardness or a linear combination of abrasion and rebound hardness.

Figure 11.10 shows R_f plotted as a function of the total hardness. The format of the figure is similar to that of Figure 11.9. In the inset figure, the best linear fit of the data is shown relative to both the 95 percent confidence and prediction limits. Using the linear equation relating penetration rate to total hardness, future predictions should generally be less than 25 percent in error for rocks with a total hardness of 50. The prediction limits depend on the number of data points included in the regression, and improvements in the predictive ability of a regressed equations can be attained with more observations.

In summary, correlations with rock index properties based on penetration rate normalized with respect to thrust show a higher statistical significance than those based solely on the penetration rate. A convenient index for relating penetration rate to thrust is the field penetration index, R_f, defined as the ratio of the average thrust per cutter to the penetration rate. Correlations of R_f with total hardness show the highest degree of statistical significance from among correlations with many single index properties including rebound hardness, abrasion hardness, uniaxial compressive strength, point load index, and Brazilian tensile strength.

11.7 GENERAL MODEL FOR INTERACTION AMONG PENETRATION RATE, THRUST, AND TORQUE

For the tunneling projects under study, the best correlations between penetration rate and rock index properties are developed when the penetration rate is normalized with respect to the average thrust per cutter. This adjustment helps show the influence of rock properties on the force required for a given level of penetration and thus provides a more comprehensive picture of the interaction between cutter and rock. Nevertheless, correlations developed on this premise cannot be expected to account for the full range of variations observed in practice. The relationship between cutter thrust and penetration is not a constant and has been shown by many investigators (Ozdemir, Miller and Wang, 1977;

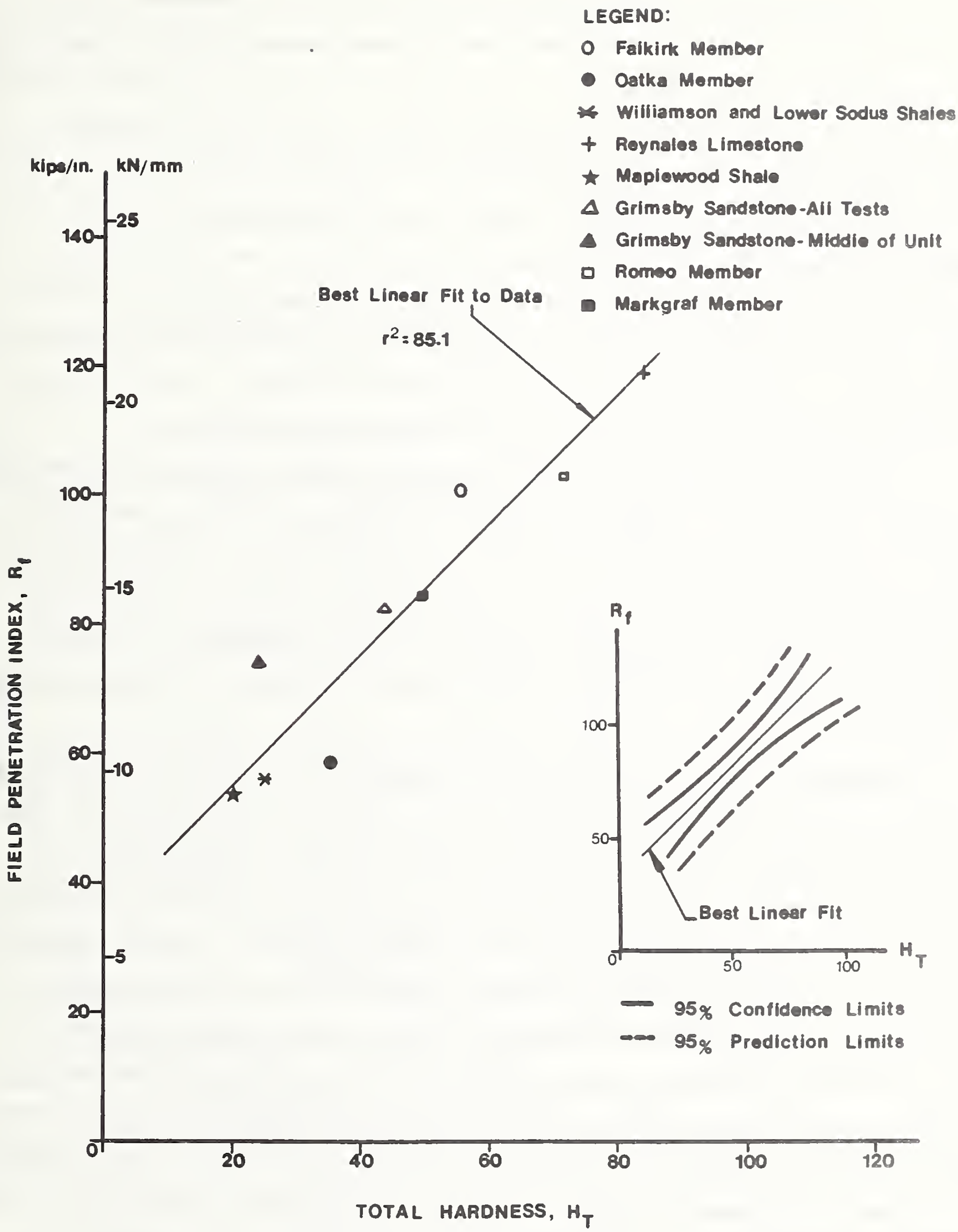


FIGURE 11.10 PLOT OF FIELD PENETRATION INDEX VERSUS TOTAL HARDNESS

Ozdemir and Wang, 1979; Hamilton and Dollinger, 1979; Howarth, 1981b) to have a distinct curvilinear trend. For a given rock, the field penetration index, R_f, can be expected to increase at a disproportionately high rate once the thrust exceeds a specific level. The thrust, however, is affected by torque and may be limited to a level well below the capacity of the TBM. Dubrignon and Janach (1981) note that cutter penetration is generally proportional to the square of the thrust, and the rolling, or tangential, force on a cutter varies directly in proportion to penetration. This relationship between rolling force and cutter penetration is corroborated by observations of Hamilton and Dollinger (1979) who studied the forces on disc cutters during raise boring operations.

A very comprehinsive set of experiments was performed and reported by Snowdon, Ryley, and Temporal (1982) in which the rolling and thrust forces on a disc cutter were measured for various depths of penetration and cutter path spacings. The results of these experiments are worth examining in detail because they provide insight regarding the interaction among penetration, thrust, and rolling force for a wide range of rock types.

Snowdon, Riley, and Temporal performed linear cutter experiments on the three rock types listed in Table 11.9. The aim of their study was to investigate relationships between cutter spacing, penetration and energy requirements for excavation, and to develop a rational approach for penetration prediction and machine system design. Testing was performed with a 7.9 in (200 mm) diameter cutter with an 80 degree edge angle disc. Many of the test results were run at a cutter spacing of 3.15 in. (80 mm), which is consistent with the cutter spacings used in practice. The linear cutting rig was capable of applying cutter thrusts comparable to the levels attained during TBM construction. As discussed by Dubrignon and Janach (1981), rolling force is not a function of cutter diameter. Therefore, the rolling forces generated in the laboratory tests with the smaller diameter cutter should also be similar to forces generated in practice.

Figure 11.11 shows the relationship between penetration and the thrust and rolling force for the three different rock types at a cutter spacing of 3.15 in (80 mm). Each data point in the figure was determined either directly from the published test results or estimated by

TABLE 11.9 DESCRIPTIONS AND PROPERTIES OF THREE ROCKS INVOLVED IN LINEAR CUTTING TESTS (Snowdon, Ryley, and Temporal, 1982)

ROCK UNIT	DESCRIPTION	UNIAXIAL COMPRESSIVE STRENGTH KSI (MPa)	BRAZILIAN TENSILE STRENGTH ksi (MPa)

extrapolating to a spacing of 3.15 in. (80 mm) from plots of the thrust and rolling force versus cutter spacing at each level of penetration. The data points for each rock type are shown according to the symbols listed in the figure. The penetration varies approximately linearly with rolling force, although a trned of successively higher force per unit of penetration is evident at the largest penetration depths. The penetration varies with thrust in a curvilinear fashion. Figure 11.11b is a plot of rolling force versus thrust for the three rock units. The relationship between these forces also follows a curvilinear trend.

The test results of Snowdon, Ryley, and Temporal provide the experimental basis for visualizing the relatively complex relationship among penetration rate, thrust, and rolling force. This relationship may be thought of as three dimensional, as illustrated in Figure 11.12. For each rock type, there is a unique relationship that defines a line in the three-dimensional space. For a variety of rock types, these lines form a critical surface. In the figure, two-dimensional projections of the critical surface for two different rock types are shown as the plots of penetration rate versus thrust and rolling force. The critical surface shows the general trend in cutting performance as the

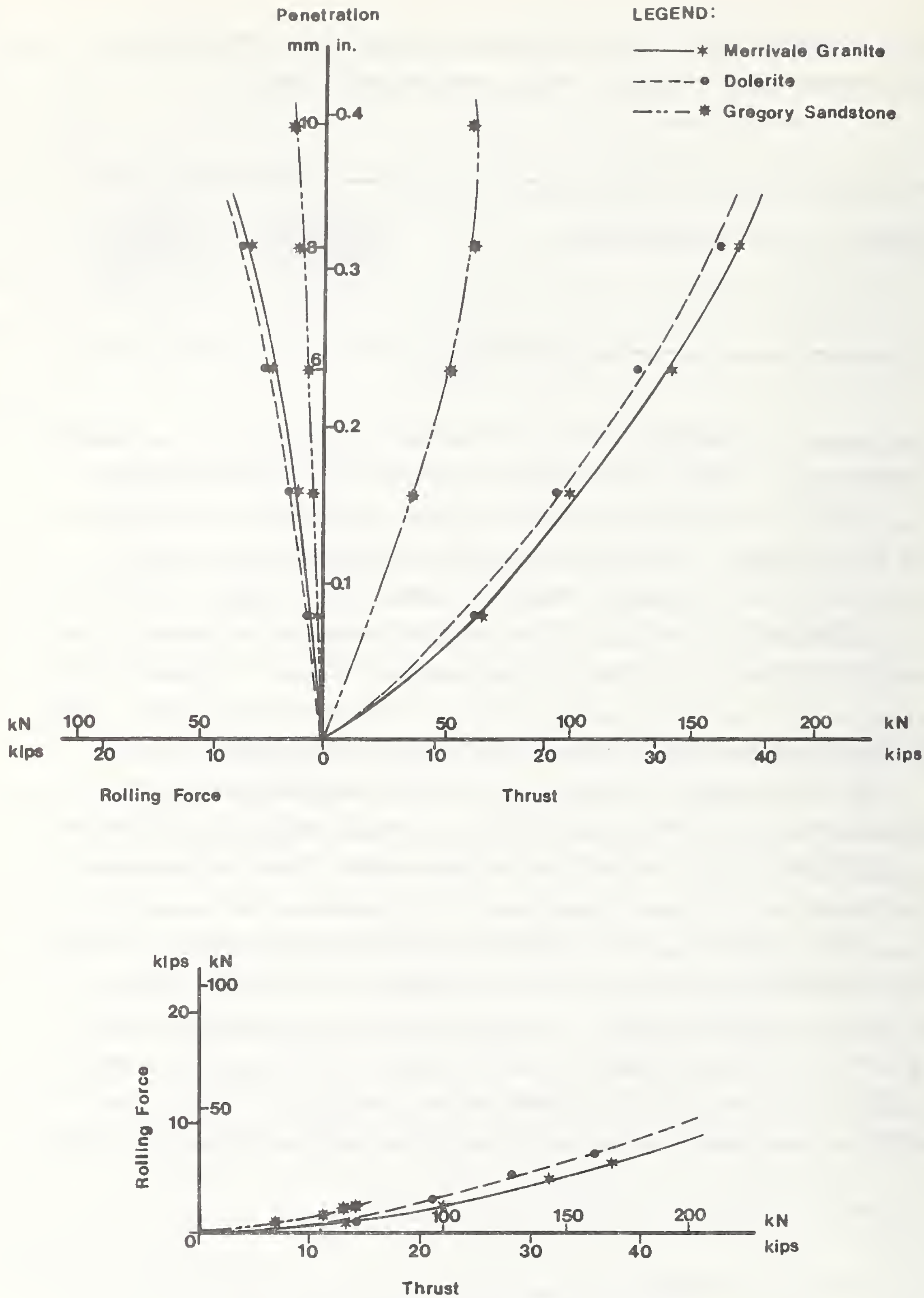


FIGURE 11.11 PLOTS OF PENETRATION VERSUS THRUST AND ROLLING FORCE, AND ROLLING FORCE VERSUS THRUST (based on data from Snowdon, Ryley, and Temporal, 1982)

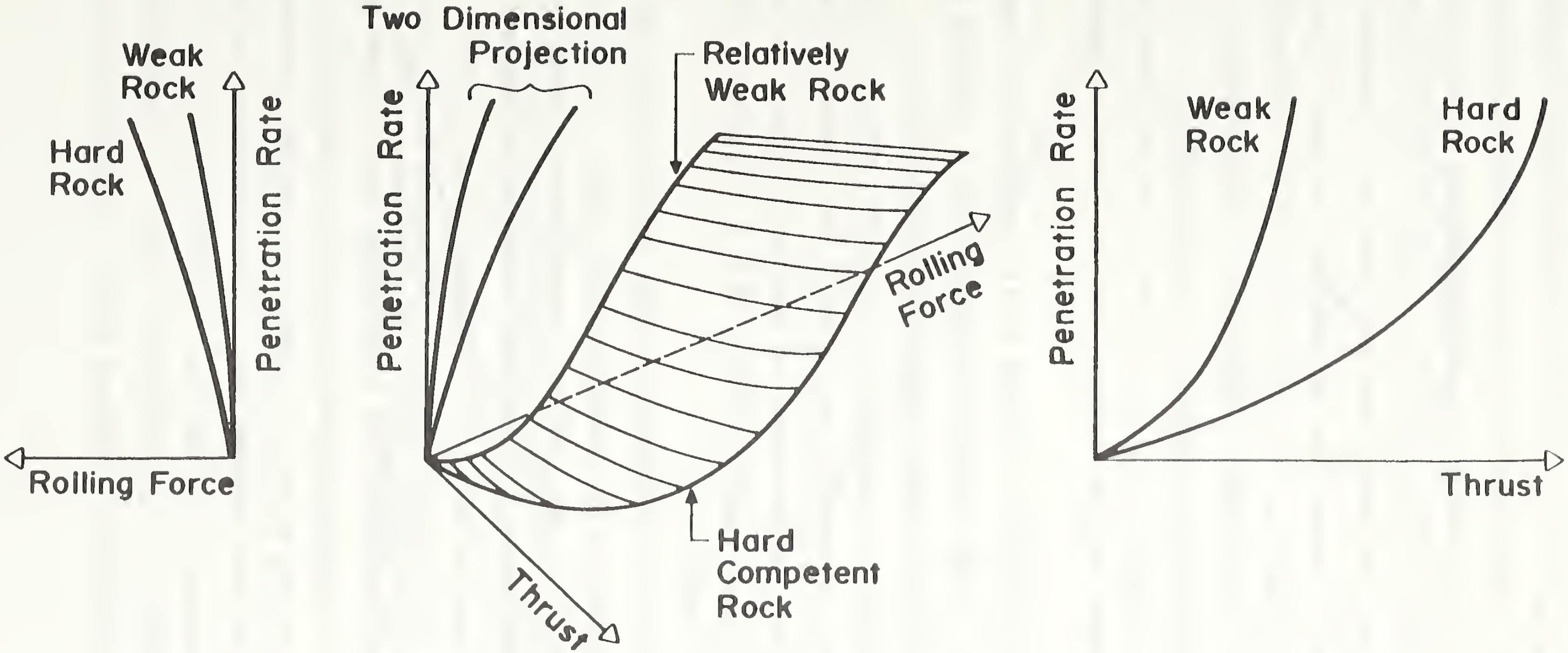


FIGURE 11.12 THREE DIMENSIONAL PLOT SHOWING INTERACTION AMONG PENETRATION, THRUST, AND ROLLING FORCE

cutter is brought into contact with rocks increasingly more competent and greater in strength and stiffness. It must be emphasized that this model is developed principally for conceptual pruposes and is intended to show general patterns. There may be occasional variations from the general trend as might be the case with a relatively low strength rock of high stiffness for which the rolling force could be disproportionately large. Nevertheless, the model does show that, at a constant rolling force, the level of thrust must decrease as the type of rock changes from a hard, competent one to a relatively weak, less competent material. Furthermore, if the thrust capacity of a given machine is increased without a corresponding expansion in torque capacity, the penetration rate is not likely to be improved for relatively weak rock, but substantial improvements may be possible for very hard, competent material.

The type of plot developed in Figure 11.11, represents a combined two-dimensional "window" on the critical surface. Such a combined plot can be used to explain TBM performance during tunneling from the Maplewood Shale to the Reynales Limestone in the Culver-Goodman Tunnel. This transition from weak, noncrystalline material to a relatively hard and stiff, crystalline rock was discussed in Section 11.3 and can now be approached with a more complete understanding of the interaction among penetration, thrust, and torque.

Figure 11.13 is a plot of penetration rate versus thrust and rolling force for excavation in the Culver-Goodman Tunnel. For both the Maplewood Shale and Reynales Limestone, the curves relating the penetration rate with the average thrust and rolling force per cutter have been drawn to be consistent with the general curvilinear trends shown by the data of Snowdon, Ryley, and Temporal (1982). The points A', A, and B on the plots represent actual values of the penetration rate, thrust, and rolling force per cutter determined from the records of machine boring. The net thrust capacity of the machine is shown as a dashed line bounding the right-hand side of the combined plot. This represents an upper limit of the thrust available for excavation with the Culver-Goodman TBM. The net torque capacity of the machine is shown as a dashed line bounding the left-hand side of the combined plot. The rolling force

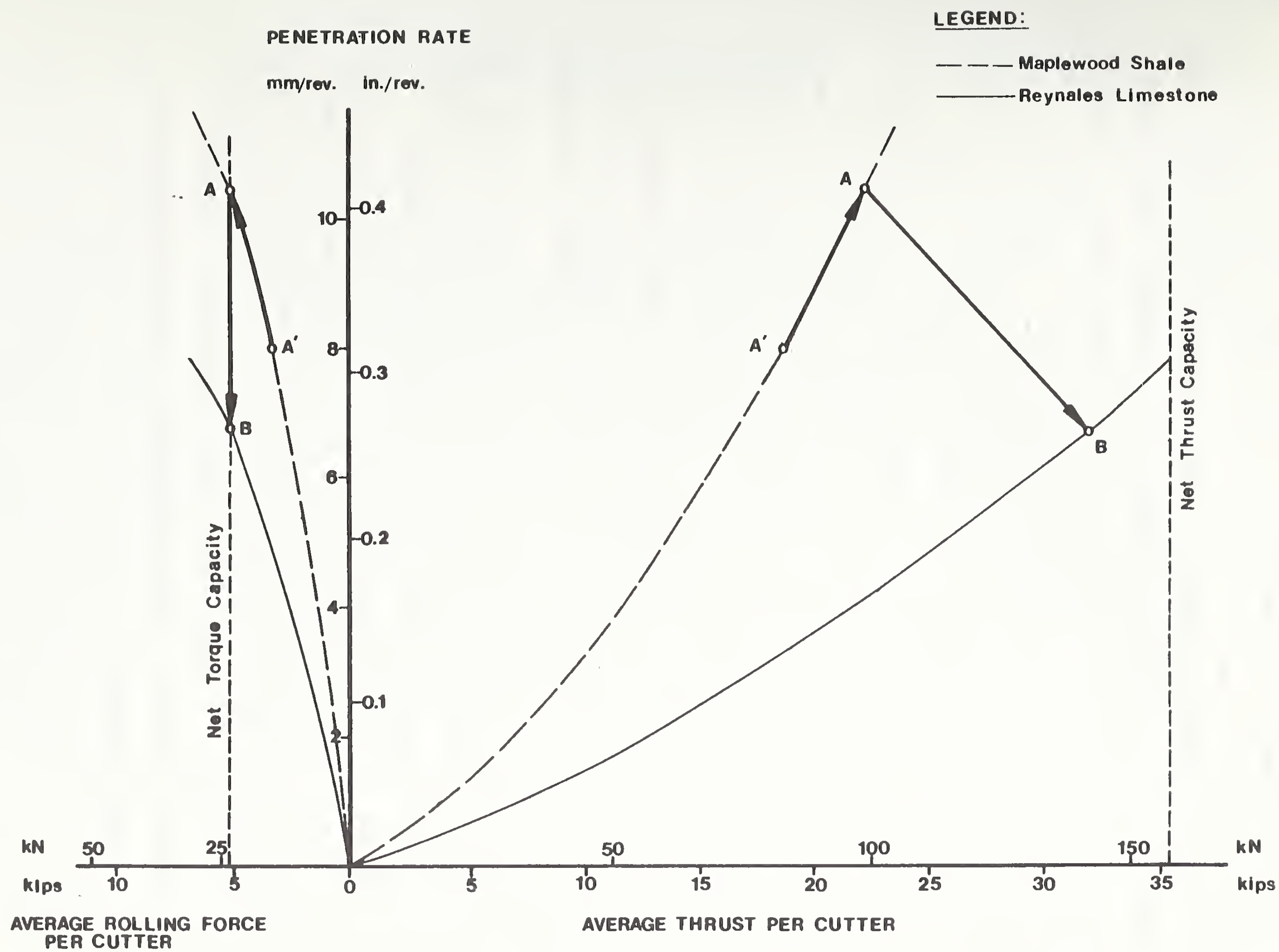


FIGURE 11.13 PENETRATION RATE AS A FUNCTION OF AVERAGE THRUST AND ROLLING FORCE PER CUTTER FOR TBM PERFORMANCE IN THE CULVER-GOODMAN TUNNEL

indicated by this line is the maximum average rolling force per cutter that could be delivered to the rock.

Point A' represents the conditions of rock cutting shortly after the second change of the main bearing seal at Station 95+09, while the TBM was boring the Maplewood Shale. Because of difficulties with packed muck buckets and saturated muck accumulation at the face, the actual torque delivered in the form of rolling force to the cutters was reduced below its maximum capacity. After the muck buckets were cleaned out and the dust abatement spray was stopped at Station 96+89, additional rolling force was available and the cutting conditions changed from Point A' to A. The path followed during this change is traced by the arrow.

As tunneling continued from the Maplewood Shale to the Reynales Limestone, the machine was operated at a constant amperage consistent with the maximum capacity of the machine. Accordingly, as cutting was performed in successively greater amounts of the Reynales Limestone, the rolling force was constrained to follow a vertical path from Point A to B along the line defining the net torque capacity of the TBM. At the same time, the penetration rate decreased and the thrust increased as successively large amounts of the harder Reynales rock were intercepted by the machine. The direction of this transition is shown by the arrow from Point A to B on the right-hand portion of the plot.

In summary, the relationships between penetration rate, thrust, and rolling force for different rock types may be thought of as a critical surface in three dimensions. The cutting process can be analyzed through the use of a combined plot of the penetration rate versus average thrust and rolling force per cutter. The complex TBM performance when boring from the Maplewood Shale to Reynales Limestone can be understood with the use of such a combined plot. This general conceptual model can be helpful for evaluating machine performance in a variety of ground conditions and for judging how changes in machine design will affect penetration rates.

CHAPTER 12

INDENTATION, CHIP FORMATION, AND CUTTER REPLACEMENT

12.1 INTRODUCTION

Efficient excavation has been shown by many investigators to correlate with the formation of large chips as the rock between cutter rolling paths is removed. It is of interest, therefore, to explain the chipping process, and to identify characteristics of the rock and cutter which are involved in this process. With the important characteristics identified and their effects understood, the cutter type, cutterhead disc array, and TBM operating levels can be selected to increase the likelihood of chip formation for a given lithological unit.

The indentation response of a given rock also affects the rate of cutter wear. In this case, however, it is the rock behavior directly beneath and around the indentor which is of importance. Rock and cutter characteristics involved with cutter wear should be evaluated separately from those affecting chip formation because the process of abrasion is very different from the chipping process.

In this chapter, the nature of disc cutter-rock interaction is discussed to evaluate what rock properties are likely to have an effect on chip formation and cutter wear. The cutter replacement records from the tunneling projects included in this study are used to investigate the effect of rock properties on the rate of cutter replacement and disc wear. The muck samples taken from each TBM are analyzed to gain insight into the effect of machine operation, design, and rock property variations on chip formation. Finally, the usefulness of a fracture mechanics approach to chip formation and TBM performance prediction is discussed.

12.2 INDENTATION AND CHIP FORMATION

The response of rock to indentation by sharp or blunt tools has been the subject of many investigations. Most approaches have started from the observation that, as a tool begins to penetrate, the rock beneath the tool is crushed. This crushed material is confined by the indentor and by the surrounding intact rock. As indentation continues, more of the rock beneath the indentor is brought to failure, forming a

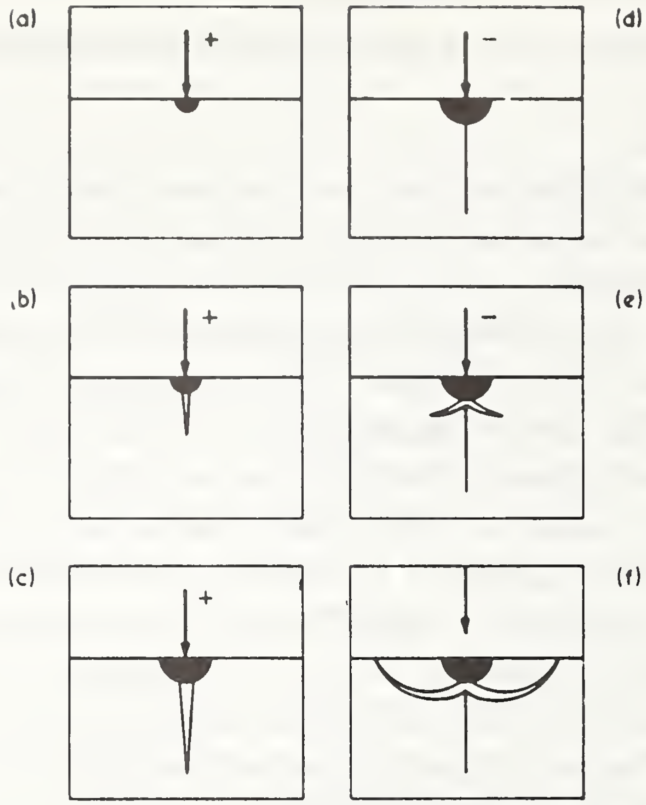


FIGURE 12.1 FRACTURE MECHANICS MODEL OF INDENTATION AND MEDIAN VENT AND LATERAL CRACK FORMATION (Lawn and Swain, 1975)

zone of crushed material, as shown in Figure 12.1a. The shape and extent of this crushed zone and the state of stress within the zone will depend on rock and indentor characteristics. Before an analysis can continue from this point to the formation of cracks, some assumptions must be made about this state of stress.

While the geometry of and the stress state within the crushed zone may be difficult to determine, several general comments can be made. Any cutter feature or rock property which acts to increase the confinement of the crushed zone will also act to increase the level of stress within the zone. Thus, cutter edge angle and rock stiffness affect the stress state. For a given indentor geometry and indenting force magnitude, the level of stress will cause a larger volume of lower strength rock to fail than higher strength rock, and the crushed zone will be larger. If a rock is highly porous, the material will be able to densify beneath the indentor, and the level of stress in the crushed zone will be low relative to the stress level for a dense rock, for which the failed material may behave dilatantly.

As indentation continues, the crushed zone continues to expand, until either: 1) loading is terminated as the cutter moves to a new position on the rock surface, or 2) the strength capacity of the material outside the crushed zone is exceeded and a vent crack develops. A vent crack will form at the base of the crushed zone, as is shown in Figure 12.1b, because this is where the tensile stresses are highest. Whether cracking occurs before unloading depends on the level and distribution of stresses in the crushed zone and the boundary conditions of the interface between the crushed zone and the intact rock.

The formation of the crushed zone and median vent crack are the first stages of chip formation. From this point, many possible mechanisms for the creation of chips have been suggested, and these are discussed at length by Korbin (1979). Several investigators have used a limit equilibrium approach in analysis and have assumed a Mohr-Coulomb material failure criterion. Paul and Sikarskie (1965), Benjumea and Sikarskie (1969), Dutta (1972), and Nishimatsu (1972) each assumed that chip formation occurred when the shear stresses along an assumed failure plane exceeded the shear strength of the rock. Korbin noted that chip formation in brittle rocks, which respond elastically with little plastic deformation, cannot be adequately described by these models in which failure was by shear at high normal stress. He suggested that stresses inside the crushed zone are responsible for radial cracking of the intact rock and that chips form by tensile-shear fracture along planes emanating from an assumed center of pressure in the crushed zone. Korbin's model generally agrees with the results of a finite element study of bit indentation performed by Wang and Lehnhoff (1976).

Recent studies by Lawn and Swain (1975), Lawn and Evans (1977), and Conway and Kirchner (1980) have approached the process of chip formation in brittle materials by using fracture mechanics principles. In the reference from which Figure 12.1 is taken, Lawn and Swain note that the crushed zone will grow until the median vent crack begins to form. The magnitude of the applied load corresponding to initiation is predictable (Lawn and Evans, 1977), and is a function of the fracture toughness of the rock. Fracture toughness, K_{Ic}, is a property of the rock and is a measure of the stress intensity required to initiate crack propagation. The median vent is a stable crack, meaning that the crack will grow only as the indenting load increases, as is shown in Figure 12.1c. The trajectory of this crack is also predictable: it will propagate straight ahead, away from the load. Therefore, the median vent cannot be responsible for chip formation since it cannot deviate from this trajectory. Lawn and Swain suggest, however, that chips might form as the cutter moves on, unloading the crushed zone. When this occurs, the median vent will close as shown in Figure 12.1d and, as the crushed material starts to relax, incompatible strains may develop between the intact rock and the crushed zone. Residual tensile stresses could therefore be superimposed on the stress field in the intact rock, and lateral cracks could initiate as shown in Figure 12.1e. These lateral cracks could not, however, extend to the surface because the surface is still under compression from the indenting load. With complete unloading, however, these cracks would be free to propagate to the surface as shown in Figure 12.1f.

Conway and Kirchner (1980) used a similar approach to study the formation of cracks beneath a moving indentor. To simulate indentor movement, they considered various combinations of loads parallel and perpendicular to the surface and treated these combinations as quasi-static loading conditions. Their analyses demonstrated that high tensile stresses could be developed both in front of and perpendicular to the path of a moving indentor. Thus, chip formation by a rolling disc cutter could result from stresses accumulated ahead of and to the side of the cutter leading edge.

The uneven surface of an excavated rock face precludes the development of compressive stresses everywhere along the surface. Each TBM cutter rolls in a groove which is close to the grooves created by other cutters. Thus, the indented surface is not a plane and chips may form as cracks propagate from one groove to the next beneath any surface compression which may exist. The actual propagation distance for any one crack may actually be shorter than the space between two grooves. This is true because TBM cutting is a continuous process. As a cutter rolls across the rock face, it continuously expands the crushed zone beneath itself, and cracks are initiated and propagated. Fractures created by any one cutter may not always propagate to the adjacent groove, but when the adjacent cutter passes, the fractures it creates may only have to propagate across part of the space between grooves before meeting a pre-existing fracture and forming a chip. Such a scenario for chip formation is illustrated in Figure 12.2, which is a hypothetical cross-sectional view of the rock between two adjacent cutter grooves. Shown to the right are the groove, median vent, and radial cracks left by a cutter which has moved on. To the left is a cutter in an adjacent groove. The crushed zone, median and radial cracks, and chip-forming crack are shown and the direction of crack propagation is indicated.

The general geometry illustrated in Figure 12.2 agrees with that which has been documented by Ozdemir and Wang (1979) and Snowdon, Temporal, and O'Reilly (1982). A chip may not form during every cutter pass, and groove deepening by multiple passes may be required before a chip is actually formed (Howarth, 1981b). In any case, fractures would be initiated in the area of high tensile stresses near the crushed zone. The direction of propagation would be controlled by the tensile and shear stresses at the crack tip, and the crack could propagate beneath any surface compression zone which may exist.

The details of the stress state and geometry of the crushed zone are important in two respects:

1) Abrasive wear can only be caused by material in contact with the cutter and, therefore, the mineralogy, grain size, and stress state in the crushed zone must be considered.
2) The energy required for excavation depends closely on the process of chip formation.

To minimize cutter wear, it is important to keep contact between cutter and crushed zone to a minimum. If the rock is porous, but not of high strength, the crushed zone can become large before chips form. If the material in the crushed zone is abrasive, cutter wear can be severe. Alternatively, if the rock is brittle so that fractures can propagate between adjacent cutter grooves, the crushed zone will be of limited size. Rock failure by crushing consumes more energy per unit volume of excavated material than failure by chip formation. Therefore,

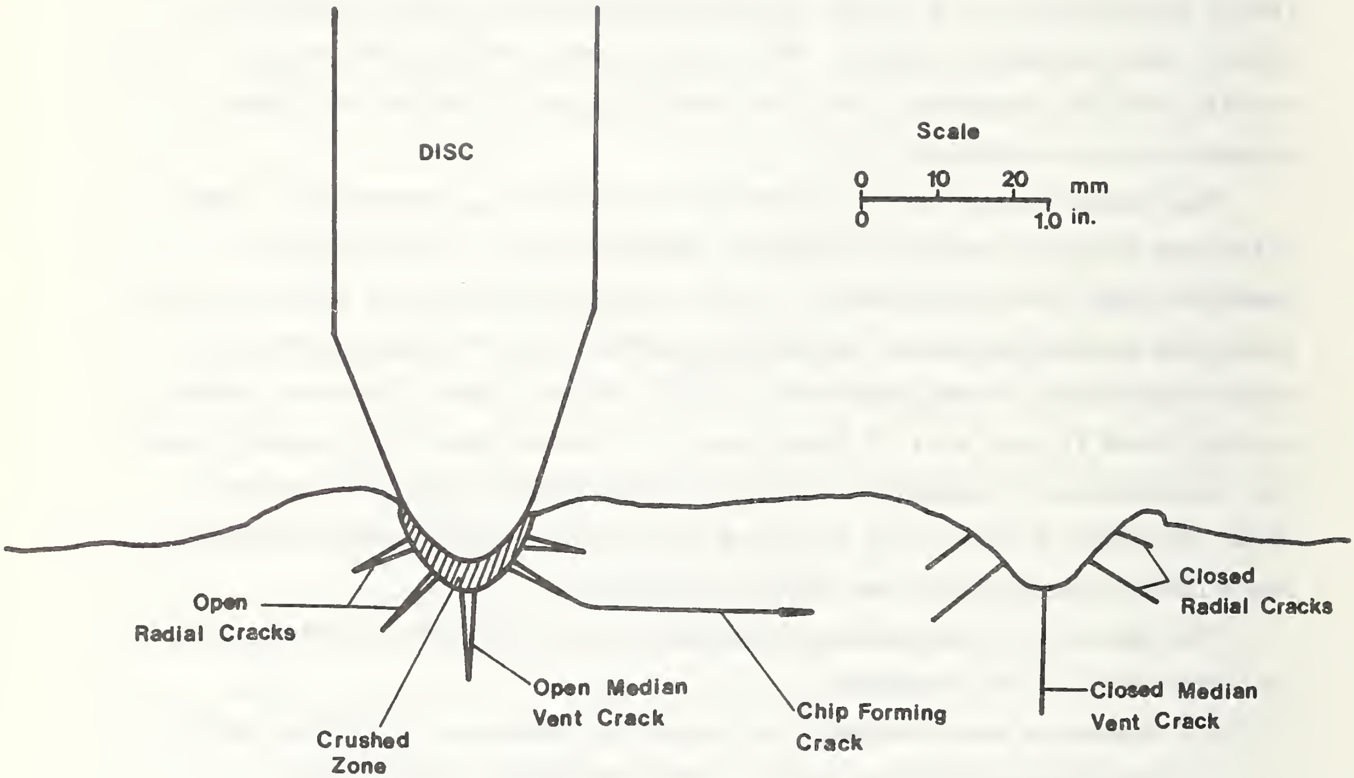


FIGURE 12.2 CROSS-SECTION VIEW OF DISC CUTTER PENETRATION AND ROCK FRACTURE BETWEEN TWO DISC CUTTER GROOVES

excavation efficiency is closely associated with the relative amounts of crushing and chipping that occur during disc cutter penetration.

12.3 CUTTER REPLACEMENT

Cutter wear can have many causes including abrasion of the disc ring, splitting or loss of fit between the ring and hub, and hub bearing failure. In addition, the frequency and tupe of cutter failure can also vary with cutter position on the face. The center cutters, which travel in a very tight circular path, may be subjected to a great amount of abrasion from scuffing. Gage cutters are mounted at an angle to the tunnel axis, so the applied thrust is not parallel to the line of action of the cutter, and a complex set of cutter loads can develop. Gage cutters travel at relatively high velocities, and this means that the bearings will be subjected to higher temperatures which decrease the bearing life. In addition, gage cutters must travel through muck accumulations in the invert. Accordingly, the disc, hub, and saddle of a gage cutter may be exposed to more abrasion than that affecting the centrally located cutters.

To understand better the patterns of cutter wear, this section concentrates on the records of cutter replacement for the tunnels under study. Although good records were available for the frequency and position of cutter replacements, little information was recorded about the type of wear associated with the replacements. Detailed information on the type of wear was only available for the Chicago TARP tunnel. For the other tunnels, it is possible to make judgments about the predominant type of wear on the basis of observations made by research personnel during tunneling and discussions with the contractors. Accordingly, the principal sources of information are the records of replacement, supplemented by observations in the field.

Table 12.1 summarized the average penetration rate and thrust per cutter for various sections in each of the tunnels corresponding to a different lithology or major change in construction procedure. The average rates of penetration fall within very narrow bound and the average cutter thrust varies by no more than 20 percent of the overall average.

TABLE 12.1 AVERAGE PENETRATION RATE AND THRUST PER CUTTER FOR THE CULVER-GOODMAN, C11, AND CHICAGO TARP TUNNELS

TUNNEL	STATIONS	AVERAGE PENETRATION RATE in./rev. (mm/rev.)	AVERAGE THRUST PER CUTTER kips (kN)
Culver-Goodman	3+98 to 28+00	0.29 (7.4)	24.0 (107)
	28+00 to 85+71	0.29 (7.3)	25.8 (115)
	85+71 to 140+00	0.30 (7.6)	21.8 (97)
	Entire Tunnel	0.30 (7.7)	24.5 (109)
C11 Outbound	Entire Tunnel	0.31 (7.9)	25.9 (115)
C11 Inbound	Entire Tunnel	0.31 (7.8)	24.7 (110)
Chicago TARP	Entire Tunnel	0.26 (6.5)	30.3 (135)

TABLE 12.2 SUMMARY OF AVERAGE NUMBER OF CUTTER REPLACEMENTS PER 1000 FT (305 M) FOR THE CULVER-GOODMAN, C11, AND CHICAGO TARP TUNNELS

TUNNEL	STATIONS	AVERAGE NUMBER OF CUTTER REPLACEMENTS PER 1000 ft (305 m) OF TUNNEL PER NUMBER OF POSITIONS IN EACH CUTTER GROUP			
		Center	Face	Gage	All Cutters
Culver-Goodman	3+98 to 28+00	2.39	1.46	3.60	2.51
	28+00 to 85+71	0.86	1.27	3.02	2.08
	85+71 to 140+00	0.61	0.69	1.16	0.89
	Entire Tunnel	1.35	1.20	2.80	1.95
C11 Outbound	Entire Tunnel	0.21	0.26	0.25	0.25
C11 Inbound	Entire Tunnel	0.21	0.25	0.28	0.26
Chicago TARP	Entire Tunnel	0.87	0.25	0.46	0.45

Table 12.2 summarizes the average number of cutter replacements per 1000 ft (305 m) of tunnel for the center, face, and gage positions, corresponding to the tunnel sections in Table 12.1. It can be seen that, although the penetration rate and cutter thrust were relatively constant among the tunnels, the number of cutter replacements varied. The frequency of cutter replacement in the Culver-Goodman Tunnel was substantially higher in all sections than that in the other tunnels. On the basis of lithology, cutter replacement rates were much higher in the Grimsby Sandstone than in any of the different rock units.

Tables 12.3 and 12.4 summarize the average rolling distance and operating hours for each of the cutter positions. The average rolling distance corresponds to the average distance traveled before replacement, and the average operating hours correspond to the average period of time before replacement, as determined by reference to the machine clock. Table 12.3 also includes a listing of the predominant rock units encountered in each tunnel section.

Average face cutter rolling distances vary from a low in the first section of the Culver-Goodman Tunnel to a high in the C11 and Chicago TARP tunnels. In the Culver-Goodman Tunnel the rolling distances were similar for the first two sections in the Queenston Shale and Grimsby Sandstone, and the average distance in the Reynales Limestone and shale units in the second half of the tunnel was approximately twice as large as in the first part of the tunnel. Face cutters in the Chicago TARP and C11 tunnels rolled from 2.5 to 5 times as far as those in the Culver-Goodman Tunnel.

The average rolling distance for gage cutters in the Culver-Goodman Tunnel increased from Stations 28+00 to 85+71 at about the same time that the 90 degree gage cutters were replaced with cutters having a much wider contact surface (See Figure 11.5). The ratio of average rolling distance of the gage cutters to that of the face cutters is nearly the same for tunneling in limestone on the Culver-Goodman and Chicago TARP Tunnels. Because the gage cutters travel, on average, about twice as far as the face cutters travel per unit of time, it is not surprising that Table 12.4 shows an average operating time for the gage positions approximately half that of the face positions in these tunnels. In the C11 Outbound and Inbound tunnels, the average rolling distance for gage

TABLE 12.3 SUMMARY OF AVERAGE ROLLING DISTANCES AT TIME OF CUTTER REPLACEMENT FOR THE CULVER-GOODMAN, C11, AND CHICAGO TARP TUNNELS

TUNNEL	STATIONS	PREDOMINANT ROCK UNITS	AVERAGE ROLLING DISTANCES FOR CUTTER POSITION GROUPS ft (m) x 10^6			
			Center	Face	Gage	All Cutters
Culver-Goodman	3+98 to 28+00	Queenston Shale and Lower Grimsby Sandstone	0.06 (0.02)	0.93 (0.28)	0.65 (0.20)	0.73 (0.22)
	28+00 to 85+71	Grimsby and Thorold Sandstones	0.17 (0.05)	1.05 (0.32)	0.80 (0.24)	0.89 (0.27)
	85+71 to 140+00	Maplewood Shale, Reynales Limestone, Lower Sodus and Williamson Shales	0.21 (0.06)	1.93 (0.59)	1.99 (0.61)	1.83 (0.56)
	Entire Tunnel		0.14 (0.04)	1.20 (0.37)	1.00 (0.30)	1.04 (0.32)
C11 Outbound	Entire Tunnel	Falkirk and Oatka Members of the Bertie Dolostone Formation	0.68 (0.21)	4.89 (1.49)	8.44 (2.57)	5.53 (1.69)
C11 Inbound	Entire Tunnel	"	0.66 (0.20)	4.70 (1.43)	7.77 (2.37)	5.43 (1.66)
Chicago TARP	Entire Tunnel	Romeo and Markgraf Members of the Joliet Formation	0.15 (0.05)	4.66 (1.420	4.82 (1.47)	3.73 (1.14)
	185+84 to 305+00 (Abrasion Failure Only)	"	——	4.80 (1.46)	4.41 (1.34)	4.64 (1.41)

TABLE 12.4 SUMMARY OF AVERAGE CUTTER LIFE FOR THE CULVER-GOODMAN, C11, AND CHICAGO TARP TUNNELS

TUNNELS	STATIONS	AVERAGE CLOCK HOURS BEFORE REPLACEMENT FOR CUTTER POSITION GROUPS			
		Center	Face	Gage	All Cutters
Culver-Goodman	3+98 to 28+00	64	106	43	74
	28+00 to 85+71	178	119	51	90
	85+71 to 140+00	238	216	122	176
	Entire Tunnel	151	136	63	103
C11 Outbound	Entire Tunnel	567	447	432	451
C11 Inbound	Entire Tunnel	551	403	403	413
Chicago TARP	Entire Tunnel	150	509	270	353
	185+84 to 305+00 (Abrasion Failure Only)	—	488	256	392

cutters was nearly twice as high as for face cutters. Correspondingly, the average operating time for the gage positions is approximately equal to that of the face positions.

The average rolling distance of the center cutters was much lower than that of the cutters in other positions. For the tunnels listed in Table 12.3, travel distances for the center cutters vary by an order of magnitude, from a minimum in the first section of the Culver-Goodman Tunnel to a maximum in the C11 tunnels where each center cutter was replaced only once.

Figure 12.3 is a plot of the average rolling distance versus cutter position for cutters changed between Stations 28+00 and 85+71 in the Culver-Goodman Tunnel. Positions numbered 1 through 4 correspond to center cutters, 5 through 33 to face cutters, and 34 through 45 to gage cutters. Many of the replacements in this tunnel section were made because of disc abrasion, and the trend toward decreased rolling distance in the outer face and gage positions reflects the fact that some of the cutter wear was caused by abrasive muck accumulations at the tunnel invert. The lowest rolling distance for gage cutters occurred at the outer three positions. Figure 12.4 is a plot of average rolling distance versus cutter position for cutters changed between Stations 85+71 and 140+00. Only five cutters were changed between Station 140+00 and the end of the tunnel at Station 169+93. The general relationship between rolling distance and cutter position in Figure 12.4 is similar to that in Figure 12.3. Cutters located at middle face positions rolled the greatest distances before replacement, with the rolling distances decreasing for lower and higher cutter numbers.

Figures 12.5 and 12.6 are plots of average rolling distance versus cutter position for cutters replaced during excavation of the C11 outbound and inbound tunnels, respectively. Numbers 1 through 4 are center cutters, 5 through 31 are face cutters, and 32 through 42 are gage cutters. The trends shown in these figures are strikingly different from the trends shown in the plots for the Culver-Goodman Tunnel. The gradual increase in rolling distance with increased radial distance from the center of the cutterhead is associated with the fact that the cutters at most positions were replaced only once, near the shaft at the midpoint of each tunnel. Information is not available on the type of wear

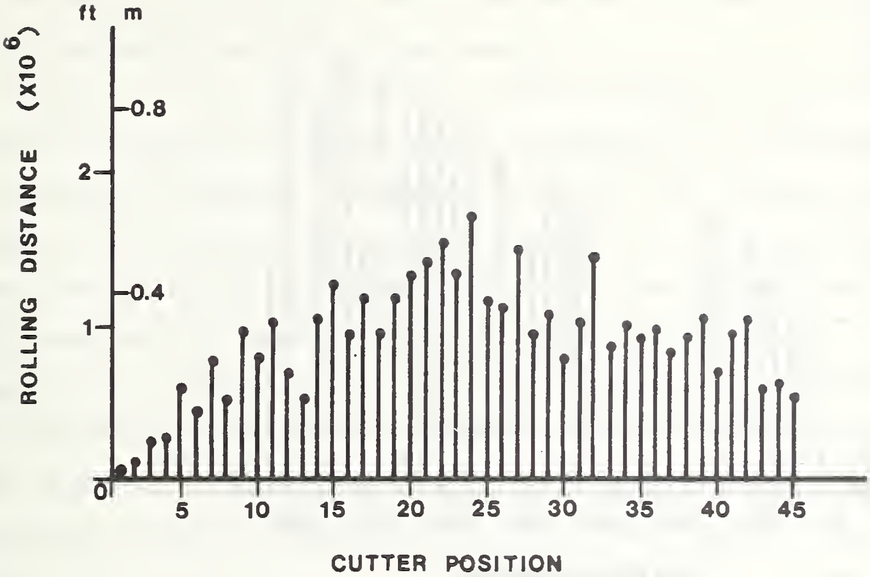


FIGURE 12.3 AVERAGE ROLLING DISTANCE PER CUTTER POSITION, STATION 28+00 TO 85+71, CULVER-GOODMAN TUNNEL

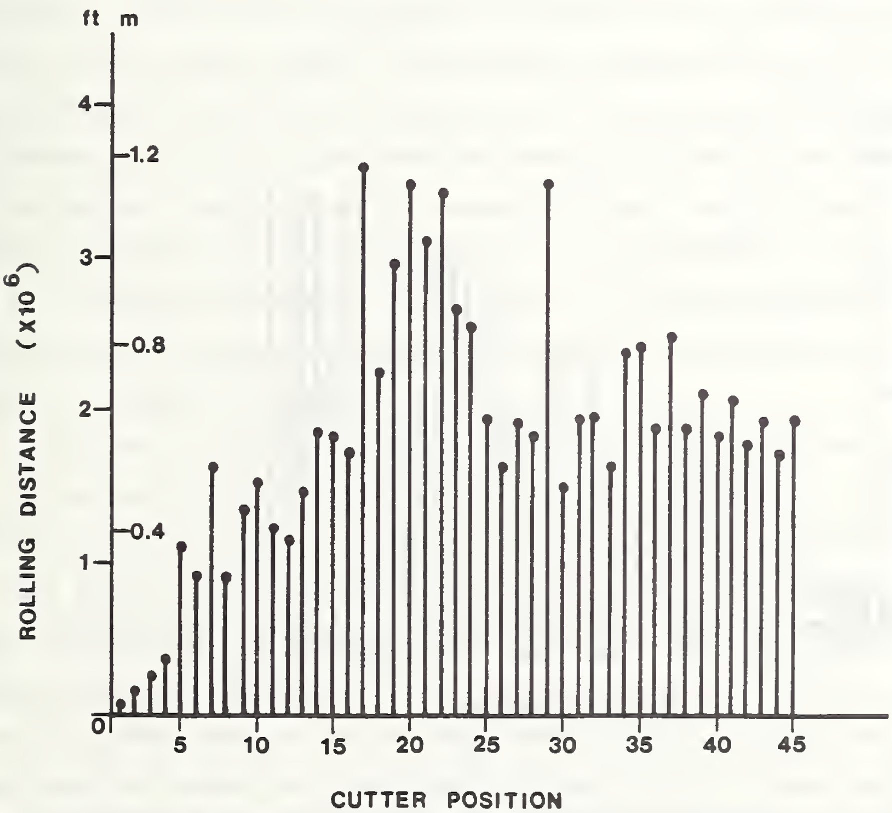


FIGURE 12.4 AVERAGE ROLLING DISTANCE PER CUTTER POSITION, STATION 85+71 TO 140+00, CULVER-GOODMAN TUNNEL

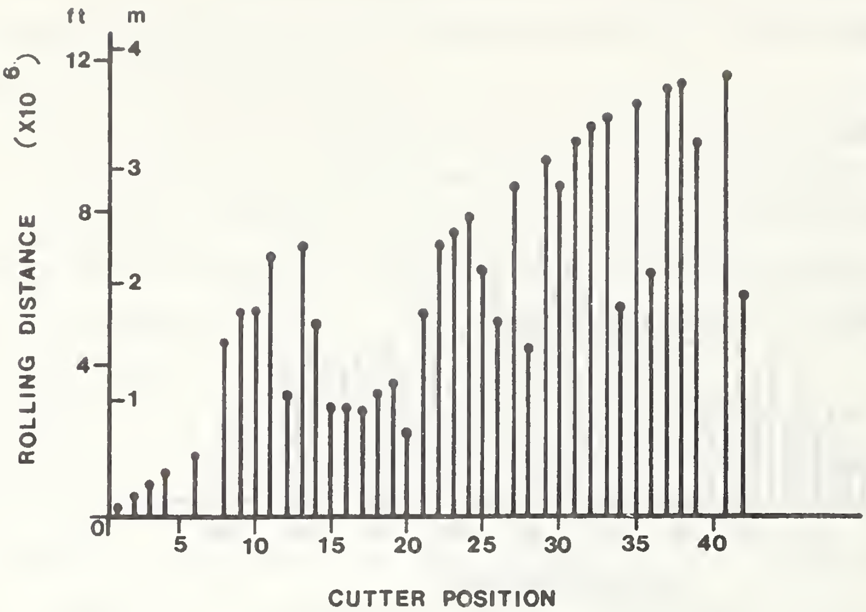


FIGURE 12.5 AVERAGE ROLLING DISTANCE PER CUTTER POSITION, C11 OUTBOUND TUNNEL

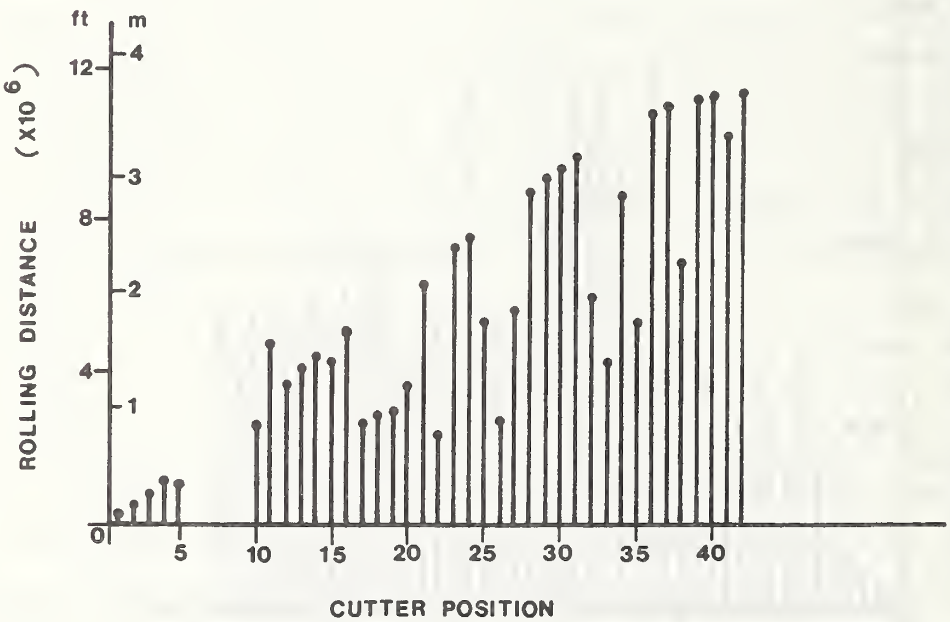


FIGURE 12.6 AVERAGE ROLLING DISTANCE PER CUTTER POSITION, C11 INBOUND TUNNEL

causing replacement, and it is possible that some cutter replacements were strongly influenced by easy face access and extra time during general TBM maintenance near the shaft.

Figure 12.7 is a plot of the average rolling distance versus cutter position for cutters replaced during excavation of the main tunnel of TARP Contract 73-287-2H. Numbers 1 through 4 are center cutters, 5 through 36 are face cutters, and 37 through 47 are gage cutters. In the figure, the rolling distances for face and gage cutters do not show a clear trend with increasing cutter number. As discussed in Chapter 8, cutters were changed in this tunnel for a variety of reasons. In the first 10,000 ft (3,046 m) of tunneling, however, most of the cutter replacements were made because of disc abrasion. Figure 12.8 is a plot of the average rolling distance versus cutter position for cutters replaced because of disc abrasion in this first tunnel section. The pattern of wear for the face cutters follows a trend similar to that of Figures 12.5 and 12.6 for the C11 tunnels, because many of the face cutters were replaced at the same time when the tunneling was stopped for cutterhead maintenance. The rolling distance decreases for the gage positions, however, and in this respect the overall trend more closely resembles that of Figure 12.4 for the second half of the Culver-Goodman Tunnel.

Although it is not possible to identify clearly the types of wear for the Culver-Goodman and C11 tunnels, visual inspections of worn cutters indicate that disc abrasion was a predominant cause for replacement on the Culver-Goodman Tunnel, while a substantial number of truncated discs were observed during the tunneling in Buffalo. Truncated discs are a sign of bearing failure.

A distinction should be made between abrasion and bearing failure. Most abrasion is concentrated along the disc ring and is, therefore, related to the abrasive nature of the rock. Bearing failures result from the forces and temperatures generated at the roller bearings enclosed in the hub. Although bearing failures may be influenced by fine-grained muck that penetrates the bearing seal, the life of a bearing depends to a large extent on the time that a certain level of thrust and variations in thrust are sustained by the cutter. These forces are not always related to the same rock properties controlling abrasion.

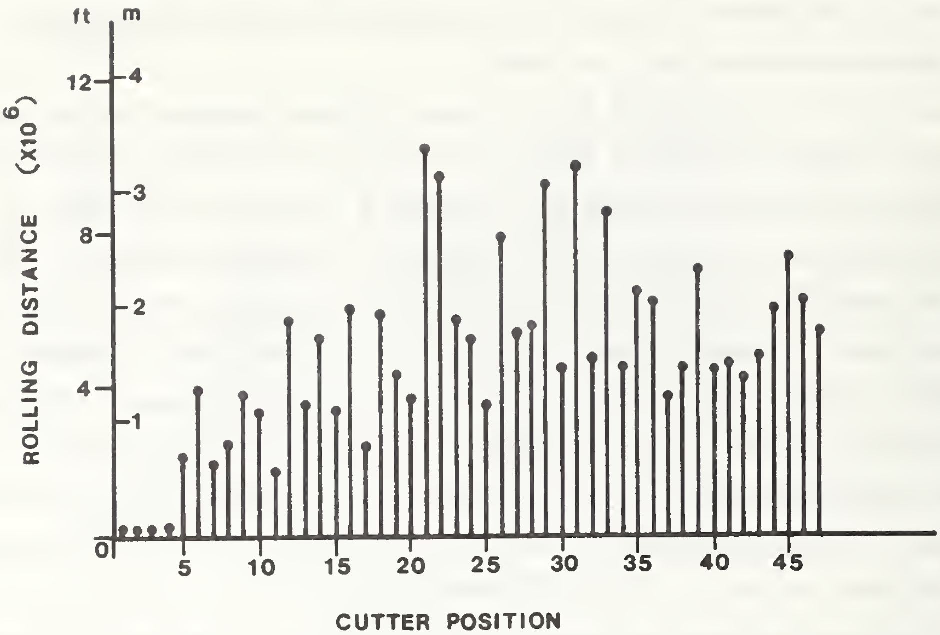


FIGURE 12.7 AVERAGE ROLLING DISTANCE PER CUTTER POSITION, MAIN TUNNEL OF TARP CONTRACT 73-287-2H

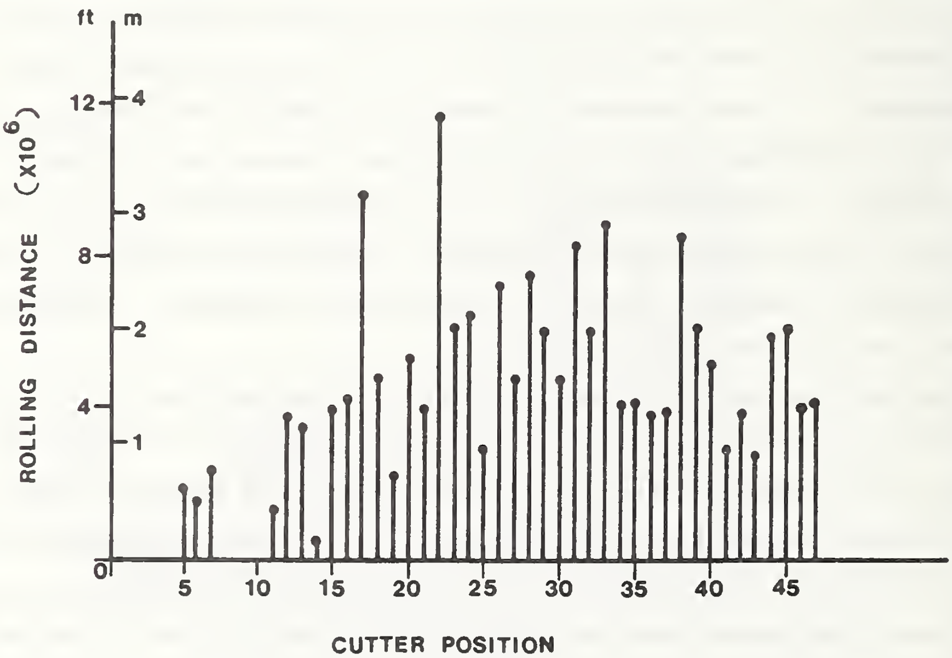


FIGURE 12.8 AVERAGE ROLLING DISTANCE PER CUTTER POSITION FOR DISC WEAR, STATION 185+84 TO 290+00, MAIN TUNNEL OF TARP CONTRACT 73-287-2H

Cutter wear caused by abrasion can be studied by using the observations at the Culver-Goodman Tunnel, where the contractor periodically measured the diameters of the outer three gage cutters. These measurements allow an estimation of disc wear regardless of the cause of replacement. Figure 12.9 is a plot of the decrease in diameter of the gage cutters versus the rolling distance of the cutters at the time of measurement. Measurements were obtained during excavation in the Grimsby Sandstone, Reynales Limestone, and Lower Sodus and Williamson Shales. The rock unit under excavation at the time of each measurement is shown in this figure by different symbols. The rates of cutter wear are clearly different in each rock type, with the shales producing the least wear and the sandstone the most. The lines drawn in Figure 12.9 represent the best fit equations from regression analysis of the data for each rock type.

The Grimsby Sandstone data in Figure 12.9 can be separated on the basis of lithologically distinct zones within this sandstone unit. The lower Grimsby is a medium to coarse-grained sandstone which is often only weakly cemented. The quartz content of this rock can be less than 50 percent and argillaceous, hematitic matrix material is abundant. The middle of the Grimsby Formation includes thin beds of fine-grained sandstone. This rock is usually well-cemented, and the argillaceous matrix content is about 30 percent with quartz grains comprising the remainder of the rock. The rock at the top of the Grimsby is thickly bedded, well-cemented sandstone with a quartz content up to about 95 percent. Decreases in diameter measured in each subdivision of the Grimsby are plotted versus cutter rolling distance in Figure 12.10. The lines drawn in the figure are plots of equations produced by linear regression analyses of the data. As shown in Figure 12.10, the rate of disc wear was highest in the lower Grimsby, and was lowest in the upper Grimsby.

West (1981) discussed various testing methods used to evaluate rock abrasiveness for tunneling applications, and recommended the quartz content and uniaxial compressive strength of a rock as useful properties. He also noted that mechanical laboratory tests, in which the weight loss of a metal tool is determined after abrasive contact with the rock, can also be helpful. While no abrasion testing was carried out by research personnel, the modified Taber abrasion testing performed by the

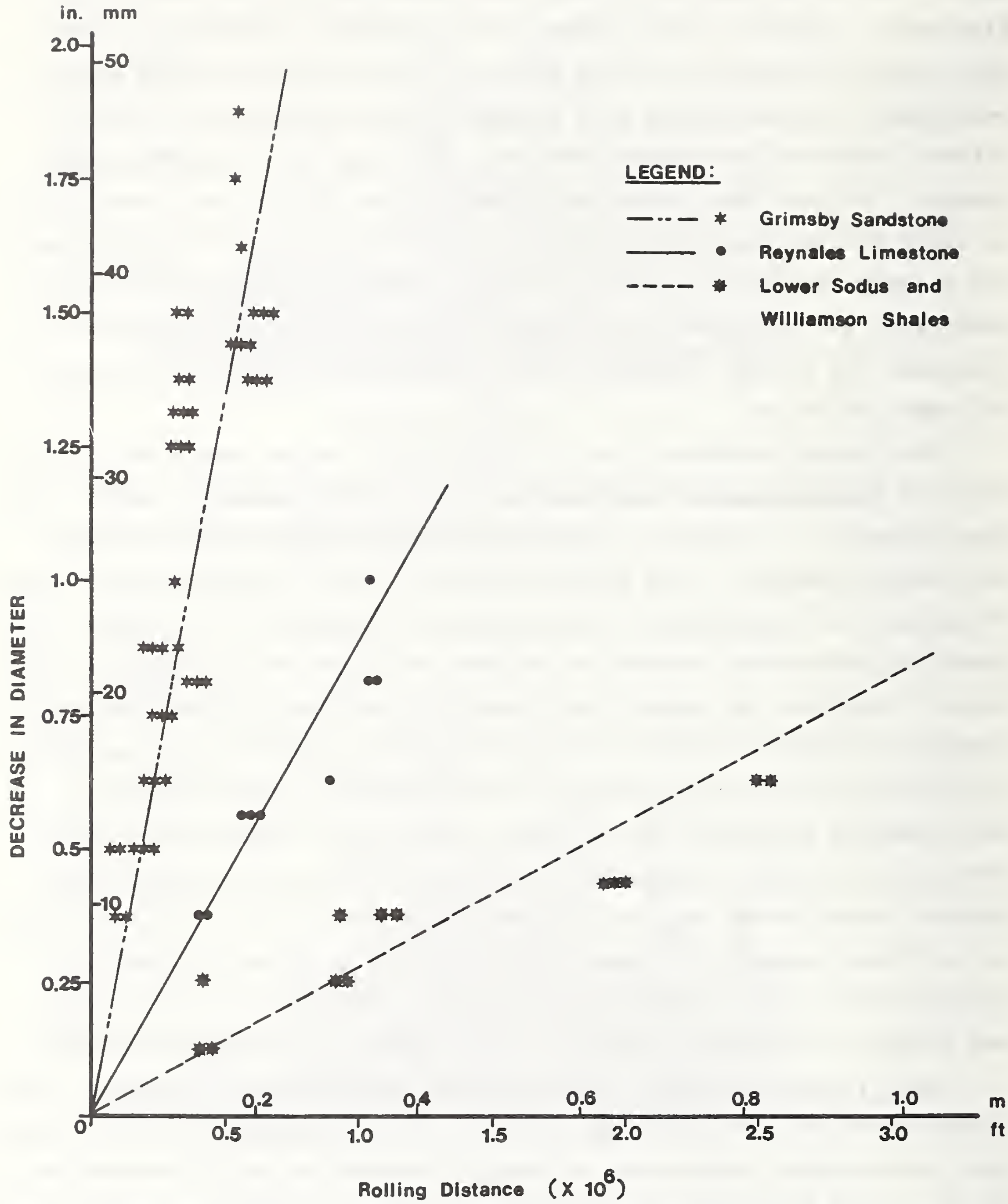


FIGURE 12.9 PLOT OF DECREASE IN DIAMETER VERSUS ROLLING DISTANCE FOR GAGE CUTTERS, CULVER-GOODMAN TUNNEL

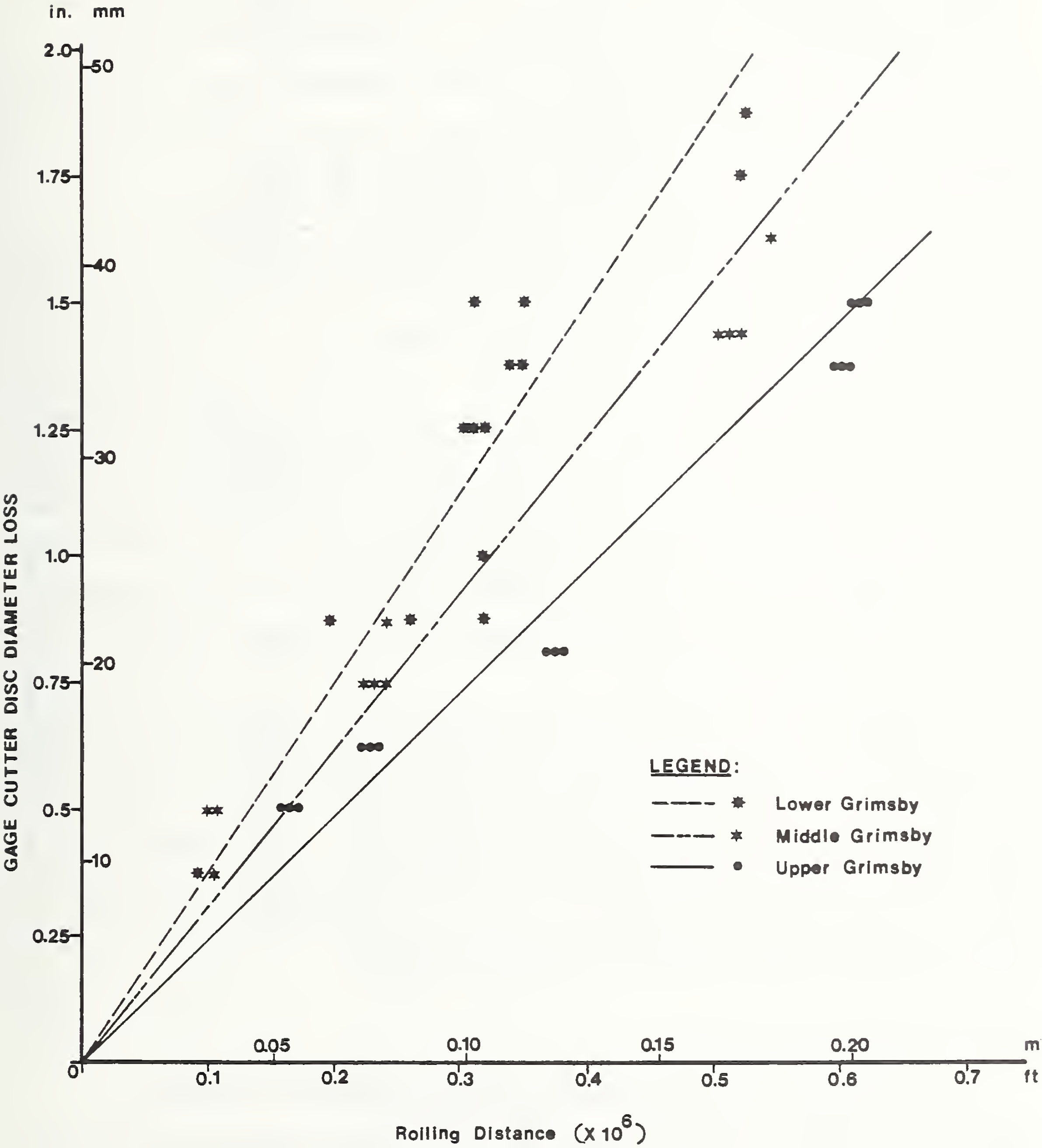


FIGURE 12.10 PLOT OF DECREASE IN CUTTER DIAMETER VERSUS ROLLING DISTANCE FOR GAGE CUTTERS IN THE GRIMSBY SANDSTONE

geotechnical consultant on the Culver-Goodman project (Haley and Aldrich, 1978) included the evaluation of rock abrasiveness. The test procedure followed the recommendation of Tarkoy and Hendron (1975), and rock abrasiveness, A_R, was evaluated as the reciprocal of the weight loss of the abrasion wheels used in the Taber abrasion test. With this definition, a low value of A_R indicates that the weight loss of the wheels was high, and that the rock is relatively abrasive.

Table 12.5 is a summary of rock properties and cutter wear parameters for the rock units included in Figures 12.9 and 12.10. The rate of cutter wear is expressed as the rolling distance per unit disc diameter loss, which is the reciprocal of the slope of the equations derived for each set of cutter wear data. The estimated quartz content for each of the rock units was determined from petrographic descriptions of thin sections, and the uniaxial compressive strengths were evaluated from test results obtained by research personnel (Gunsallus, 1983). Rock abrasiveness values were taken from the geotechnical project report, but the test results for the lower and middle Grimsby could not be differentiated. The value of A_R reported in Table 12.5 for these units is therefore a combined average.

In Figure 12.11, each of the rock properties in Table 12.5 is plotted against the rate of cutter wear. The rock property which appears to correlate best with the rate of cutter wear is A_R. Uniaxial compressive strength and quartz content show little correlation with cutter wear. Of the three Grimsby lithologies, the upper Grimsby, with the highest quartz content and compressive strength, was less abrasive than the lower strength middle and lower Grimsby material.

12.4 MUCK SAMPLE ANALYSIS

To investigate relationships among muck gradation, machine operating levels, and rock properties, and to gain insight into the rock cutting process, muck samples were obtained at each of the tunnels included in this study. All samples were taken from the TBM conveyor with the exception of the Chicago TARP sample which was taken from a muck pile at the ground surface. Up to 50 lbs (222 N) of muck were sampled, and a 2.5 lb (11 N) portion was used to determine the sample water content. Water contents of the samples were generally between 4 and 6

TABLE 12.5 ROCK PROPERTIES AND RATES OF CUTTER DISC WEAR FOR FIVE ROCK UNITS IN THE CULVER-GOODMAN TUNNEL

ROCK UNIT	ROLLING DISTANCE PER UNIT DISC DIAMETER LOSS, ft/in. (m/mm) x 10^6	ESTIMATED QUARTZ CONTENT (%)	UNIAXIAL COMPRESSIVE STRENGTH[a] ksi (MPa)	ROCK ABRASIVENESS[b]
Lower Grimsby Sandstone	0.27 (0.003)	60	13.5 (93)	3
Middle Grimsby Sandstone	0.32 (0.004)	70	8.3 (57)	3
Upper Grimsby Sandstone	0.41 (0.005)	90	29.4 (203)	6
Reynales Limestone	1.13 (0.014)	10	15.0 (103)	12
Lower Sodus and Williamson Shales	3.65 (0.044)	5	11.6 (80)	42

[a] evaluated by Cornell personnel

[b] evaluated by Haley and Aldrich (1978)

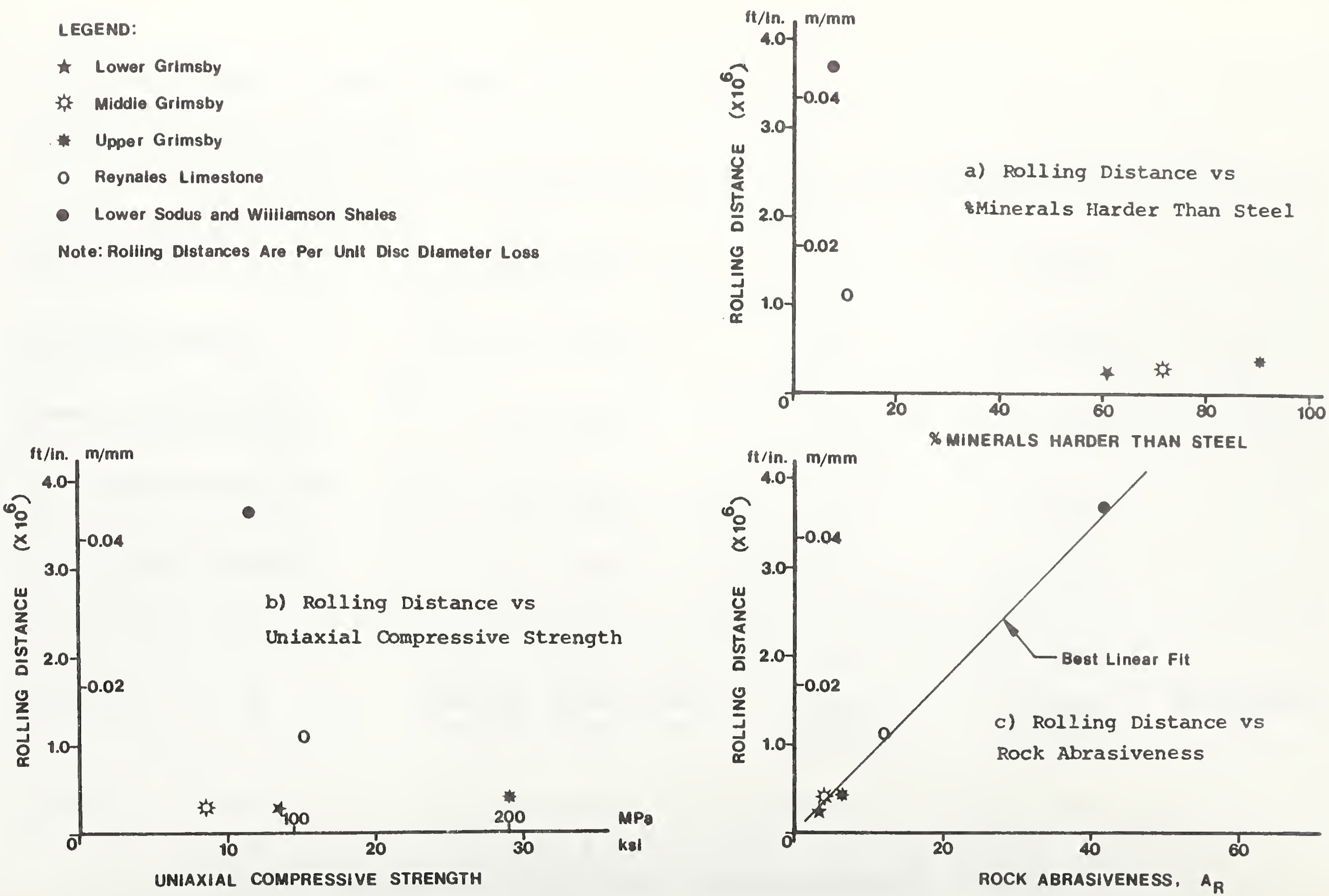


FIGURE 12.11 PLOT OF ROLLING DISTANCE PER UNIT DECREASE IN DIAMETER VERSUS ROCK PROPERTIES

percent by weight. Each sample was then weighed and wet sieved by hand through Numbers 4 and 200 sieves, with openings of 0.19 in. (4.76 mm) and 0.0029 in. (0.074 mm), respectively. The material retained on the Number 4 sieve was dried and sieved by hand with a series of sieves from the 1.5 in. (38.1 mm) sieve to the Number 4 sieve. The material retained on the Number 200 sieve was analyzed according to ASTM Test Designation: D 422-63 (ASTM, 1982), the standard method for particle-size analysis of soils. The amount of material finer than the Number 200 sieve was determined by weight loss during the initial wet sieving of the bulk sample.

In addition to the sieve analysis, the size of the largest muck chip in each sample was determined and the number of chips retained on the 1.5 in. (38.1 mm) and 1.0 in. (25.4 mm) sieves were counted. For each sample, a plot of percent material retained versus the logarithm (base 10) of the sieve opening size was prepared. The value of d_{50}, the the median particle diameter of the sample, was determined from this plot. The results of the gradation analyses are presented in Table 12.6. Table 12.7 includes the penetration rate, average thrust per cutter, number of operating motors, amperage, initial rock suport, and the rock unit present at the heading at the time of sampling. In addition, the coarseness index was determined for each sample by summing the cumulative percentage weight of sample retained on each gravel-sized sieve, from the 1.5 in. (3.81 mm) to the Number 4 sieve (4.76 mm). Coarseness indices have been used in previous studies of muck gradation by Barker (1964), Rad and Olson (1974), Toombs, Snowdon, and O'Reilly (1976), and Hignett (1978). Since there were five sieves in the series used in this study, the maximum coarseness index, CI, would be 500, indicating that the cumulative percentage weight on each sieve was equal to 100 percent. A CI of zero would indicate that the entire sample passed through the Number 4 (4.76 mm) sieve. The CI values for each sample are included in Table 12.6.

Of the 18 samples summarized in Table 12.6, the muck gradations of 14 are very similar. The coarseness indices of the 14 samples vary only from about 120 to 190, and the coarseness index and other quantities descriptive of the gradation are largely independent of the penetration rate, cutter loads, operating torque levels and cutterhead rotation

TABLE 12.6 SUMMARY OF RESULTS OF MUCK GRADATION ANALYSES

LOCATION	TUNNEL	STATION	COARSENESS INDEX	PERCENT OF SAMPLE PASSING #4 (476 mm) SIEVE	d_{50} in. (mm)	LARGEST CHIP DIMENSION in. (mm)	NUMBER OF CHIPS RETAINED ON 1.0 IN. (25.4 MM) SIEVE PER LB (N)
Buffalo	C11 Outbound	61+75	172	40	0.33 (8.4)	3.0 (76)	1.7 (0.39)
		67+45	186	28	0.37 (9.5)	3.8 (97)	0.6 (0.14)
		91+60	159	38	0.30 (7.7)	4.8 (122)	1.0 (0.23)
		98+50	296	10	0.79 (20.0)	4.0 (102)	3.8 (0.86)
	C11 Inbound	29+00	171	34	0.41 (10.5)	3.3 (84)	0.7 (0.15)
		74+00	316	7	0.83 (21.0)	4.4 (112)	3.2 (0.71)
		90+10	179	39	0.32 (8.0)	5.5 (140)	0.91 (0.20)
		100+69	285	8	0.72 (18.2)	4.0 (102)	2.9 (0.66)
	C31 Outbound	71+30	141	45	0.24 (6.0)	2.8 (71)	0.7 (0.17)
	C31 Inbound	39+07	156	45	0.25 (6.4)	3.3 (84)	1.4 (0.31)
		42+61	171	40	0.30 (7.5)	3.5 (89)	1.7 (0.39)
		50+50	122	55	0.16 (4.0)	4.3 (109)	0.6 (0.14)
		63+15	143	49	0.22 (5.6)	3.8 (97)	0.7 (0.16)
		66+80	173	38	0.33 (8.4)	6.0 (152)	1.3 (0.29)
		70+70	166	39	0.33 (8.3)	3.8 (97)	1.1 (0.25)
Rochester	Culver-Goodman	14+81	129	61	0.04 (1.0)	5.5 (140)	1.1 (0.25)
		62+00	181	43	0.32 (8.0)	4.0 (102)	1.8 (0.40)
Chicago	TARP	Muck Pile	187	41	0.24 (6.0)	5.6 (142)	2.1 (0.47)

TABLE 12.7 SUMMARY OF TBM OPERATING LEVELS, ROCK SUPPORT, AND ROCK UNIT AT THE HEADING DURING MUCK AT THE HEADING DURING MUCK SAMPLING

LOCATION	TUNNEL	STATION	AVERAGE CUTTER THRUST FACE kips (kN)	NUMBER OF CUTTERHEAD MOTORS	OPERATING AMPERAGE	ROCK SUPPORT	ROCK UNIT[a]
Buffalo	C11 Outbound	61+75	27.8 (124)	6	———	Bolts	40% Oatka
		67+45	11.4 (51)	6	Low Speed[b]	Steel Sets	40% Oatka
		91+60	24.0 (107)	6	———	Bolts/Straps	80% Oatka
		98+50	25.9 (115)	6	———	Bolts/Straps	60% Oatka
	C11 Inbound	29+00	22.8 (101)	6	———	Bolts	100% Oatka
		74+00	25.3 (113)	6	———	Bolts/Straps	40% Oatka
		90+10	17.7 (79)	6	———	Steel Sets	80% Oatka
		100+69	26.5 (118)	6	———	Bolts/Straps	50% Oatka
	C31 Outbound	71+30	21.0 (93)	6	150	Bolts	60% Oatka
	C31 Inbound	39+07	18.6 (83)	4	200	Steel Sets	50% Oatka
		42+61	17.2 (77)	5	200	Bolts	50% Oatka
		50+50	18.6 (83)	5	200	Bolts	75% Oatka
		63+15	16.5 (73)	4	175	Bolts	60% Oatka
		66+80	15.8 (70)	4	175	Bolts	60% Oatka
		70+70	18.6 (83)	4	170	Bolts	60% Oatka
Rochester	Culver-Goodman	14+81	26.3 (117)	6	175	Bolts/Straps	Lower Grimsby
		62+00	23.3 (104)	5	230	Bolts/Straps	Upper Grimsby
Chicago	TARP	Muck Pile	———	———	———	———	Romeo and Markgraf

[a]For the Buffalo Tunnels, only the percent of the tunnel face in the Oatka Member of the Bertie Formation is listed; the remainder of the rock face was composed of the Falkirk Member of the Bertie Formation.

[b]The lower of the two cutterhead rotation rates was used when mining in this area.

rates. The muck samples retrieved at Stations 74+00 and 100+69 in the C11 inbound tunnel and at Station 98+50 in the C11 outbound tunnel are characterized by relatively coarse particles and reflect the jointed nature of the in-situ rock at the sampling locations. The muck sample retrieved at Station 14+81 in the Culver-Goodman Tunnel is characterized by relatively fine particles and reflects both the worn condition of the cutters and poorly cemented nature of the rock at this location.

Figure 12.12 shows the muck gradations as plots of weight percentage passing a given sieve versus the sieve opening size. The 14 samples with similar characteristics fall within the shaded zone in the figure. The average cutter thrust associated with the gradations included in this zone varied from 11.4 kips (51 kN) to more than 27.8 kips (124 kN), and the average penetration rate varied from 0.20 to 0.42 in./rev. (5.1 to 10.7 mm/rev.). Within the ranges of thrust and penetration rate observed during sampling, there is no clear evidence that significant changes in particle size occur as a function of either operating thrust or penetration. Hence, the muck sample measurements do not corroborate the general trends in increased particle size with increased thrust and penetration proposed by several researchers (e.g., Hustrulid, 1972; Haller, Pattison, and Baldonado, 1973; Rad and Olson, 1974; Tarkoy and Hendron, 1975). However, size variations may have occurred at lower levels of thrust and penetration rates than those observed.

The muck gradation for the sample obtained at Station 74+00 in the C11 inbound tunnel is plotted in Figure 12.12. This sample was similar to the samples obtained at Station 100+69 in the same tunnel and at Station 98+50 in the C11 outbound tunnel. The rock units at the heading at all three locations were similar to those elsewhere in the tunnels but, at these locations, the average bedding frequency of the Falkirk Member was 4 to 6 in. (102 to 152 mm), and the beds of both the Falkirk and Oatka Members were heavily intersected by short, discontinuous joints. For such a rock mass condition, the rock pieces bounded by the discontinuities could be mined without extensive breakage or chipping, and the muck correspondingly had a low content of fines.

The two muck samples listed in Tables 12.6 and 12.7 which were obtained during the mining of the Grimsby Sandstone in Rochester are very different. The particle size distribution of the sample taken at

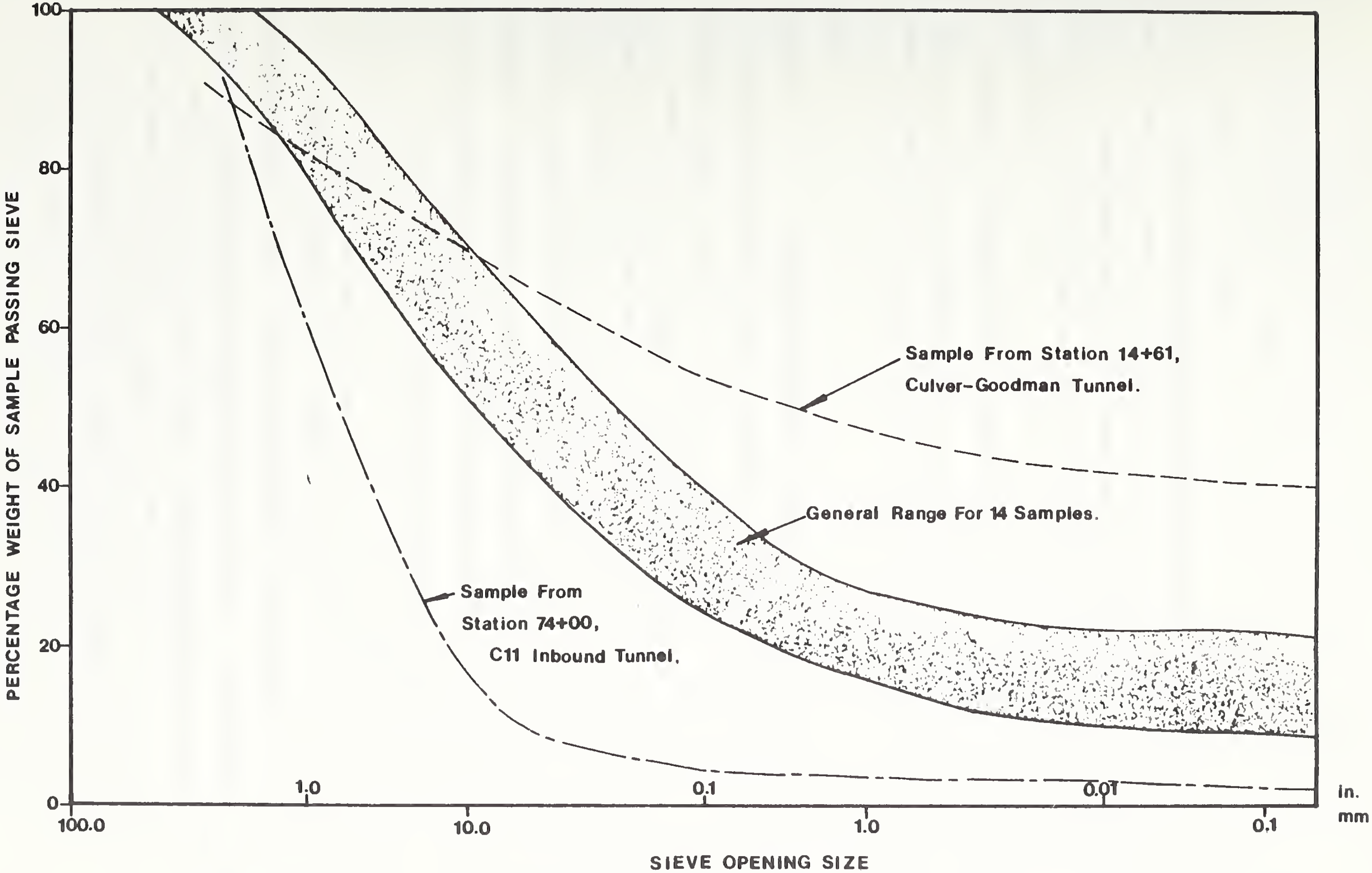


FIGURE 12.12 MUCK GRADATIONS FOR THE SAMPLES COLLECTED AT THE TUNNELS UNDER STUDY

Station 62+00 plots within the shaded zone in Figure 12.12, while the gradation of the sample taken at Station 14+81 is shown separately in the figure. The sample at Station 14+81 contained a very high percentage of fine material. The differences between these two gradations may be a reflection of the change in rock type at the heading. The lower Grimsby rock is a poorly cemented, coarse-grained sandstone which was easily crushed under cutter loads. The upper Grimsby rock is a well-cemented, medium to fine-grained sandstone which chipped much more readily than the lower Grimsby rock. However, the amount of cutter wear at each location varied substantially and may have strongly influenced the gradations. At Station 14+81, the cutters were completely worn, and most of them were replaced during the next shift, whereas the cutters on the TBM at Station 62+00 had been replaced the day before the sample was taken.

12.5 PERFORMANCE PREDICTION WITH ROCK FRACTURE PARAMETERS

Of the rock units included in this study, three were selected as most likely to have formed chips by the fracture mechanism illustrated in Figure 12.2. These rocks are the Reynales Limestone and the Romeo and Markgraf Members of the Joliet Formation. Each rock unit is a relatively isotropic, crystalline limestone or dolostone of low porosity. Individual beds are about 12 in. (305 mm) or greater in thickness and the spacing of other discontinuities is many times the magnitude of the bedding plane spacing. The muck produced while mining these rocks was observed to contain many large chips, sometimes greater than 6 in. (152 mm) in maximum dimension.

Fracture and chip formation is a process in which energy is consumed in the creation of new surface area. The fracture material property which is a measure of the energy required to create new surface area is G_{Ic}, alternatively defined as the critical energy release rate or as the critical crack driving force. It is logical to anticipate that, if chipping is a fracture process, then G_{Ic} should be a material property of importance which might be used in penetration rate prediction.

The value of G_{Ic} is calculated as follows:

$$G_{Ic} = \frac{K_{Ic}^2 (1 - \nu^2)}{E} \qquad (12.1)$$

where ν is Poisson's ratio and E is the modulus of elasticity, both evaluated from uniaxial compressive strength testing results. The fracture toughness, K_{Ic}, is a measure of stress intensity required to initiate and propagate a fracture and has the units of ksi $\sqrt{in.}$ (MPa $\sqrt{m}$).

Both K_{Ic} and G_{Ic} were evaluated by Cornell personnel (Gunsallus, 1983). Fracture toughness, K_{Ic}, tests were performed using the test system and specimen geometry described by Ingraffea, et al. (1982). The modulus, calculated from uniaxial compressive strength testing results, was taken as the tangent modulus at 50 percent failure stress, and Poisson's ratio was evaluated from the same test results and was calculated as the ratio of the slopes of the axial strain versus diametric strain curves.

Values for K_{Ic}, G_{Ic}, E, and ν are listed in Table 12.8 for the three rock units selected. Also included in this table are the average cutter thrusts, penetration rates, and field penetration indices, R_f, which represent optimum TBM performance in each of these units as discussed in Chapter 11. The penetration rates have been plotted against the K_{Ic} values in Figure 12.13 and against the G_{Ic} values in Figure 12.14. While there is no clear relationship in Figure 12.13, a linear trend is clear in Figure 12.14. Since there were only three data points, a linear regression was not performed, but it is evident that the critical energy release rate, G_{Ic}, might serve as a useful predictor of penetration rate. The R_f values have been plotted against K_{Ic} in Figure 12.15 and against G_{Ic} in Figure 12.16. As with the penetration rate plots, no trend is indicated in the K_{Ic} plot whereas a linear variation of R_f with G_{Ic} is apparent in Figure 12.16.

The average thrust per cutter associated with the three rock units was nearly constant, as shown in Table 12.8, and the torque capacities of the TBMs were proportionally similar. This implies that the wide

TABLE 12.8 MODULUS, POISSON'S RATIO, FRACTURE PROPERTIES, AND MACHINE PENETRATION INDICES FOR LIMESTONE AND DOLOSTONE

ROCK UNIT	ELASTIC MODULUS $E_{t_{50}}$ ksi (MPa) x 10^3	POISSON'S RATIO ν	FRACTURE TOUGHNESS K_{IC} ksi $\sqrt{In}$ (MPa $\sqrt{m}$)	CRITICAL ENERGY RELEASE RATE G_{IC} $\frac{lb}{in.}$ $(\frac{N}{M})$ or $\frac{in.\ lb}{in.^2}$ $(\frac{mN}{m^2})$	AVERAGE CUTTER THRUST kips (kN)	PENETRATION RATE in./rev. (mm/rev.)	FIELD PENETRATION INDEX R_f $^{kips}/_{in.}$ ($^{kN}/_{mm}$)
Reynales Limestone	7.1 (49)	0.23	1.88 (2.07)	0.47 (83)	31.8 (141)	0.27 (6.8)	119 (20.9)
Romeo Dolostone	13.1 (90)	0.22	2.25 (2.47)	0.37 (65)	32.6 (145)	0.32 (8.0)	103 (18.0)
Markgraf Dolostone	8.8 (61)	0.19	1.64 (1.80)	0.29 (51)	30.9 (137)	0.37 (9.3)	85 (14.8)

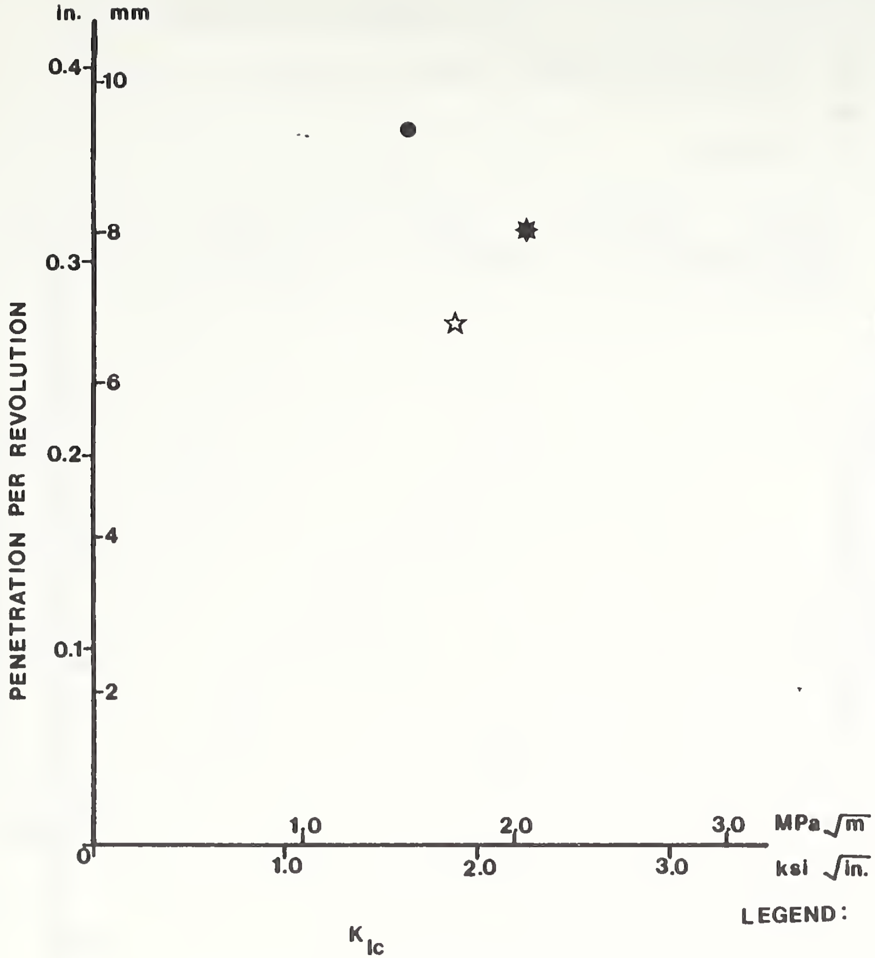


FIGURE 12.13 PLOT OF PENETRATION RATE VERSUS FRACTURE TOUGHNESS, K_{Ic}

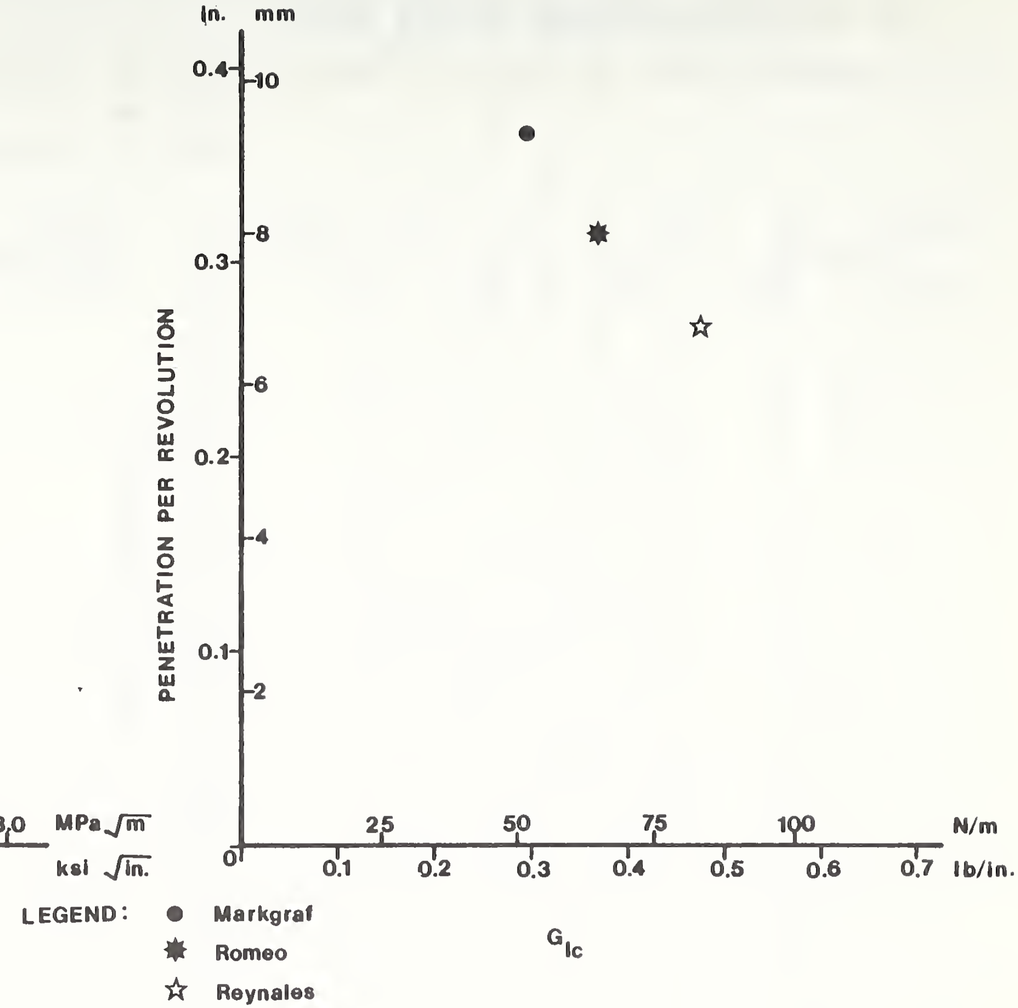
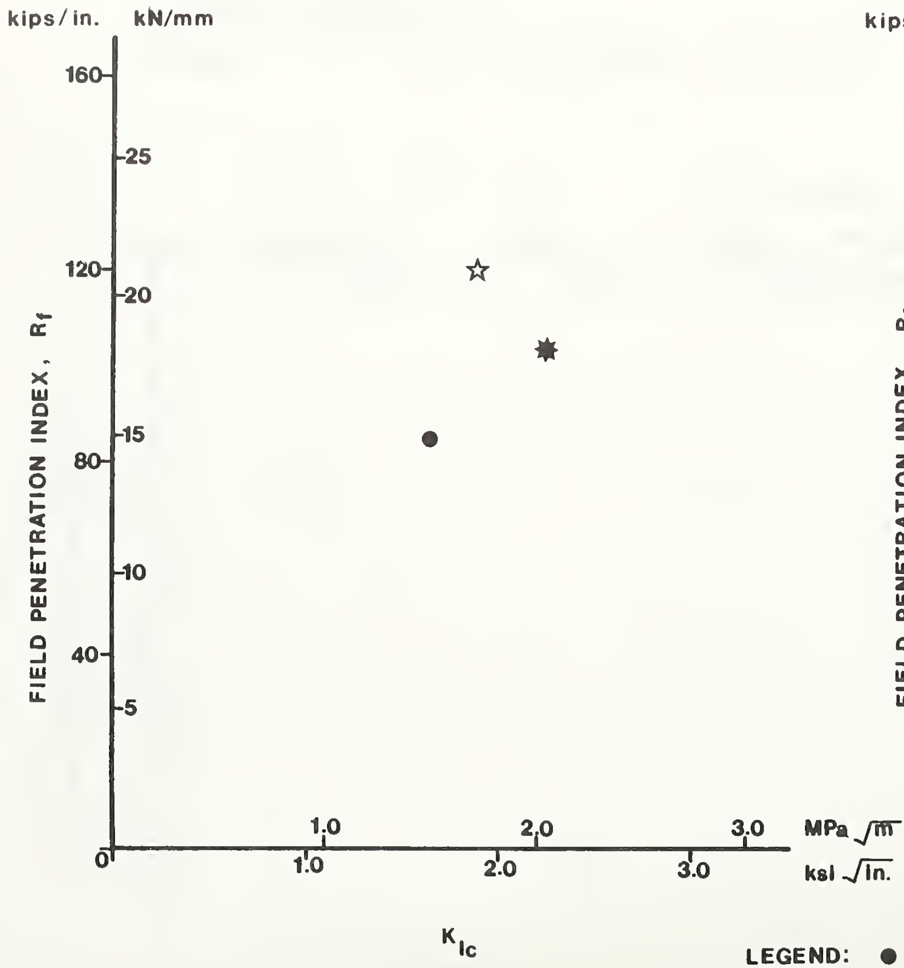
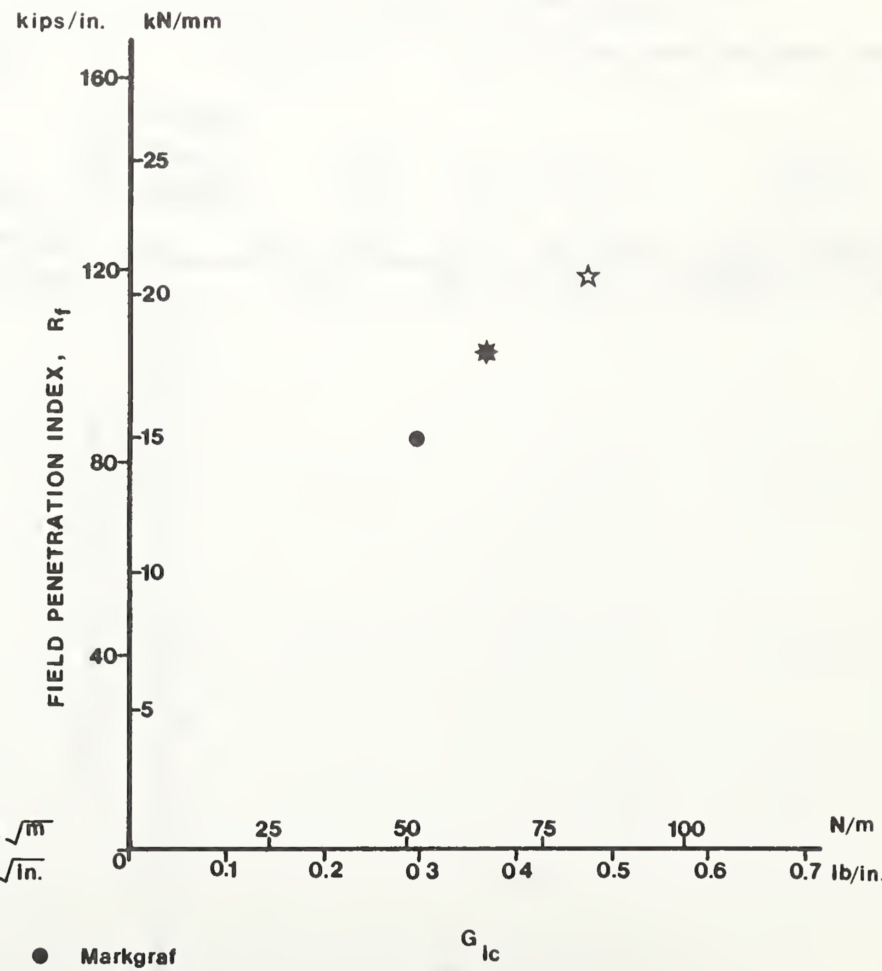


FIGURE 12.14 PLOT OF PENETRATION RATE VERSUS CRITICAL ENERGY RELEASE RATE, G_{Ic}





LEGEND: ● Markgraf
✸ Romeo
☆ Reynales

FIGURE 12.15 PLOT OF FIELD PENETRATION INDEX VERSUS FRACTURE TOUGHNESS, K_{Ic}

FIGURE 12.16 PLOT OF FIELD PENETRATION INDEX VERSUS CRITICAL ENERGY RELEASE RATE, G_{Ic}

range in penetration rate from 0.27 to 0.37 in./rev. (6.8 to 9.3 mm/rev.) must be a reflection of a variation in rock material properties. The relationships shown in Figure 12.14 and 12.16 indicate that G_{Ic}, which includes the effects of rock strength and stiffness, may be closely related to the penetration rate for brittle, relatively high strength rock.

As a property which reflects the energy required to propagate fractures in a given rock, G_{Ic} deserves further consideration. It should be cautioned that correlations between penetration rate and rock fracture indices are not likely to show clear trends for rock units which are thinly bedded or highly jointed. In these rocks, much of the surface area associated with chip formation may already exist by virtue of the discontinuities in the intact rock. However, rock fracture indices, such as G_{Ic}, may be suitable for hard, more massive, brittle materials.

CHAPTER 13

TBM VIBRATIONS AND EFFECTS ON STRUCTURES AND THE PUBLIC

13.1 INTRODUCTION

The four TBMs used to excavate the twin rock tunnels of the Buffalo LRRT provided an opportunity to examine the nature and extent of ground vibrations generated during construction. The urban setting close to the tunnels made it possible to evaluate the effects of TBM vibrations on a variety of residential and commercial processes.

13.2 MONITORING PROCESS

A Sprengnether Engineering Seismograph Model VS-1100 was used to monitor the TBM-induced ground vibrations. The Model VS-1100 is a portable seismograph that simultaneously records particle velocities in three mutually perpendicular directions on light-sensitive photographic paper. Internal filters provide a flat response between 2 and 200 Hertz (Hz). The VS-1100 and similar equipment were also used to monitor blast-induced vibrations on the Buffalo LRRT project.

TBM vibration monitoring was done throughout the excavation process. The seismograph was taken to the approximate location of the TBM and assembled. The seismometer was placed on the ground surface, leveled, and weighted with sand bags to prevent extraneous movement. The seismograph was then started and allowed to run for several minutes while the TBM was operating. Additionally, records of the monitoring location, weather conditions, ground surface at monitoring location, date and time of reading were written on each tape for future information.

Monitoring locations were selected so that the seismometer was placed between the TBM and the structure nearest the tunnel heading. The distance between the TBM and the seismometer varied so as to examine the attenuation characteristics of the TBM vibrations.

13.3 MONITORING RESULTS AND ANALYSIS

Seismograms for TBM-induced, ground borne vibrations were obtained from each of three mutually perpendicular axes: transverse (T), vertical (V), and logitudinal (L), oriented as shown in Figure 13.1. The seismograms were analyzed for the following parameters:

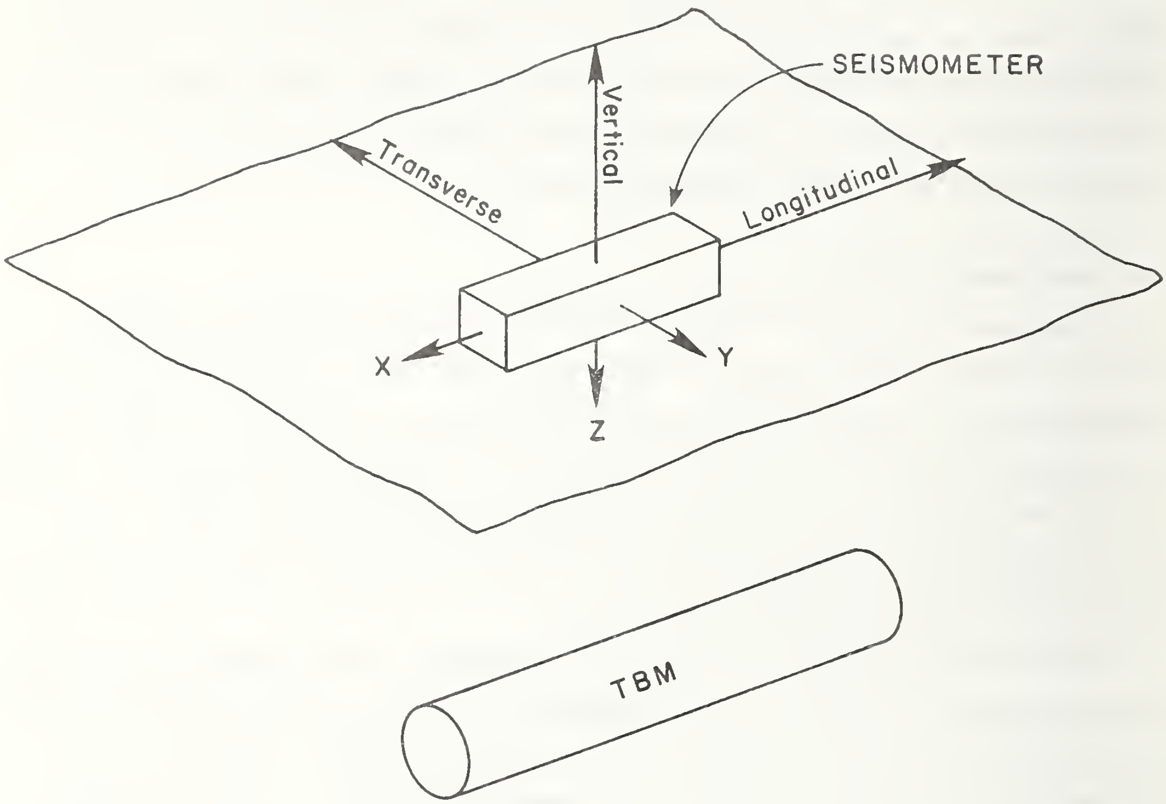


FIGURE 13.1 SEISMOGRAPH MONITORING AXES

1. Peak particle velocity (PPV) in inches per second (in./sec).
2. Frequency (f) of vibration at each of the peak particle velocities in Hz.
3. Acceleration of vibration at each of the peak particle velocities in units of standard gravity acceleration (g).

Accelerations were computed assuming sinusoidal wave forms and the following steady state approximation:

$$\text{Acceleration} = \frac{2\pi}{T_W} \frac{A}{S_V} \qquad (13.1)$$

where: T_W = Wave Period
A = Trace Amplitude
S_V = Seismograph Gain

Data points selected for this analysis represent values which were repeated throughout the monitoring record and, thus, are typical TBM-generated vibrations. It was observed that monitoring tapes were uniform sinusoidal traces over several minute periods. Hence, vibrations were assumed to be steady-state. Occasionally, random peak particle velocities were recorded which were larger than the values reported herein, but since they occurred infrequently, they were attributed to anomalies in ground conditions or unrelated vibrations and disregarded in the analysis.

Tables 13.1 through 13.4 summarize the monitoring results of each of the four TBMs used on the Buffalo LRRT project. These tables also contain information on the monitoring conditions, including distance between the TBM and the monitoring station and the thickness of overburden and rock cover over the tunnel crown. The distance represents the horizontal separation between the seismometer and the TBM cutterhead. Also presented in the tables is a resultant distance, based on the vertical and horizontal distances between the seismograph unit and the TBM cutterhead. Table 13.5 is a summary of the maximum PPV and the resultant distance for each TBM.

13.4 TBM VIBRATION ATTENUATION AND FREQUENCIES

An important aspect of ground borne vibration studies is the distance propagation equation or vibration attenuation rate. Blasting and other

TABLE 13.1 SUMMARY OF VIBRATION MONITORING RESULTS: C11 OUTBOUND TBM

DATE	DISTANCE TO TBM (ft)	COVER		PEAK PARTICLE VELOCITY AND FREQUENCY						ACCELERATION			RESULTANT DISTANCE TO TBM (ft)	REMARKS
		Overburden (ft)	Rock (ft)	Transverse in./sec	Hz	Vertical in./sec	Hz	Longitudinal in./sec	Hz	Transverse (g)	Vertical (g)	Longitudinal (g)		
7/08/80	110	6.5	39	.0046	63.7	.008	56.4	.0076	58.9	0.0048	0.0073	0.0067	119	
7/24/80	16	6.5	42	.022	57.1	.031	56.2	.025	51.3	0.020	0.028	0.021	51	
7/30/80	182	2.5	47	.011	46.7	.023	72.1	.018	53.8	0.0084	0.027	0.016	189	Monitored on top of manhole cover
8/18/80	24	4.5	48.5	.041	48.7	.067	65.5	.038	45.9	0.032	0.071	0.028	58	
10/08/80	32	4.0	43	.002	Too Small to Interpret	.004	78.8	.003	132.2	-	0.0051	0.0064	57	Data for rock drills TBM not operational
11/12/80	38	5.5	18	.037	52.2	.044	31.6	.021	48.0	0.031	0.023	0.016	45	
11/12/80	24	5.5	18	.027	32.3	.053	33.2	.040	34.4	0.014	0.029	0.022	34	
11/12/80	39	5.5	18	.035	44.7	.045	60.3	.029	61.3	0.025	0.044	0.029	46	
11/14/80	70	6.5	17	.012	49.4	.019	81.4	.016	56.4	0.0096	0.025	0.017	74	Monitored in basement of bank building

1 ft = 0.305 m; 1 in./sec = 25.4 mm/sec; 1 g = 32.2 ft/sec^2 = 9.8 m/sec^2

TABLE 13.2 SUMMARY OF VIBRATION MONITORING RESULTS: C11 OUTBOUND TBM

DATE	DISTANCE TO TBM (ft)	COVER		PEAK PARTICLE VELOCITY AND FREQUENCY						ACCELERATION			RESULTANT DISTANCE TO TBM (ft)	REMARKS
		Overburden (ft)	Rock (ft)	Transverse in./sec	Transverse Hz	Vertical in./sec	Vertical Hz	Longitudinal in./sec	Longitudinal Hz	Transverse (g)	Vertical (g)	Longitudinal (g)		
7/09/80	27	56.0	13.0	.045	54.2	.028	33.3	.040	50.0	0.039	0.015	0.033	74	
7/24/80	34	14.0	48.0	.018	44.1	.021	51.8	.027	55.0	0.013	0.018	0.024	71	
8/19/80	10	10.0	49.0	.052	44.3	.068	71.7	.044	47.5	0.037	0.079	0.034	60	
10/07/80	32	2.5	48.5	.017	58.3	.030	66.4	.026	52.7	0.016	0.032	0.022	60	
11/25/80	34	4.5	37.5	.024	32.2	.034	41.7	.016	32.8	0.013	0.023	0.0085	54	
12/03/80	14	2.5	9.0	.047	46.1	.076	76.4	.041	41.3	0.035	0.094	0.028	18	
12/03/80	20	2.5	9.0	.026	40.1	.069	69.8	.048	46.1	0.017	0.078	0.036	23	
12/19/80	16	5.5	16.0	.027	62.9	.079	28.9	.039	67.2	0.028	0.037	0.043	27	
12/22/80	60	6.0	14.0	.0095	130.6	.0097	155.8	.010	96.4	0.020	0.024	0.016	63	Monitored in basement of building
12/22/80	23	6.0	14.0	.020	69.6	.079	31.7	.033	67.2	0.023	0.041	0.036	30.5	

1 ft - 0.305 m; 1 in./sec = 25.4 mm/sec; 1 g = 32.2 ft/sec^2 = 9.8 m/sec^2

TABLE 13.3 SUMMARY OF VIBRATION MONITORING RESULTS: C31 OUTBOUND TBM

DATE	DISTANCE TO TBM (ft)	COVER		PEAK PARTICLE VELOCITY AND FREQUENCY						ACCELERATION			RESULTANT DISTANCE TO TBM (ft)	REMARKS
		Overburden (ft)	Rock (ft)	Transverse in./sec	Transverse Hz	Vertical in./sec	Vertical Hz	Longitudinal in./sec	Longitudinal Hz	Transverse (g)	Vertical (g)	Longitudinal (g)		
3/07/80	79	22.5	20.0	.023	43.5	.017	76.7	.024	51.5	0.016	0.021	0.019	90	
4/30/80	28	5.0	36.0	.015	57.8	.020	58.8	.011	55.5	0.012	0.014	0.011	50	
5/09/80	44	2.5	35.0	.014	56.5	.0073	61.2	.018	61.5	0.013	0.0072	0.018	58	
5/14/80	66	3.5	29.5	.066	46.5	.035	44.6	.024	60.8	0.05	0.025	0.024	74	Monitored on top of manhole cover
5/14/80	145	3.5	29.5	.0036	19.8	.0017	28.7	.0023	33.7	0.0012	0.0008	0.0013	149	Monitored on concrete bridge abutment
7/09/80	41	4.5	16.0	.041	44.6	.014	45.8	.076	43.4	0.03	0.01	0.054	46	
7/24/80	35	4.5	13.5	.025	58.6	.029	41.8	.028	92.1	0.024	0.02	0.042	39	
8/01/80	1	4.5	12.5	.052	44.2	.299	21.2	.061	30.2	0.037	0.103	0.03	17	Monitored at holethrough
8/01/80	0	4.5	12.0	.052	44.1	.266	27.2	.045	37.3	0.037	0.118	0 .027	15.5	Monitored at holethrough

1 ft = 0.305 m; 1 in./sec = 25.4 mm/sec; 1 g = 32.2 ft/sec^2 = 9.8 m/sec^2

TABLE 13.4 SUMMARY OF VIBRATION MONITORING RESULTS: C31 INBOUND TBM

DATE	DISTANCE TO TBM (ft)	COVER		PEAK PARTICLE VELOCITY AND FREQUENCY						ACCELERATION			RESULTANT DISTANCE TO TBM (ft)	REMARKS
		Overburden (ft)	Rock (ft)	Transverse in./sec	Hz	Vertical in./sec	Hz	Longitudinal in./sec	Hz	Transverse (g)	Vertical (g)	Longitudinal (g)		
7/10/80	62	10.5	34.5	.0063	66.7	.0024	62.2	.0044	57.5	0.0068	0.0024	0.0041	76.6	
7/24/80	68	5.0	36.0	.028	59.2	.02	30.2	.016	80.8	0.027	0.0098	0.021	79	
8/08/80	8	4.0	30.5	.012	60.5	.012	90.0	.011	71.1	0.012	0.018	0.013	36	Data for rock drills TBM not operational
10/03/80	30	3.0	21.0	.041	62.2	.036	58.3	.032	68.8	0.042	0.034	0.036	38	
10/07/80	43	3.0	19.0	.038	55.9	.024	48.2	.027	54.1	0.035	0.019	0.024	48	
10/08/80	18	3.5	18.0	.014	49.4	.081	44.4	.032	56.4	0.011	0.065	0.029	28	
10/09/80	119	4.0	18.0	.006	65.5	.005	59.4	.007	66.7	0.0064	0.0048	0.0075	121	
10/09/80	99	4.0	18.0	.015	53.1	.005	53.5	.016	50.7	0.013	0.0043	0.013	101	
10/09/80	79	4.0	18.0	.029	40.3	.009	43.7	.018	44.9	0.019	0.0064	0.013	82	
10/09/80	59	4.0	18.0	.032	47.8	.013	54.2	.041	33.9	0.025	0.011	0.023	63	
10/09/80	10	4.0	18.0	.034	39.2	.137	37.1	.042	47.6	0.022	0.083	0.033	24	
10/15/80	16	4.5	16.0	.068	57.2	.063	59.1	.043	70.9	0.063	0.061	0.049	26	

1 ft = 0.305 m; 1 in./sec = 25.4 mm/sec; 1 g = 32.2 ft/sec^2 = 9.8 m/sec^2

TABLE 13.5 MAXIMUM PEAK PARTICLE VELOCITY FOR BUFFALO LRRT TBMs

TBM	PEAK PARTICLE VELOCITY in./sec	mm/sec	RESULTANT DISTANCE ft.	m
C11-OB	0.067	1.70	58	17.7
C11-IB	0.079	2.01	30.5	9.3
C31-OB *	0.299	7.59	17	5.2
C31-IB	0.137	3.48	24	7.3

* Monitored at hole-through into Shaft D

sources of vibrations are commonly presented as the following power function between PPV and distance:

$$PPV = KD^{n'} \qquad (13.2)$$

where K = intercept at D = 1

d = distance

n'= attenuation rate

This relationship, for all TBM monitoring data, is presented in Figure 13.2 using the resultant distance. A least square fit was used and a reasonable coefficient of determination of 0.73 was obtained. Initially, data using the horizontal distance was used but these yielded a poorer fit, because several locations were nearly over the TBM cutterhead, and the small horizontal distances which would not indicate the proper attentuation characteristics. At close distances, the relatively large diameter of the TBM cutterhead as well as possible vibrations transmitted through the grippers, preclude assigning an accurate "point source" to the vibrations when monitoring. Best fit analyses using various overburden and rock thicknesses did not improve the correlation of PPV with distance.

It is apparent from Figure 13.2 that the measured TBM vibrations are typically small and attenuate appreciably with distance. Beyond 100 ft (30.5 m), PPVs are less than 0.01 in./sec (0.25 mm/sec). The figure also suggests there is no significant difference in vibration magnitudes among the four Buffalo LRRT TBMs.

Figure 13.2 also presents the typical range of blasting-induced groundborne vibrations on the Buffalo LRRT. The data include both shaft and tunnel blasting operations. In general, at a given distance, TBM-induced PPV

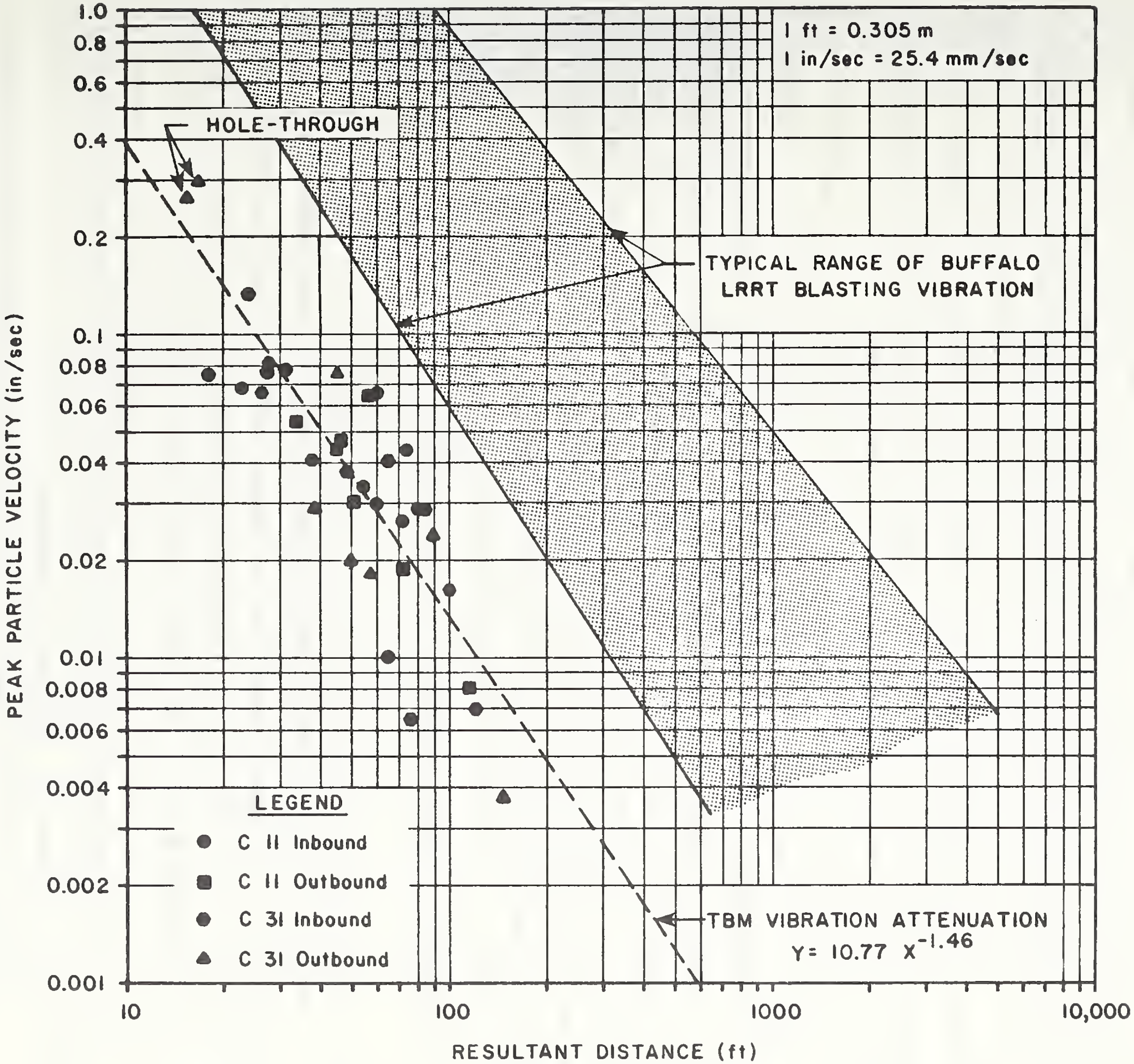


FIGURE 13.2 TBM VIBRATION ATTENUATION

vibrations are one-half to two orders of magnitude lower than the blasting.

The power function for the attenuation of vibration, i.e., energy dissipation with distance, varies from site to site. The exponent or attenuation rate has been found, based on monitoring of various construction equipment, to be about -1.5 (Wiss, 1981). The TBM vibration attenuation rate of -1.46 compares favorably. A study cited by New (1982) for a full-face TBM operating with drag picks in a mudstone reports an attenuation rate of -1.97, and PPVs at various distances are very similar to those measured from the Buffalo LRRT TBMs. Wiss (1981) presents PPV data for various construction equipment as a power function of distance; these are shown in Table 13.6 in comparison with TBM vibrations.

TBM frequency relationships were also studied but there was no apparent relationship between frequency and distance, velocity or acceleration. Generally, however, it is possible to conclude that the TBMs typically induced ground vibration frequencies of 30 to 90 Hz at PPV. Lower frequencies, 20 to 35 Hz, were observed for the C31 inbound machine when operating at lowered thrust during its holethrough. There were occasional frequencies greater than 80 Hz with very low amplitudes, that were observed when the TBMs were down but with the rock bolt drill operating.

Figure 13.3 presents TBM PPVs and corresponding frequencies. There is no apparent common frequency for a given TBM.

13.5 TBM VIBRATION EFFECTS ON ADJACENT STRUCTURES AND THE PUBLIC

The Buffalo LRRT TBMs passed through commercial and residential neighborhoods, including sensitive buildings such as churches, hospitals and schools. The majority of nearby structures are located within 50 to 75 ft(15.2 to 22.9 m) of the tunnel centerlines, with many within 20 ft (6.1 m). Despite these distances, fewer than one complaint per 1000 ft (304.8 m) of the tunnel length was registered, and no monetary settlements were paid by insurance carriers for damage.

Figure 13.3 also presents in the shaded area steady state vibration, frequency-related damage criteria, suggested by the Building Research Station (1955) and presented by Richart, et al (1970). The typical TBM PPV as a function of frequency, assuming then to be steady-state, are at least one-half an order of magnitude lower than the above criteria. As a comparison

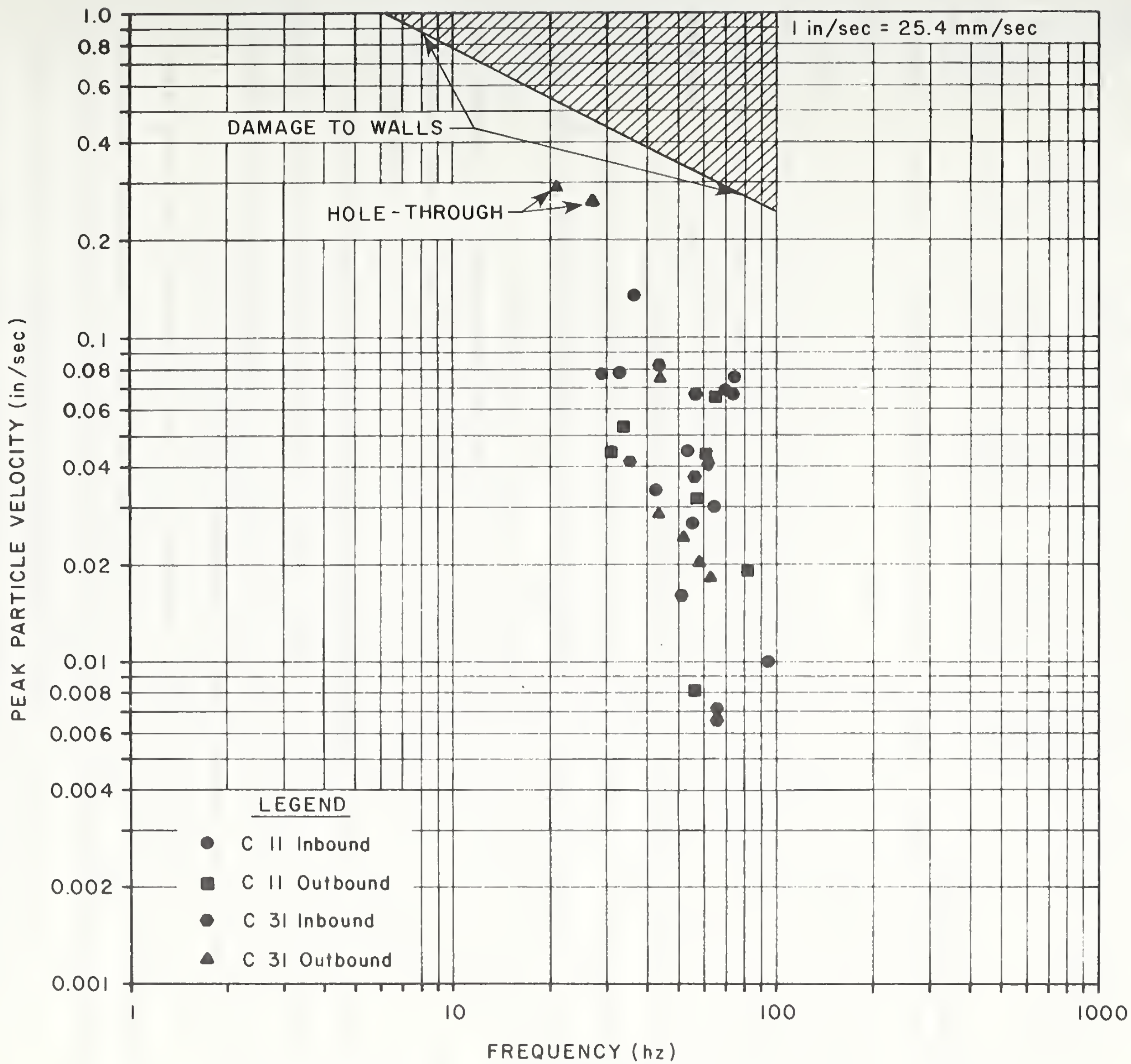


FIGURE 13.3 TBM VIBRATION MAGNITUDES AND FREQUENCIES

TABLE 13.6 TYPICAL PEAK PARTICLE VELOCITY INTENSITIES AT VARYING DISTANCES FROM CONSTRUCTION EQUIPMENT

EQUIPMENT	DISTANCE 10 ft (3 m)		50 ft (15.2 m)		100 ft (30.5 m)	
	in./sec	mm/sec	in./sec	mm/sec	in./sec	mm/sec
Jack Hammer*	0.15	3.8	0.013	0.3	0.004	0.1
Trucks*	0.25	6.4	0.025	0.6	0.010	0.2
TBM	0.40	10.2	0.035	0.9	0.014	0.4
Pavement Breaker* at 6 ft (1.8 m) drop	1.50	38.1	0.150	3.8	0.050	1.3

* From Wiss (1981)

to a generally accepted blasting vibration limit, the Bureau of Mines (Nicholls, et al, 1971) recommends a safe PPV level of 2.0 in./sec (50.8 mm/sec). Others suggest lower PPV values, such as 0.5 in./sec (12.5 mm/sec) for old residential structures in very poor condition (Chae, 1978). However, it appears that acceptable steady-state vibration limits are lower than transient vibration limits. Nevertheless, PPV observed from the TBMs are well below those normally accepted for damage prevention.

Buffalo LRRT TBM-induced vibration complaints were few. In most cases, it was the continuous nature of TBM vibrations, rather than their magnitude, which complainants found most distressing. An operator of a film-processing service, for example, complained that the TBM vibrations agitated his developing tanks for a sufficient time period to cause blurred photographs. In another case, a funeral director complained that the constant vibrations were particularly annoying during services.

There are probably several reasons for the relatively few complaints. Extensive shaft and starter tunnel blasting was done prior to TBM excavation and the public may have become desensitized. An additional reason may be that the TBM excavation does not involve a sound effect. On the other hand blasting involves a physchoacoustic effect, i.e., noise would be sufficient to be damaging since it was audibly disturbing. Blasting, a transient vibration, is noticeable at PPVs of 0.02 in./sec (0.51 mm/sec) and severe complaints are possible at 0.2 in./sec (5.08 mm/sec) (Hendron, 1976). However, steady-state vibrations are perceptible by humans at lower

PPVs. A classic study done by Reiher and Meister (1931) indicates that such vibrations can be detected at about a 0.01 in./sec (0.025 mm/sec) PPV. More recent studies have indicated that human response to a given steady state vibration level is a function of the frequency. Goldman and Von Gierke presents such a study in Chapter 44 of a book edited by Harris and Crede (1976). Figure 13.4 presents those results along with the TBM induced PPV and corresponding frequency. The figure shows that the vibrations are definitely detected and may be "unpleasant" to humans at close distances. However, the vibration magnitudes are well below what is considered as "intolerable." If one took a PPV of 0.01 in./sec (0.25 mm/sec) as being threshold regardless of frequency, TBM vibrations would probably not be felt more than 150 ft (45.7 m) away, when using the attenuation curve. Richart, et al (1970) presents tables of various disturbing forces as a function of PPV and frequency. The TBM vibrations and corresponding frequencies are most similar to those generated by light to heavy traffic within 50 ft (15.2 m) of the observer.

It should be noted that the monitoring data are somewhat limited and site-specific to the Buffalo LRRT which has relatively shallow rock cover. There may be considerable variations on other sites under different ground conditions. Nonetheless, this study could be used to estimate vibrations and effects on other TBM projects.

13.6 SUMMARY

TBM vibrations were measured at relatively close distances, about 150 ft (45.7 m) or less for peak particle velocity (PPV). A maximum PPV of 0.3 in./sec (7.6 mm/sec) was observed but more typically the range is 0.02 to 0.1 in./sec (0.51 to 1.54 mm/sec). The attenuation rate for PPV, a power function of distance, is similar to those found for various construction equipment. There were no significant differences in attenuation characteristics for various soil and rock depths. However, the characteristics should be considered site-specific.

There was no TBM-induced vibration damage on the Buffalo LRRT. Assuming vibrations induced by the TBMs are steady-state, the PPV are below any well-recognized damage criteria for most structures.

There were relatively few complaints from TBM vibrations on the Buffalo LRRT. Generally complaints were because of the steady-state

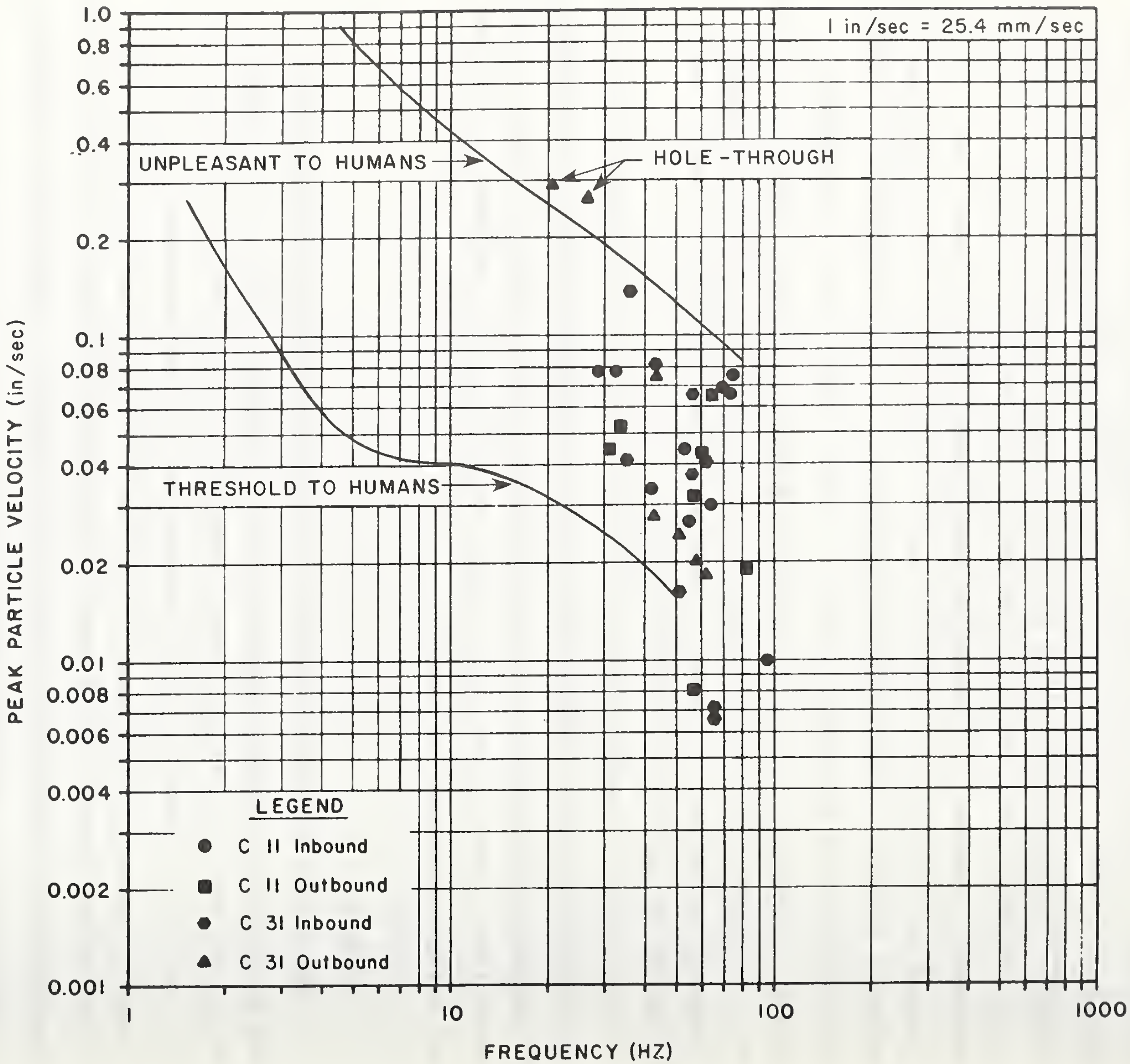


FIGURE 13.4 STEADY-STATE AND TBM VIBRATION EFFECTS ON HUMANS

nature of the vibrations. Where felt at close distances, TBM vibrations may be uncomfortable to humans. At distances greater than approximately 150 ft (45.7 m), vibrations will probably not be felt. The TBM vibration characteristics are similar to those of light to heavy traffic.

CHAPTER 14

CONCLUSIONS AND RECOMMENDATIONS

14.1 INTRODUCTION

Full-face tunnel boring machine (TBM) performance during the excavation of six tunnels has been considered in terms of utilization, penetration rate and cutter wear. Construction records for over 75,000 ft (22,860 m) of tunnel in sedimentary rock have been analyzed, and the results of the analyses hav been used as a data base to investigate trends and identify factors affecting performance. Seismograph records were reviewed to examine relative magnitudes and characteristics of vibrations from four TBMs. In this chapter, conclusions are made regarding estimates of TBM performance, downtime, adverse ground conditions, penetration rate, cutter wear, muck gradation, the use of fracture mechanics for TBM evaluation and design and ground vibrations from TBMs. Conclusions regarding the planning and use of four TBMs for the Buffalo LRRT are also presented.

Recommendations are made for future research, including further study of cutter wear, the application of fracture mechanics, the interaction among torque, thrust, penetration rate, and TBM vibration characteristics. Recommendations are also made for observations and record keeping on other TBM projects.

14.2 TBM PLANNING FOR THE BUFFALO LRRT PROJECT

A decision to use four separate TBMs to drive twin tubes on two separate line contracts were necessary to help meet a five-year system-wide construction schedule by releasing the line section work sites early for the subsequent station contracts. Alternate construction schedules, avoiding the specification of two TBMs per contract were considered but led to significant increases in line completion dates and costs.

Contract documents allowed a modification of diameter size to permit a wider range of existing TBMs that could be used. One contractor ordered two new TBMs that were delivered several months late. This time loss was offset by excavation time that was 1 to 2 months shorter than that originally planned. Total contract duration was 10 percent greater than that originally planned. The second contractor reconditioned two existing TBM's, completed excavation slightly ahead of schedule. On this contract, actual contract duration was equal to the planned duration.

The successful construction time for both contracts indicated that the use of multiple TBMs was a prudent decision. Furthermore, the time analysis illustrates that either new or used TBMs are effective in a tunneling project, provided proper planning is done.

14.3 ESTIMATES OF TBM PERFORMANCE

A summary of the average utilizations, penetration rates, and advance rates for the six tunnels under study shows little variation. For example, the mean advance rate for all the tunnels was 2.7 ft/hr (0.82 m/hr) with a standard deviation of approximately 10 percent of the mean value. In a similar manner, the mean utilization and penetration rates were 33.2 percent and 0.29 in./rev. (7.3 mm/rev.), respectively, each with a standard deviation of approximately 10 percent of the mean. This consistency in performance is surprising because of the differences in ground conditions, machines, construction planning, and contractor practices among the jobs. The average advance rates observed in this study are approximately 30 percent greater than estimated during construction planning for the Buffalo LRRT System (Ball, et al., 1981). The average TBM availability for all six jobs was 86.7 percent, with a standard deviation of about 5 percent of the mean. Overall, no significant difference can be detected between the availability of new as opposed to old machines.

Average values of these performance parameters can provide a broad evaluation of TBM use, but cannot supply adequate detail for many of the judgments needed on a specific job. There is ample evidence in this study of significant variations in delay from different ground conditions, mechanical difficulties and construction approaches. If the results of the case histories are used to plan future projects, it would be prudent to emphasize the differences between the tunnels as well as the similarities. Although average values contribute to a general appreciation of the construction process, site-specific characteristics must be emphasized and analyzed with great care.

14.4 DOWNTIME

In this work, the total shift time, expressed as a percentage for each project, was analyzed as the sum of the machine utilization and the downtime percentages caused by: 1) maintenance and repair of the TBM, 2) repair of the backup system including trailing gear, rail, and shaft and surface mucking equipment, and 3) ground conditions. In addition, a general category was used to cover downtime causes that could not be recorded on a consistent basis or were difficult to associate with a specific category of the TBM system. This additional category includes delays from shift changes, delivering supplies to the heading, recycling the stroke of the forward thrust cylinders, contract restrictions, and delays that were planned to coincide with the interception of adits and shafts. A table and pie chart showing the breakdown of total shift time were included for each of the tunnels studied, and a summary of a shift-by-shift analysis of the downtime for each project is provided in Appendix B.

On the average, the percentages of the total shift time associated with delay from TBM maintenance and repair, backup system repair, and ground conditions were 21, 20, and 14 percent, respectively. Delays caused by additonal sources accounted for an average 13 percent of the total shift time, while approximately 32 percent of the total shift time was used for TBM excavation. If the average times associated with ground conditions and cutter changes are combined, they represent roughly 19 percent of the shift time.

Consideration of average values in each category helps to develop a general picture of the relative importance of each downtime cause, but judgments based solely on averages can be very misleading. For example, the delays associated with cutter changes for the Culver-Goodman Tunnel amounted to 16.5 percent of the total shift time as compared with an average of 5.2 percent for all the tunnels. This discrepancy is primarily related to the Culver-Goodman tunneling conditions within the Grimsby Sandstone. In a similar manner, the delays associated with ground conditions for the Chicago TARP tunnel accounted for 6.3 percent of the total shift time as opposed to an average of 14.2 percent for all the tunnels studied. This discrepancy is related to the in-situ structure of the dolostone in the TARP tunnel, which was thickly bedded and did not have weathered zones that were intercepted by tunneling.

A detailed comparison of the downtimes for specific equipment, operation, and geologic factors can show aspects of TBM construction that are particularly vulnerable to delay. Table 14.1 summarizes the downtime

TABLE 14.1 SUMMARY OF THE RELATIVE IMPORTANCE OF DOWNTIME CATEGORIES AND COMMON REASONS FOR DOWNTIME

COMBINED CATEGORY	INDIVIDUAL DOWNTOWN CATEGORY	IMPORTANCE RATING[a] Minor	Moderate	Significant	Major	REASONS FOR DOWNTIME
TBM Maintenence and Repair	General Maintenance and Inspection					
	-General Maintenance		X			minor repairs, add hydraulic and lube oil to reservoirs
	-Cutterhead Check		X			cutter and cutterhead inspection
	-Lube Oil System	X				oil pump repair and replecement
	Hydraulic System		X			hose and valve replacement, repair cylinder pins
	Cutterhead Motors		X			overheeting, eir clutch repeir, tighten bolts, replace motors
	Electrical System		X			tripped breekers, wiring and transformer repair
	TBM Conveyor		X			repair of tears, bearing and belt replacement
	Cutter Change				X	abrasive wear, bearing failure, worn hub, disc slippage
Backup System Maintenance and Repair	Power Supply	X				loss of supply
	Air, Water, and Electric Lines					air, water, and electric line extension
	-new equipment	X				
	-reconditioned equipment		X			
	Ventiletion System					instell fan line and booster fans, reroute fan line exit
	-new equipment	X				
	-reconditioned equipment		X			
	Survey	X				laser reeets, target adjustments and repairs
	Car Pass			X		drive chain and bearing replacement, muck accumulation on trailing floor and in muck cars
	Tripper	X				muck accumulation in mechanism, repair flashing on deflector
	Trailing Conveyor(s)		X			repair of tears; motor, roller, belt, and beering replacement
	Train Delay			X		travel timee, logistics of working with single tunnel track, slow muck removal in shaft
	Shaft/Portal Operations					
	-Crane		X			cable changes
	-Rollover	X				muck accumulation in mechanism, motor repeir
	-Conveyors in Shafts		X			belt, motor, and bearing repair and replecement
	-Bucket Elevetor				X	affected by shaft flooding
	-Conveyors outside of Tunnel	X				
	Laying Rails	X				lay and repair rails
	Derailments		X			uneven track, obstructions in tunnel, muck accumulations on track, switching errors
Ground Conditions	Steel Set Installation				X	install steel sets and lagging
	Bolts/Straps/Channels		X			install bolts, straps, channels, and lagging
	Bolt Drill Repair					
	-new equipment	X				hose replacement
	-reconditioned equipment		X			hose, rotation motor, and drill replacement
	Scaling/Muck Jams		X			most muck jams at hopper between cutterhead and main beam
	Gripper Difficulty	X				install cribbing at springline overbreak, gripper pad slippage
	Clearance	X				ventilation system components hang up on steel sets
Other	Thrust Cylinder Restroke			X		
	Probe Hole			X		

[a] Importance Ratings correspond to the following downtime percentages: minor, 0 to 1%; moderate, 1 to 3%; significant, 3 to 5%; major, more than 5%.

causes identified for the projects under study. Individual downtime categories are grouped into four combined categories including: 1) TBM maintenance and repair, 2) backup system maintenance and repair, 3) ground conditions, and 4) other downtime causes including recycling of thrust cylinders and probing for methane. Each source of downtime in Table 14.1 is rated with regard to its relative importance, and the classes of importance used in the table correspond to the following downtime percentages of the total shift time: 0 to 1 percent, minor; 1 to 3 percent, moderate; 3 to 5 percent, significant; more than 5 percent, major. Importance ratings noted in this table were established without including downtime because of job specific conditions such as the extensive cutterhead structural repairs performed on the Chicage TARP project, and the frequent cutter changes required during excavation of the Grimsby Sandstone in the Culver-Goodman Tunnel. Therefore, each importance rating listed in Table 14.1 reflects the amount of downtime which could be expected in each category on future jobs. This table also includes a summary of the most common reasons for downtime in each category.

Individual sources of delay under TBM maintenance and repair were of minor or moderate importance with the exception of cutter change. It is of interest to note that the impact of equipment failure was frequently more severe on other aspects of TBM performance than on downtime. Although difficulties with cutterhead motors caused only moderate delays, they nevertheless affected the penetration rate. In aggregate, their influence on penetration rate may have resulted in a significant increase in construction time. More than 30 percent of the tunneled distance on all the projects was excavated with less than the full complement of functioning motors.

In the category of backup system delays, car pass systems required significantly more repair time than tripper systems. Train delays were significant or major on each project. An average of 42 percent of all shifts were affected by train delays, and for 17 percent of all shifts, the delays were 1 hour or more. Derailments downtime was moderate, and more than 50 percent of all derailments occurred on the trailing floor. Delays caused by installation of ventilation system components and air, water and electric lines were of moderate importance on projects using reconditioned equipment, but were of only minor importance in the tunnels excavated by new equipment.

Delays associated with steel sets installed manually were important. The amount of downtime varied but was not directly related to the number of sets installed. Some of the variation may be related to differences in machine design. For example, some TBMs were equipped with a crane mounted beneath the main beam which was used to move and position steel segments during installation. Rock bolts, straps, and channel sections were the most common support installed, and delays associated with their installation were moderate. Larger amounts of repair time were required for reconditioned than for new rock bolt drills. The frequency of occurrence and the location of muck jams varied, but the most common muck jam location was at the hopper between the cutterhead and the TBM conveyor located inside the main beam. Muck jams were most frequent on the reconditioned TBMs. The category of water inflow is not included in Table 14.1 because the amount of associated downtime was strongly affected by site-specific conditions involving geology and construction planning. Water inflow was, however, a major source of downtime for three of the tunnels included in this study.

Modifications in the design of several excavation system components and maintenance procedures could help to reduce delays. The following modifications are recommended:

1) The car pass mechanism should be protected from the effects of muck accumulations.
2) Provisions should be made to avoid residual accumulations of muck in muck cars.
3) Equipment should be installed which can speed the transport and positioning of steel segments.
4) Provisions should be made to allow fan line segments and additional lengths of utility service lines to be installed during TBM operation without extended periods of downtime.
5) Equipment should be installed which can aid in the removal of scaled rock and muck accumulations in the tunnel invert beneath the TBM.
6) The hopper between the cutterhead and main beam should be redesigned to allow easier access for the removal of muck blockages and to reduce the frequency of muck jam occurrence.

Delays associated with mechanical repairs varied with each project, and generalizations about the relative efficiency of new and reconditioned equipment cannot be made. Rather, it is clear that effective use of a TBM depends closely on the maintenance program and experience of the contractor.

14.5 ADVERSE GROUND CONDITIONS

The six tunnels included in this study were driven through sedimentary rock for which bed thicknesses varied from less than 1.0 in. (25.4 mm) in shale to more than 5 ft (1.5 m) in the more massive sandstone and dolostone units. In general, rock mass changes coincided with stratigraphic changes, and bedding planes were the most frequent discontinuities. The spacings of vertical and inclined joint sets were generally much larger than bedding plane spacings. Much of the initial support installed in these tunnels was used to stabilize rock wedges which were bounded by bedding planes and vertical discontinuities. Crown instability was influenced by both the joint frequency and geometry of the rock blocks formed by joint intersections. The loosening of rock in the crown and consequent danger of fallout were pronounced in zones with two, approximately mutually orthogonal, vertical joint sets.

Adverse ground conditions were usually associated with closely jointed and/or weathered rock. Extra rock support, including bolts, straps , channels, and steel sets, was often installed. For the tunnels in this study, however, only about 50 percent of the total downtime associated with ground conditions was required for support installation. Additional problems encountered when mining in areas of closely jointed and/or weathered rock included: 1) cutterhead and TBM conveyor damage from blocky muck, 2) difficulty of establishing contact between gripper pads and intact rock in areas of springline overbreak, 3) ventilation system components snagging on steel supports, 4) loss of grade in areas of weak invert rock or loss of line in areas of springline overbreak, and 5) scaling of loose rock and removal of rock slabs which fell on the TBM shields.

For the tunnels in this study, a relationship between joint spacing and penetration rate could not be established. In tunnel sections where discontinuities were closely spaced, penetration rates were often affected by intentional reductions in operating thrust. In addition, penetration rates were often difficult to determine reliably because of frequent stopping and machine clock inaccuracies. In these areas, advance rates generally decreased, and any improvement in penetration rate was more than offset by decreased utilization.

14.6 PENETRATION RATE

The average penetration rate for each tunnel was generally within 10 percent of the overall average of all the tunnels. However, penetration rates showed much greater variation within each project. Construction records from the Culver-Goodman Tunnel were used to investigate several sources of variation, including mechanical difficulties, contractor practice, machine operating levels of thrust and torque, cutter wear, and rock lithology and structure. Comparisons of machine performance on different projects can best be made if an optimum condition of maximum thrust and torque can be identified. Similarly, predictions of TBM performance should take into account the interaction of thrust, torque, rock type and machine design in the prediction of penetration rates for future projects.

14.6.1 Influence of Machine Operation on Penetration Rate

Penetration rates calculated as overall averages for a given rock unit will be lower than those representing optimum TBM performance at maximum levels of thrust and torque. Average rates determined from data screened to discount shifts with mechanical and support difficulties on the Culver-Goodman Tunnel were generally 10 to 14 percent higher than those calculated on the basis of all observation within a given rock unit. Penetration rates were consistently higher in the Culver-Goodman Tunnel for a particular operator and crew, but the differences between operators and crews were not large, being on average within 5 percent of the highest rates.

It is recommended that correlations between penetration rate and rock index properties be developed for penetration rates under conditions of maximum thrust and torque. In this way, the influence of mechanical and support difficulties are discounted so that the correlations reflect the rock-tool interaction as defined principally by rock properties. Correlations were developed in this work on the basis of penetration rates chosen to remove shifts in which one or more cutterhead motors were not functioning, cutters were changed, steel sets were erected, and obvious mechanical problems were encountered. In addition, shifts with less than 1 hour clock time were discounted to reduce the likelihood of erroneous time measurements. This selection process should provide an adequate basis for analyzing data at other tunnels. In general, penetration rates determined as overall averages for a given rock unit are likely to be 10 to 20 percent less than those corresponding to conditions of maximum torque and thrust, although larger reductions may occur in the event of significant mechanical difficulties.

14.6.2 Influence of Cutter Wear on Penetration Rate

There is no clear evidence that cutter wear had a significant effect on penetration rate for the Buffalo LRRT and Chicago TARP tunnels. An effect of wear on penetration rate could only be discerned in the Culver-Goodman Tunnel for tunneling in sandstone under conditions of exceptionally high abrasive wear. Measurements during tunneling in the Grimsby Sandstone at the Culver-Goodman Tunnel showed that penetration rates were not influenced until approximately 1.5 in. (38 mm) of cutter disc diameter had been worn from the gage cutters. With this amount of wear, the penetration rate either decreased at a constant thrust or remained approximately the same at 10 percent increase in thrust. In general, cutter wear should not be regarded as a significant influence on penetration rate for the types and spacings of cutters represented in this study.

14.6.3 Correlations Between Penetration Rates and Rock Index Properties

In this study, correlations were investigated between rock index properties and penetration rates, where penetration rate is defined as the TBM advance or penetration per cutterhead revolution. Using the penetration per revolution reduces the influence of cutterhead rotation speed on the results.

Statistically, the most significant correlations between penetration rate and rock index properties were found for both abrasion hardness and a linear combination of abrasion and rebound hardness. The coefficient of determination is approximately 0.60 for correlation equations including these indices. This indicates that 60 percent of the data variation can be explained by a linear regression of penetration rate against abrasion hardness or a linear combination of this parameter and rebound hardness. In contrast, correlations between penetration rate and either uniaxial compressive strength or point load index result in coefficients of determination of 0.04 and 0.18, respectively. These results indicate that there were very poor correlations between penetration rate and these parameters.

Correlations between rock index properties and penetration rate normalized with respect to thrust show substantial improvements in statistical significance relative to those based solely on penetration rate. A convenient index for relating penetration rate to thrust is the field penetration index, R_f, defined as the ratio of the average thrust per cutter to the penetration rate. Linear regressions of R_f against total hardness or a linear combination of abrasion and rebound hardness result in a coefficient of determination of approximately 0.85. These correlations show the highest degree of statistical significance compared to correlations with many single index properties, including rebound hardness, abrasion hardness, uniaxial compressive strength, point load index and Brazilian tensile strength.

Table 14.2 includes a list of rock index tests performed for this study and summarizes the degrees of correlation between index properties and penetration rates and field penetration indices. The degree of correlations for each set of parameters is noted as being low, moderate, or high, corresponding to coefficients of determination of less than 0.50, between 0.50 and 0.80, and greater than 0.80, respectively. The statistical significance of correlations on the basis of hardness indices is greater than that of other index properties, and R_f predictions can be made with greater statistical significance than penetration rate predictions. Overall, best predictions are possible when total hardness or a linear combination of rebound and abrasion hardness is used to predict R_f, the field penetration index.

TABLE 14.2 SUMMARY OF DEGREES OF CORRELATION BETWEEN ROCK INDEX PROPERTIES AND PENETRATION RATES AND FIELD PENETRATION INDICES

ROCK INDEX PROPERTY	CORRELATION WITH PENETRATION RATE			CORRELATION WITH FIELD PENETRATION INDEX		
	Low[a]	Moderate[b]	High[c]	Low[a]	Moderate[b]	High[c]
Hardness Indices						
Rebound	X				X	
Abrasion		X			X	
Total		X				X
Linear Combination of Rebound and Abrasion		X				X
Uniaxial Compressive Strength	X			X		
Point Load Index	X			X		
Brazilian Tensile Strength	X			X		

[a] coefficient of determination less than 0.50.

[b] coefficient of determination between 0.50 and 0.80.

[c] coefficient of determination greater than 0.80.

14.6.4 Relationships Among Penetration Rate, Thrust, and Rolling Force

The relationships among penetration rate, thrust and rolling force for different rock types may be thought of as a critical surface in three dimensions. The cutting process can be analyzed through the use of a combined plot of the penetration rate versus average thrust and rolling force per cutter. In this work, a combined plot is used to analyze the TBM boring records for the Culver-Goodman Tunnel where the TBM was driven from the Maplewood Shale to the Reynales Limestone. The model provides a rational basis for explaining variations in thrust and torque as a function of rock type. This model can be helpful for evaluating machine performance in a variety of ground conditions and for judging how changes in machine design will affect penetration rates.

Test data from Snowdon, Ryley and Temporal (1982) and boring records from the Culver-Goodman Tunnel indicate that the average rolling force per cutter varies curvilinearly with respect to the average thrust per cutter for a variety of rock types. In general, the rolling force increases at a faster rate than the thrust. At an average rolling force per cutter of 5 to 6 kips (22 to 27 kN), which is consistent with the level of maximum torque provided by the TBMs in this study, the ratio of the average rolling force to average thrust per cutter varies from approximately 0.15 to 0.25, depending on the rock type. On a conservative basis, this ratio may be estimated as 0.25 for rock with low to medium strength, such as a shale or porous sandstone, and as 0.20 for rock with relatively high strength such as a crystalline limestone or well indurated sandstone. These ratios can be used to estimate the average thrust consistent with optimum machine use. The estimated thrust can be used to evaluate the penetration rate by means of the correlations developed for total hardness or linear combinations or abrasion and rebound hardness.

14.7 CUTTER WEAR

Table 14.3 includes the rolling distances, number of changes per 1,000 ft (305 m) of tunnel, and cutter clock life for cutters in center, face, and gage positions for three lithologic groups. The numbers in this table are average values including the changes made at all cutter positions in each group. The Grimsby Sandstone, Maplewood Shale, and Reynales Limestone were encountered in the Culver-Goodman Tunnel, and the Romeo and Markgraf Dolostones were encountered in the Chicago TARP tunnel. Cutter changes in the Grimsby were made over approximately 6,000 ft (1,929 m) of tunnel. The Maplewood Shale and Reynales Limestone units are less than 20 ft (6.1 m) thick and are grouped together in Table 14.3. Cutter changes in these two formations were made over approximately 5,500 ft (1,676 m) of tunnel. Changes in the Romeo and Markgraf Members of the Joliet Formation were made over approximately 22,000 ft (6,706 m) of tunnel. Cutter changes for the Buffalo LRRT tunnels are not included in the table because of incomplete records, relatively few replacements, and the possibility that several of the changes were made because of easy face access when the TBMs intersected adits or shafts.

Average center cutter rolling distances were similar in all rock units included in Table 14.3. This consistency is surprising because of the variety in lithology and the variation of uniaxial compressive strength from about 10 ksi (69 MPa) for the Maplewood Shale to about 34 ksi (234 MPa) for the Romeo Dolostone. Center cutter rolling distances are far less sensitive to rock type than are face and gage cutter distances. Rolling distances of gage cutters were less than that for face cutters in the abrasive Grimsby Sandstone, and gage and face cutter rolling distances were comparable in the less abrasive shale, limestone and dolostone units. Face and gage cutter rolling distances were from 5 to 30 times greater than center cutter rolling distances.

In each of the rock units included in Table 14.3, gage cutters were changed more often than face cutters. In the Grimsby Sandstone, the replacement rate for gage cutters was 2.4 times higher than for face cutters. In the shale, limestone and dolostone units, the replacement rate for gage cutters was from 1.7 to 1.8 times higher than for face cutters. For cutters in face and gage positions, the rate of replacement was highest in the Grimsby Sandstone, where the replacement rate was from 5.1 to 6.7 times higher than in the Romeo and Markgraf Dolostones. In the Grimsby Sandstone, Maplewood Shale and Reynales Limestone, center cutters

TABLE 14.3 SUMMARY OF CUTTER WEAR FOR CUTTER POSITION GROUPS

MEASURE OF CUTTER WEAR	ROCK UNITS	CUTTER POSITION GROUP		
		CENTER	FACE	GAGE
Rolling Distance ft(m) x 10^6	Grimsby Sandstone	0.17 (0.05)	1.05 (0.32)	0.80 (0.24)
	Maplewood Shale and Reynales Limestone	0.21 (0.06)	1.93 (0.59)	1.99 (0.61)
	Romeo and Markgraf Dolostones	0.15 (0.05)	4.66 (1.42)	4.82 (1.47)
Number of Changes per 1,000 ft (305 m) of Tunnel per Cutter Position	Grimsby Sandstone	0.86	1.27	3.03
	Maplewood Shale and Reynales Limestone	0.61	0.69	1.16
	Romeo and Markgraf Dolostone	0.87	0.25	0.45
Cutter Clock Life (hours)	Grimsby Sandstone	178	119	51
	Maplewood Shale and Reynales Limestone	238	216	122
	Romeo and Markgraf Dolostones	150	509	270

were changed less often than cutters in other positions, and in the Romeo and Markgraf Dolostones, center cutters were changed more frequently than cutters in other positions.

Abrasive wear was investigated using records of gage cutter disc diameter measurements made on the Culver-Goodman project. The rate of abrasive wear was highest in the Grimsby Sandstone and lowest in the Lower Sodus and Williamson Shales. Of the rock properties investigated in this work, rock abrasiveness, A_R, showed a higher degree of correlation with the rate of cutter disc wear than did uniaxial compressive strength. Little correlation was found between cutter wear and the percent of minerals harder than steel.

14.8 MUCK GRADATION

The particle size distribution of the muck samples collected in this study showed little sensitivity to operating thrust levels and penetration rates. Most of the gradations were similar, with the exceptions of muck produced by extremely worn cutters and muck produced while mining closely jointed rock. Of the parameters used to describe the gradations, the percent of material passing the Number 4 sieve, the coarseness index, and the number of large chips per unit weight were the most sensitive measures of gradation variation.

14.9 FRACTURE MECHANICS APPLICATIONS

The predictive ability of a theoretical model for rock-tool interaction depends on the relevance of the assumed chip formation mechanism to the actual rock cutting process, and on the rock properties and loading geometry employed in the model. A fracture mechanics approach which should be of use in modeling the process of chip formation was proposed in this work, and the results of an investigation into the use of fracture material properties for the empirical prediction of TBM performance were reported. Penetration rates and field penetration indices were correlated with the fracture toughness, K_{Ic}, and critical energy release rate, G_{Ic}, for three relatively brittle and high strength rock units. The penetration rate and field penetration index showed a linear variation with respect to G_{Ic}, and no trend between K_{Ic} and performance could be identified. For massive, brittle materials, it appears that

G_{Ic}, which includes the effects of rock strength and stiffness, shows potential for use in penetration rate and R_f prediction.

14.10 TBM VIBRATIONS

Vibrations from the four Buffalo LRRT TBMs were monitored with seismographs at distances of 150 ft. (45.7 m) or less. The measured maximum peak particle velocity (PPV) of the motions, in any axis, is 0.3 in./sec (7.6 mm/sec). Generally, more than 90 percent of the PPVs are below 0.1 in./sec (2.54 mm/sec). Comparison with blasting vibrations indicates that TBM vibrations are one-half to two orders of magnitude lower. The attentuation rate is similar to those of heavy construction equipment.

Public complaints were fewer than one complaint per 1,000 ft (304.8 m) of tunnel length. No monetary settlements were paid by insurance carriers for damages despite the fact that some structures were within 20 ft of the tunnel. Comparison with existing vibration criterion indicates that the TBM vibrations are well below damage levels. TBM vibrations are similar to those induced by light to heavy traffic.

14.11 RECOMMENDATIONS FOR FUTURE RESEARCH

Research in the following areas is recommended:

1) Additional performance and hardness index property data should be obtained to refine and extend the correlations between rock hardness indices and penetration rate and field penetration indix. In particular, data pertaining to abrasion and rebound hardness are important for developing improved prediction capabilities in hard to very hard rocks such as quartzite, granite, and gneiss.

2) Linear cutter tests should be performed on additional rocks to cover a wide variety of strength, stiffness and porosity. The test results can be used to verify the curvilinear trends of rolling force versus thrust and of penetration rate versus thrust and rolling force. The results can also be used to investigate the changes in these trends as a function of rock type and machine design. Korbin (1979) pointed out that the relative stiffness of rock mass and machine can affect the

response of rock to disc cutter indentation. The importance of relative stiffness can be evaluated from the results of linear cutter tests performed with cutting machines of varying stiffness.

3) Cutter replacement records that include the reason for each replacement and identification of cutter hubs should be obtained. Replacement rates associated with bearing deterioration and abrasive wear should be evaluated separately. Relationships between each replacement rate and rock type, operating thrust, cutter rolling distance, and cutterhead position should be investigated so that the predominant type of wear can be identified for different conditions of geology, thrust and torque.

4) Excavation efficiency is closely linked with chip formation, and muck gradation analysis can potentially be of use in evaluating relative machine efficiencies in different rocks. For such an evaluation, muck sampling should be performed as machine operating levels are systematically varied. Changes in machine efficiency should be reflected in gradation parameters such as percent of material passing the Number 4 sieve, coarseness index, and the size, shape, and number of large chips.

5) The usefulness of a fracture mechanics approach to rock-tool interaction and chip formation should be investigated with available finite element fracture propagation computer codes. Important rock material properties, and loading and tool geometries can be identified, and the sensitivity of the chipping process to variation of these parameters can be investigated. With this information, laboratory tests to be used in TBM performance prediction can be effectively designed.

6) Additional fracture material property testing should be performed, not only to investigate the potential for empirical correlations with TBM performance, but also to understand how these properties are related to the many rock types encountered in practice.

7) Additional monitoring for TBM vibrations should be done for more varied geologic conditions and formations. Detailed observations should be kept for vibration effects on sensitive structures.

14.12 RECOMMENDATIONS FOR FUTURE OBSERVATIONS AND RECORDS

Table 14.4 summarizes the items and the amount of detail that should be included in a shift report. The information in this table does not require significant amounts of time to gather. Several items should be recorded for each thrust cylinder restroke. These include thrust cylinder pressure, the number of functioning cutterhead motors and operating amperage, and machine clock time at the start or end of a restroke. The cutter wear record should be complete, as detailed in the table. It is recommended that shift events be recorded with reference to machine clock time, since this reference is not subject to errors caused by incorrect tunnel stations and survey inaccuracies.

TABLE 14.4 ITEMS TO BE INCLUDED IN A SHIFT REPORT

ITEM	REQUIRED DETAIL
Shift Identification	Sequential numbering of shifts, day, date, shift time, and duration.
Tunnel Station	Stations at start and end of shift.
Operating Hydraulic Pressures	For each thrust cylinder restroke, record the thrust cylinder pressure and gripper cylinder pressure (not required if preset).
Cutterhead Motor Information	For each thrust cylinder restroke, record the number of functioning motors and operating amperage.
Hydraulic Fluid and Lube Oil Temperatures	At least once during each shift, more often if possible.
Machine Clock Time	Clock time at start and end of shift and at each thrust cylinder restroke.
Downtime	Downtimes should be listed discretely and may be recorded on a shift time grid. Downtimes should be explained. Time increments of 10 to 15 minutes are usually adequate.
Cutter Wear Record	For each cutter change, record: 1) cutter position number 2) cutter hub identification 3) type of disc on cutter 4) description of reason for replacement 5) station and clock time of replacement.
TBM Laser Target Readings	Record front and rear target readings at start and end of shift, as a minimum.
Rock Support	Type and location of rock support installed. Description of overbreak and problems related to rock quality.
Personnel	Number of personnel in tunnel and name of operator or other identification of the crew required when contractor uses rotating shifts.

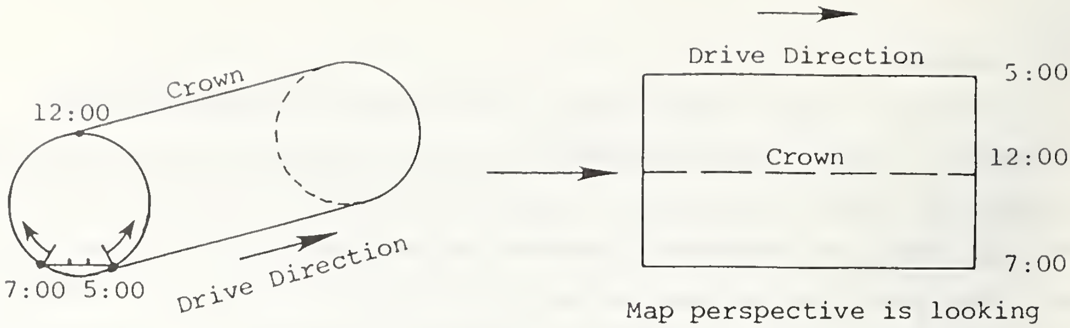
APPENDIX A TUNNEL GEOLOGY AND ROCK SUPPORT

A.1 GENERAL

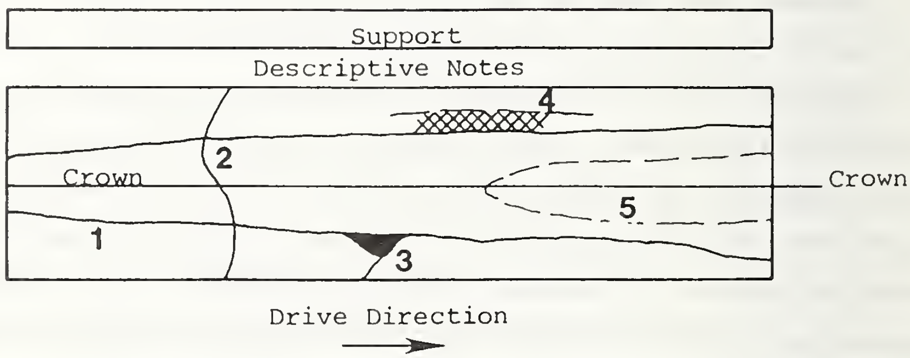
As part of this study, maps of the tunnel wall geology were prepared. Mapping was performed for the Buffalo LRRT and Culver-Goodman tunnels by research personnel. Maps for Contract 73-287-2H of the Chicago TARP were prepared by Kiefer Engineering, Inc., and made available for this study by the Metropolitan Sanitary District of Greater Chicago. All maps are drawn with consistent notation to a common scale of 1:3000 along the tunnel alignment and approximately 1:1000 around the tunnel circumference. Figure A.1 shows a three dimensional view of the mapping perspective with keys for the geology, support and description notations.

The maps were prepared as if the tunnel wall surface, as viewed from inside the tunnel, were peeled back and laid flat. It is common for tunnelers to use the hours on a clock face to describe positions on a tunnel cross-section. This notation is shown in Figure A.1. At the time of mapping, the tunnel inverts were covered with muck and the rail tracks were still in position so that the tunnel walls were mapped around an angle of 300 degrees from approximately 7 to 5 o'clock. This perspective allows discontinuities which continue across the crown to be shown as continuous features on the maps. All maps are oriented so that the tunnel drive direction is from left to right on each map strip. The crown centerline, directly overhead of an observer standing inside the tunnel, is shown in the middle of each map. The lower half of each map corresponds to the tunnel wall facing a viewer standing with his right side toward the drive direction.

Stratigraphic contacts are shown as dark lines in the maps. The most prominent bedding planes are shown as dashed lines. In general, bedding is referred to as thin if bed spacing is less than 1.0 ft (0.3 m), as medium if bed spacing is between 1.0 and 3.0 ft (0.3 and 0.9 m), and as thick if bed spacing is more than 3.0 ft(0.9 m). Traces of joints other than bedding planes are indicated by continuous lines. The strike and dip of joints can be determined from the shape and extent of joint traces. Overbreak areas and zones of fractured, weathered rock are also included.



Map perspective is looking up at crown with drive direction to viewer's right



Legend

1 Stratigraphic Contact or Prominent Bedding Plane Trace

2 Joint (not bedding plane) Trace

3 Overbreak

4 Fractured and/or Weathered Rock

5 Bedding Plane Trace

FIGURE A.1 DIAGRAM OF MAP CONSTRUCTION AND ROCK STRUCTURE IDENTIFICATION

Rock support is described in a strip above each map. Support notations are explained in Table A.1. The locations of various bolt patterns and sections supported with steel sets are shown.

Water inflow and the presence of gypsum and fresh fractures are indicated in the maps and explained in Figure A.1. Water inflow is noted with reference to its origin above or below the tunnel springline.

The geologic maps for each tunnel under study are presented in each of the following sections of this appendix together with brief discussions of the geology and initial rock support.

A.2 TUNNEL WALL GEOLOGY AND SUPPORT FOR THE C11 OUTBOUND TUNNEL

Figures A.2 and A.3 include tunnel wall geologic maps, descriptions and support notations for the outbound tunnel of Contract C11. The tunnel walls were mapped from Station 10+00, near the start of the drive, to Station 107+03 where the tunnel intersects Work Shaft D at Amherst Station. The tunnel was bored mostly in the Falkirk and Oatka Members of the Bertie Formation. The Cammillus Shale was observed in only one area near Station 32+00, where bedded gypsum was present in the tunnel invert.

The C11 outbound tunnel was driven along a trend of approximately N 40 degrees E. Bedding plane dip and tunnel grade vary throughout the C11 outbound tunnel so that the amounts of Falkirk and Oatka Members in the rock face change along the tunnel alignment. Tunneling started with nearly equal amounts of Falkirk and Oatka at the heading. Since the initial grade was more shallow than the rock dip, the amount of Oatka in the face gradually increased to Station 33+00. From this point to Station 43+00, the tunnel was driven at a grade steeper than the dip of the rock. Accordingly, the heading was excavated with increasing amounts of Falkirk Member in the face. Tunneling was predominantly in the Falkirk Member until approximately Station 80+00 where the excavation began a downhill grade. The amount of the Falkirk Member in the face decreased until Station 90+00. From this point until the end of the tunnel, excavation was performed with 60 to 70 percent of the heading in the Oatka Member.

Joints in the Oatka Member from Stations 20+00 to 35+00 are vertical with a strike of N 60 degrees to 80 degrees E. These joints intersect the

TABLE A.1 SYMBOLS AND NOMENCLATURE FOR TUNNEL SUPPORTS, AND DESCRIPTIVE NOTES

ITEM	SYMBOL	DESCRIPTION
Patterned Support	n/m nS/m nC/m R	n=number of rock bolts in pattern m=longitudinal spacing of bolt pattern S=straps across crown C=steel channel sections across crown R=steel sets
Other Support - not patterned	B	isolated rock bolts
	M	steel mesh and bolts
	S	straps and bolts
Descriptive Notes	∇	water inflow from rock above springline or from bolt holes
	▼	water inflow from rock below springline
	*	gypsum present in rock near invert
	•	fresh fracture, possibly associated with the TBM

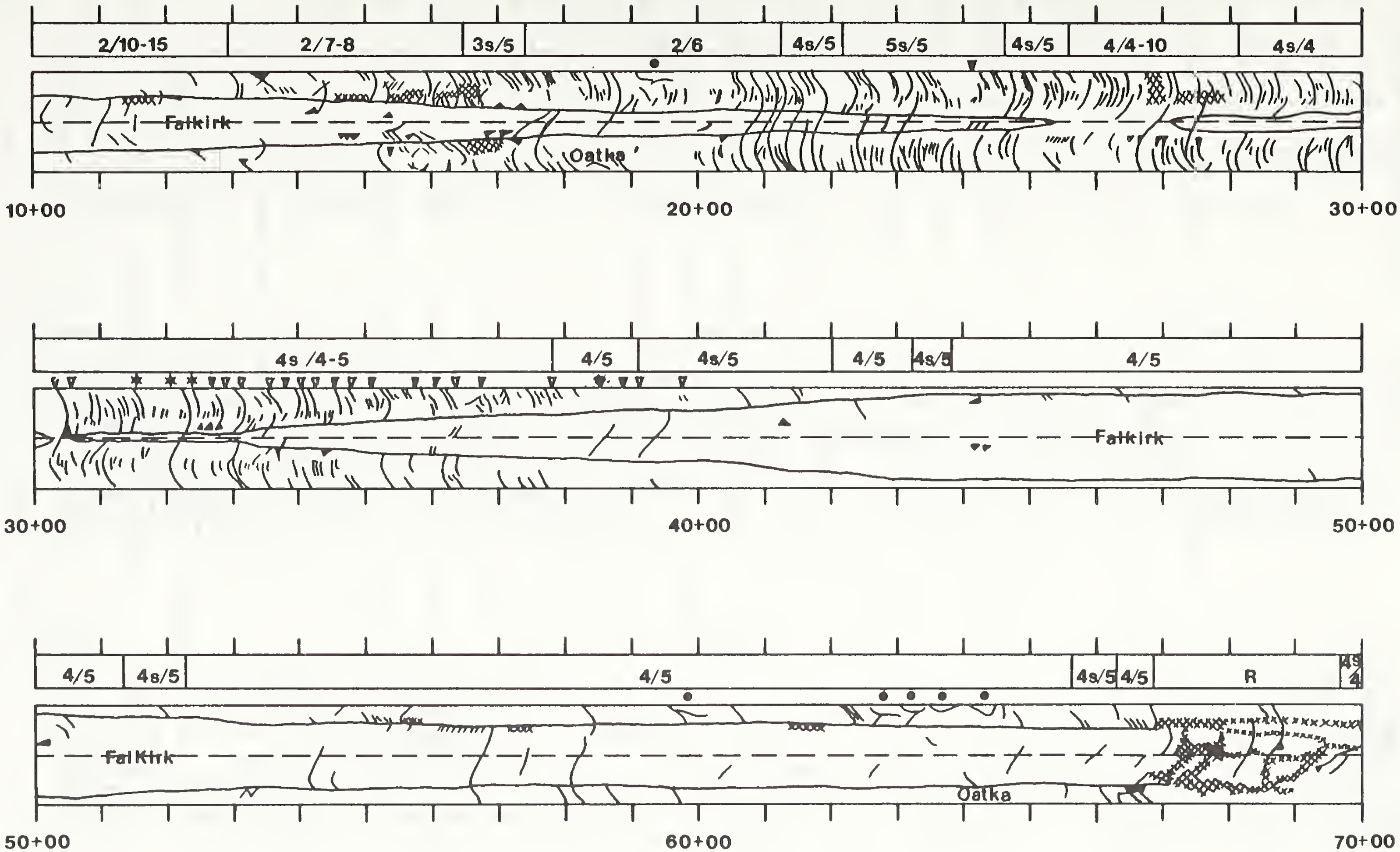


FIGURE A.2 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE C11 OUTBOUND TUNNEL, STATIONS 10+00 TO 70+00

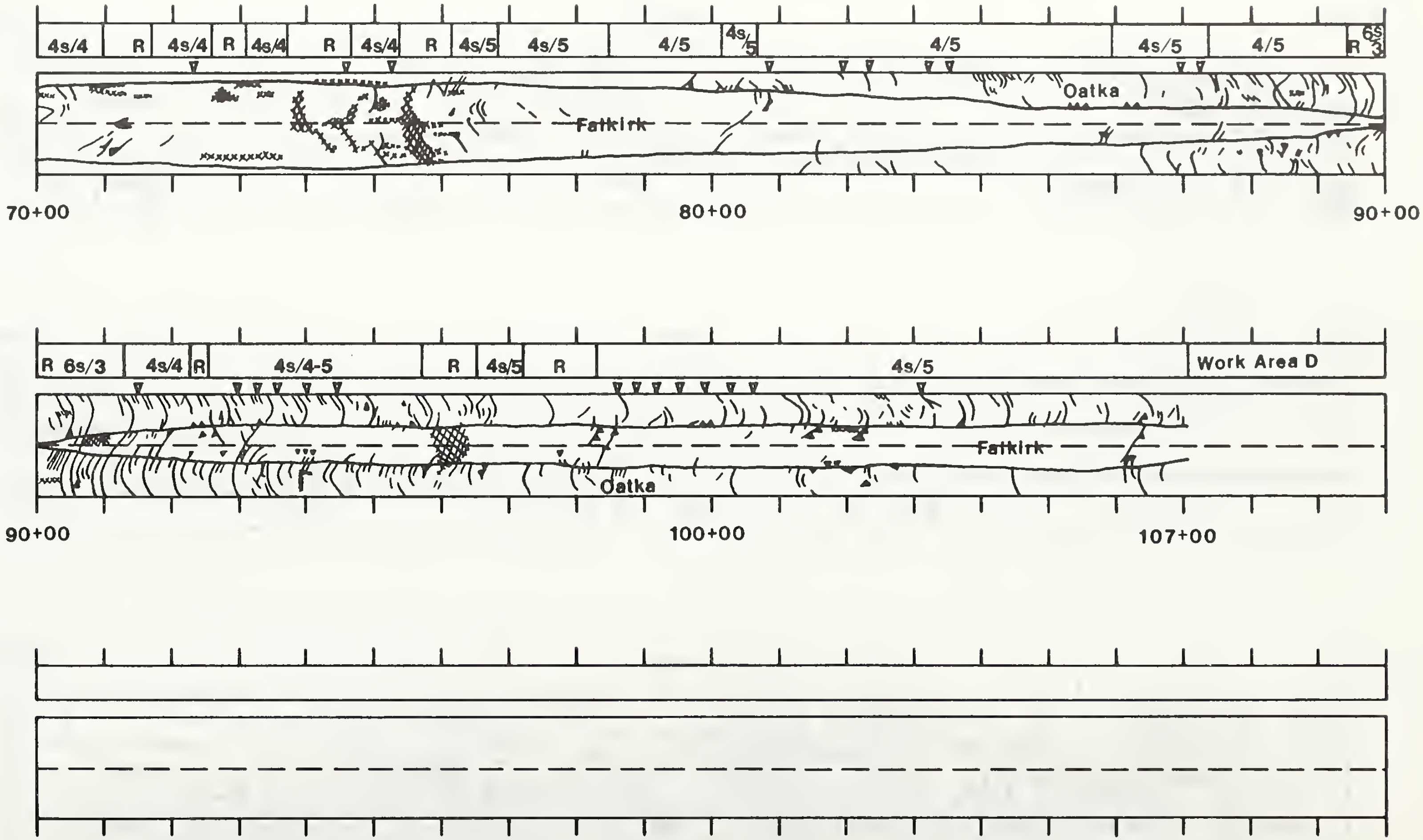


FIGURE A.3 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE C11 OUTBOUND TUNNEL, STATIONS 70+00 TO 107+03

tunnel axis at 20 degrees to 40 degrees. Many of the joints are discontinuous with an average spacing of 20 to 30 ft (6 to 9 m). They are noticeably discontinuous at the Falkirk/Oatka contact. The joints in the Oatka are commonly tight, smooth and often healed with calcite. The rate of water inflow near Station 24+00 was 10 to 30 gal/min (38 to 114 liters/min). Water infiltration at Station 30+00 and between Stations 33+00 and 40+00 originated from rock bolt holes. Flow from the bolt holes was often 10 to 20 gal/min (38 to 76 liters/min) immediately after the holes were drilled, decreasing to less than 2 gal/min (7.6 liters/min) by the end of the shift.

The rock is very sparsely jointed from Station 35+00 to 66+00. From Station 66+00 to 76+00, however, joints in the Falkirk are weathered with extensive solutioning along some vertical joints. Bedding planes are weathered so that seams of clay and shale fragments, 3.0 to 6.0 in. (76 to 152 mm) thick, are often present at bedding contacts. The rock is blocky in places, and overbreak at springline was as large as 6.0 ft (1.8 m). Local inflows in this area were about 1.0 to 3.0 gal/min (4 to 11 liters/min), mainly from bolt holes. Most of the vertical joints strike at N 60 degrees to 80 degrees E, but toward the end of the section several N 10 degrees W vertical joints are present. Two sets of lower angle joints, striking N 20 degrees W with a dip of 30 degrees NE and striking N 70 degrees W with a dip of 20 degrees to 30 degrees SW, were identified between Stations 66+00 and 72+00, but their frequency and continuity could not be determined due to the presence of ribs and lagging.

From Station 76+00 to 86+00 few joints are present, and overbreak is minimal. Joint frequency increases between Station 86+00 and 96+00. The most common joints are vertical and oriented at about N 70 degrees E. Many of the bedding planes have been weathered. Vertical joints, particularly in the Falkirk, had been solutioned and weathered. Rock above springline is blocky in places, and crown overbreak is locally as large as 1.5 ft (0.5 m). Water infiltration in this area was primarily from rock bolt holes and from bedding planes above springline.

From Station 96+00 to 107+03, most of the joints are discontinuous and were observed in the Oatka Member. The rock cover in this section of the tunnel is shallow, and the Falkirk Member is more thinly bedded than elsewhere in the tunnel. Many of the bedding planes are locally enlarged due to weathering. Water infiltration was primarily from these zones.

Most rock bolts were 8 ft (2.4 m) long, steel reinforcing bars with a diameter of 0.88 in. (22 mm). All bolts were resin grouted along their full length. The bolts were placed at a 4 to 5 ft (1.2 to 1.5 m) circumferential spacing for the four bolt pattern in the tunnel crown, and at a 3 to 4 ft (0.9 to 1.2 m) spacing for the six bolt pattern. A fifth bolt was added to the four bolt pattern in places. These bolts were 6 ft (1.8 m) long and were installed vertically into the crown centerline with a jack leg drill mounted on the trailing gear. Steel sets were W 6x25 section segments. From Station 89+52 to 91+28 five segments of steel were used to construct the circular ribs. At other stations, four-segment steel sets were erected. Straps were 10 in. (254 mm) wide sections of 14 gage steel. Most straps were 8 to 13 ft (2.4 to 4.0 m) long and were placed across the tunnel crown.

A.3 TUNNEL WALL GEOLOGY AND SUPPORT FOR THE C11 INBOUND TUNNEL

Figures A.4 and A.5 include tunnel wall geologic maps, descriptions, and support notations for the inbound tunnel of Contract C11. The tunnel walls were mapped from Station 10+00 near the start of the drive to Station 107-05 where the tunnel intersects the shaft at Work Area D. The tunnel was bored mostly in the Falkirk and Oatka Members of the Bertie Formation. The Camillus Shale was identified in only one area between Stations 31+00 and 32+00, where bedded gypsum was present in the rock at the tunnel invert.

The C11 inbound tunnel was driven along a trend identical with that of the C11 outbound tunnel. The stratigraphic and discontinuity description included in Section A.2 for the outbound tunnel is also valid as a description of the rock encountered in the inbound tunnel. Two minor differences in the geology for each of these tunnels, however, can be noted. The first difference is that the inbound rock between Stations 66+00 and 76+00 was less extensively weathered than was the rock at comparable locations in the outbound tunnel. The second difference is that water inflow from the tunnel crown and bolt holes into the outbound tunnel was significantly larger than water inflow into the inbound tunnel.

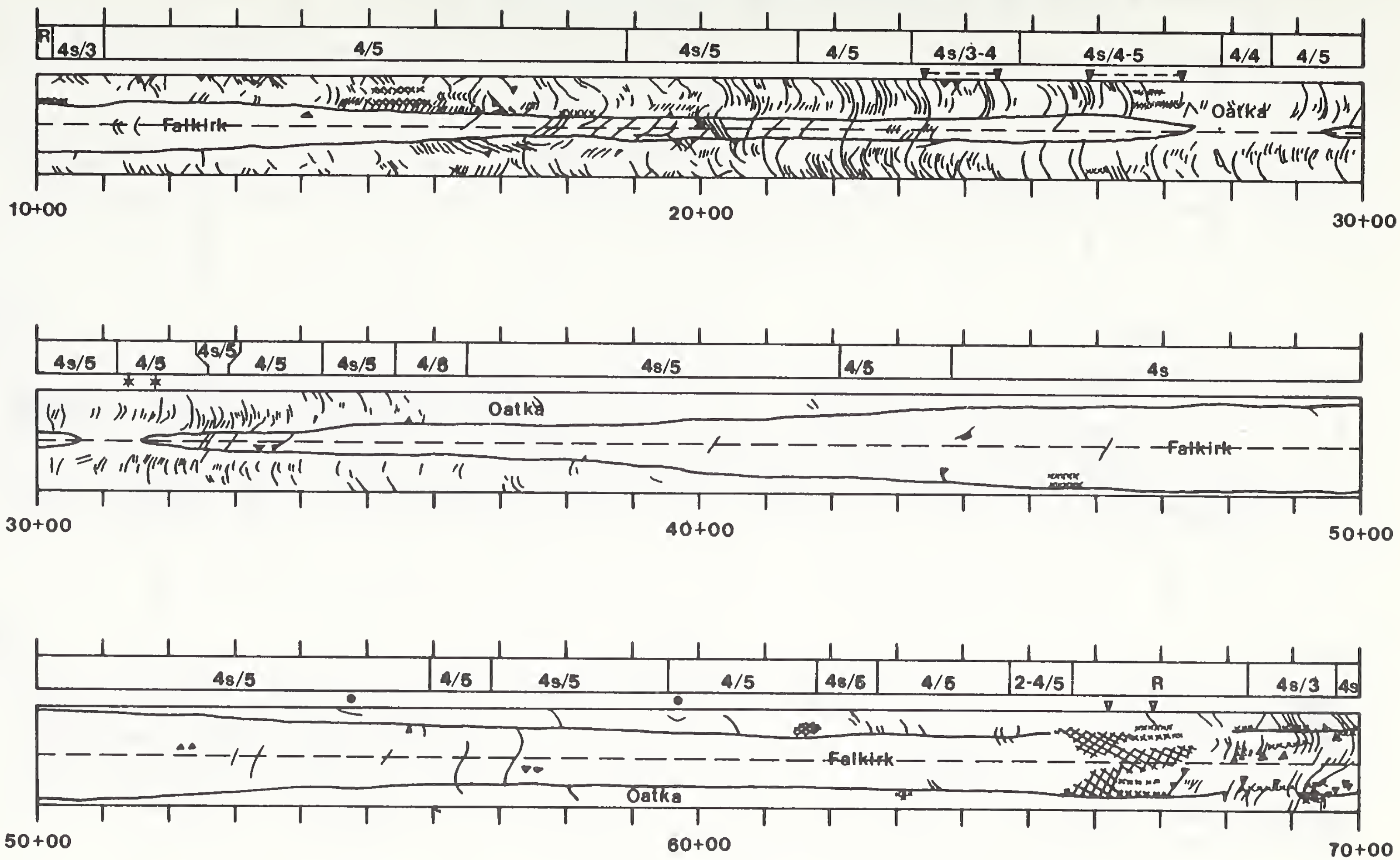


FIGURE A.4 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE C11 INBOUND TUNNEL, STATIONS 10+00 TO 70+00

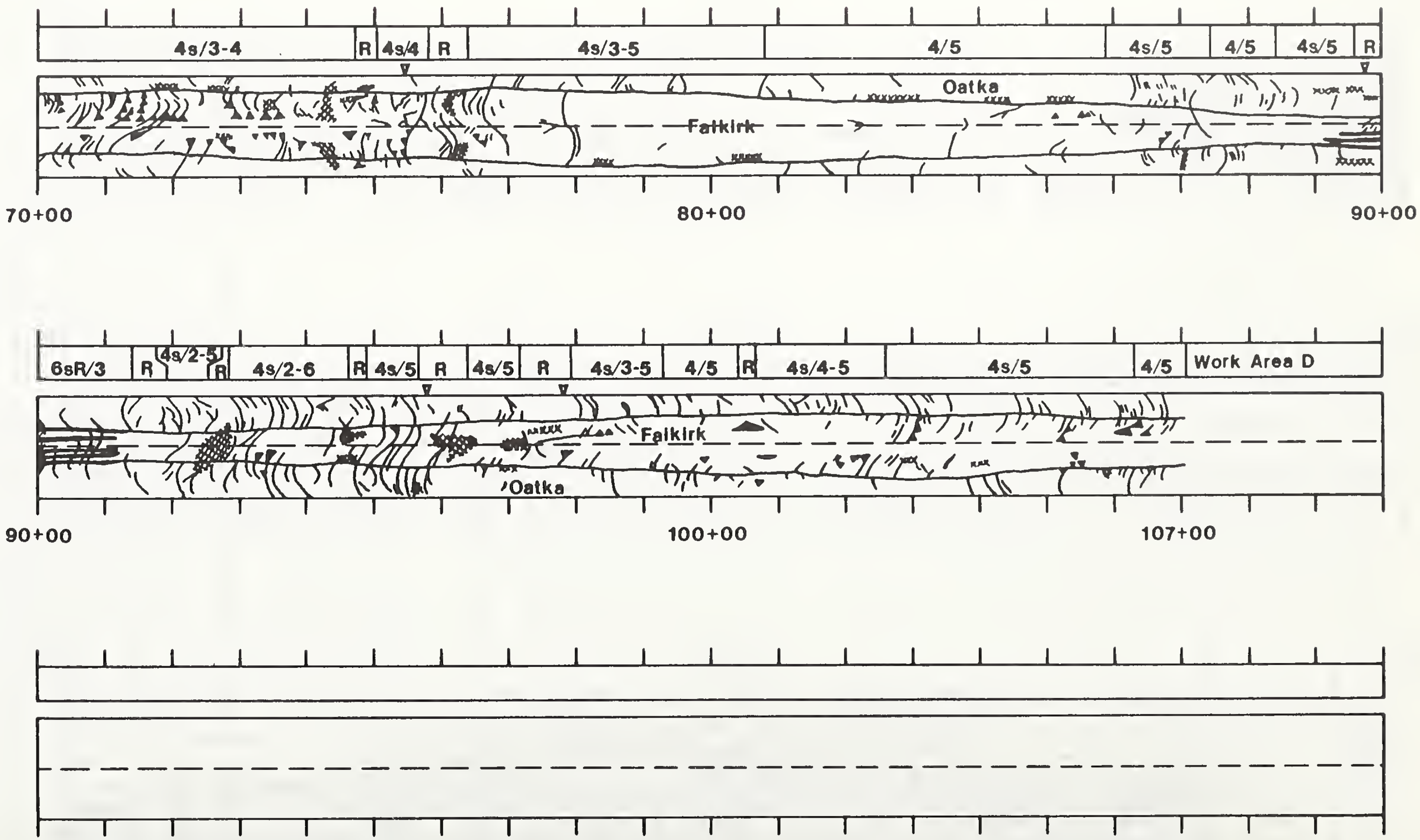


FIGURE A.5 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE C11 INBOUND TUNNEL, STATIONS 70+00 TO 107+05

A.4 TUNNEL WALL GEOLOGY AND SUPPORT FOR THE C31 OUTBOUND TUNNEL

Figures A.6 and A.7 include tunnel wall geologic maps, descriptions and support notations for the outbound tunnel of Contract C31. The tunnel walls were mapped from Station 4+00, near Shaft B, to Station 72+12, where the tunnel intersects the shaft at Work Area D. The tunnel was bored in the Falkirk and Oatka Members of the Bertie Formation.

The initial part of the C31 outbound tunnel was bored along a trend of N 55 degrees E. Between Stations 11+00 and 16+50, boring was around a horizontal curve, and the trend of the tunnel axis was gradually changed to approximately N 40 degrees E. This trend was maintained for the remainder of the tunnel. Bedding plane dip and tunnel grade vary throughout the C31 outbound tunnel, but the design grade was selected so that the amounts of Falkirk and Oatka Members in the rock face were approximately constant. In general, excavation was performed with between 60 and 76 percent of the heading in the Oatka Member.

There are no significant joints in the initial 250 ft (76 m) of the tunnel. Between Stations 6+50 and 11+00, the most common joints are near vertical with a strike of N 5 degrees W to N 15 degrees E. These joints intersect the tunnel axis at 40 to 60 degrees, and many of these joints are discontinuous, particularly at the Falkirk/Oatka Contact. In the Oatka Member, joint spacing is generally less than 10 ft (3.0 m), joint planes are tight and smooth, and are often healed with calcite. Beds in the Oatka are usually 2 to 6 in. (51 to 152 mm) thick. In the Falkirk Member, the spacing of continuous joints is between 10 and 30 ft (3.0 and 9.1 m), and the joint surfaces commonly are weathered and infilled with 1 to 3 in. (25 to 76 mm) of crushed shale and weathered material. Joint frequency and joint and bedding plane weathering generally increases to about Station 14+00. In this area, an additional joint set is present, striking at about N 65 degrees to 85 degrees E with a near vertical dip. In several sections, high joint frequency and weathering led to instability in the tunnel crown so that the contractor installed steel sets and continuous lagging.

From Station 16+00 to 41+50, the frequency of occurrence for each joint set decreases, and overbreak is generally restricted to locations where intersecting joint sets and bedding planes produce isolated rock wedges. The most common vertical joint set in this tunnel section is

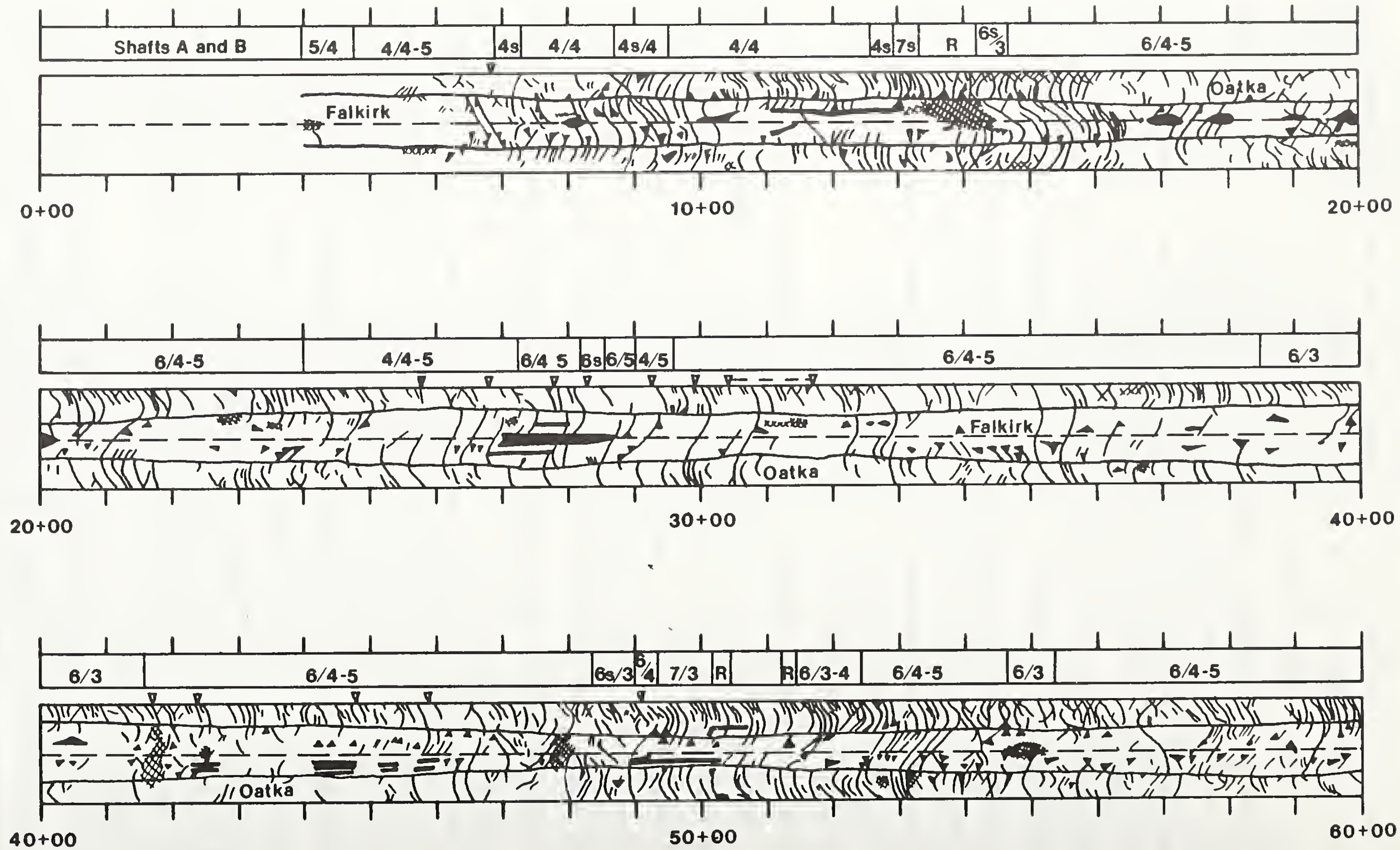


FIGURE A.6 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE C31 OUTBOUND TUNNEL, STATIONS 4+00 TO 60+00

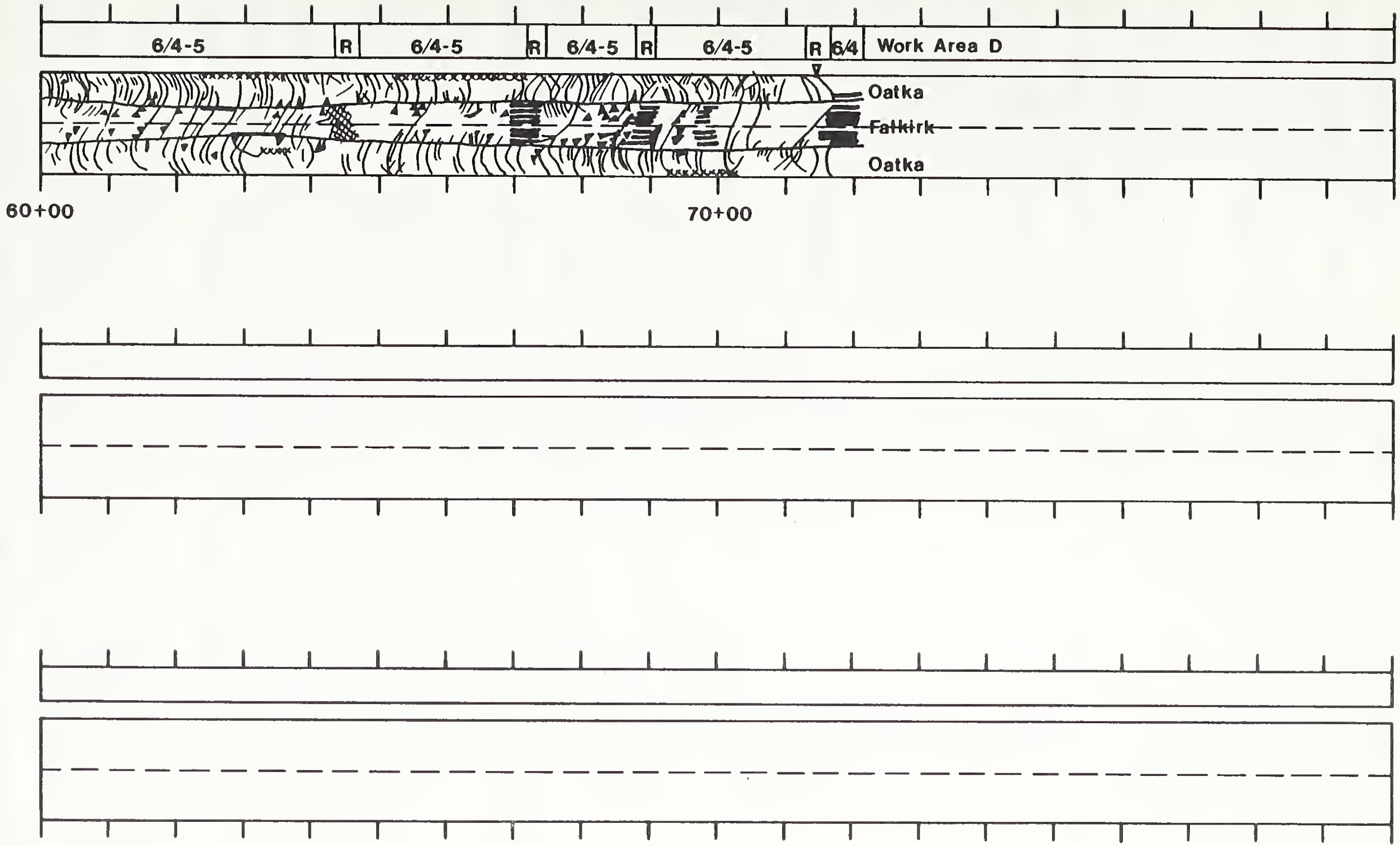


FIGURE A.7 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE C31 OUTBOUND TUNNEL, STATIONS 60+00 TO 72+12

oriented with a strike of N 65 degrees to 80 degrees E. The rock is, in general, less weathered than elsewhere in the tunnel, but closely jointed rock is still present near springline. Slow seepage and minor inflows, usually less than 5 gal/min (18 liters/min) per 100 ft (30 m) of tunnel, occur in this area, and muck of the water inflow enters the tunnel from near the Falkirk/Oatka contact.

Between Station 41+50 and the end of the tunnel, rock of the Falkirk Member becomes increasingly weathered. The most common vertical joint set strikes N 65 degrees to 80 degrees E, and in several tunnel sections, vertical joints with N 0 degrees E strike and joints striking approximately N 90 degrees E and dipping about 40 degrees to the south are present. The tunnel walls below springline were generally covered with muck in this area, but in places where the rock was washed clean, the Oatka Member appeared closely fractured, with joint spacings on the order of 2 to 6 in. (51 to 152 mm). The bedding thickness of the Falkirk Member generally decreases from more than 1 ft (0.3 m) to about 6 in. (152 mm) at the end of the tunnel. The combination of multiple vertical joint sets, thinly bedded Falkirk rock, and weathered joints and bedding planes occurs at three locations between Stations 67+00 and 72+00. In these areas, steel sets and continuous lagging were installed during mining.

Most rock bolts were 8 ft (2.4 m) long, steel reinforcing bars, with a diameter of 0.88 in. (22 m). All bolts were resin grouted along their full length. Bolts were usually installed at a 4 to 5 ft (1.2 to 1.5 m) circumferential spacing for the four bolt pattern in the tunnel crown, and at a 3 to 4 ft (0.9 to 1.2 m) spacing for the six bolt pattern. Additional bolts were installed as needed to restrain rock wedges. Steel sets were composed of four W 6x25 section segments. Straps were 10 in. (254 mm) wide sections of 14 gage steel. Straps varied from 7 to 23 ft (2.1 to 7.0 m) in length, and were placed across the tunnel crown.

A.5 TUNNEL WALL GEOLOGY AND SUPPORT FOR THE C31 INBOUND TUNNEL

Figures A.8 and A.9 include tunnel wall geologic maps, descriptions and support notations for the inbound tunnel of Contract C31. The tunnel walls were mapped from Station 0+08 to 3+13 between shafts A and B at the South Campus Station, and from Station 3+60 to 72+20, where the

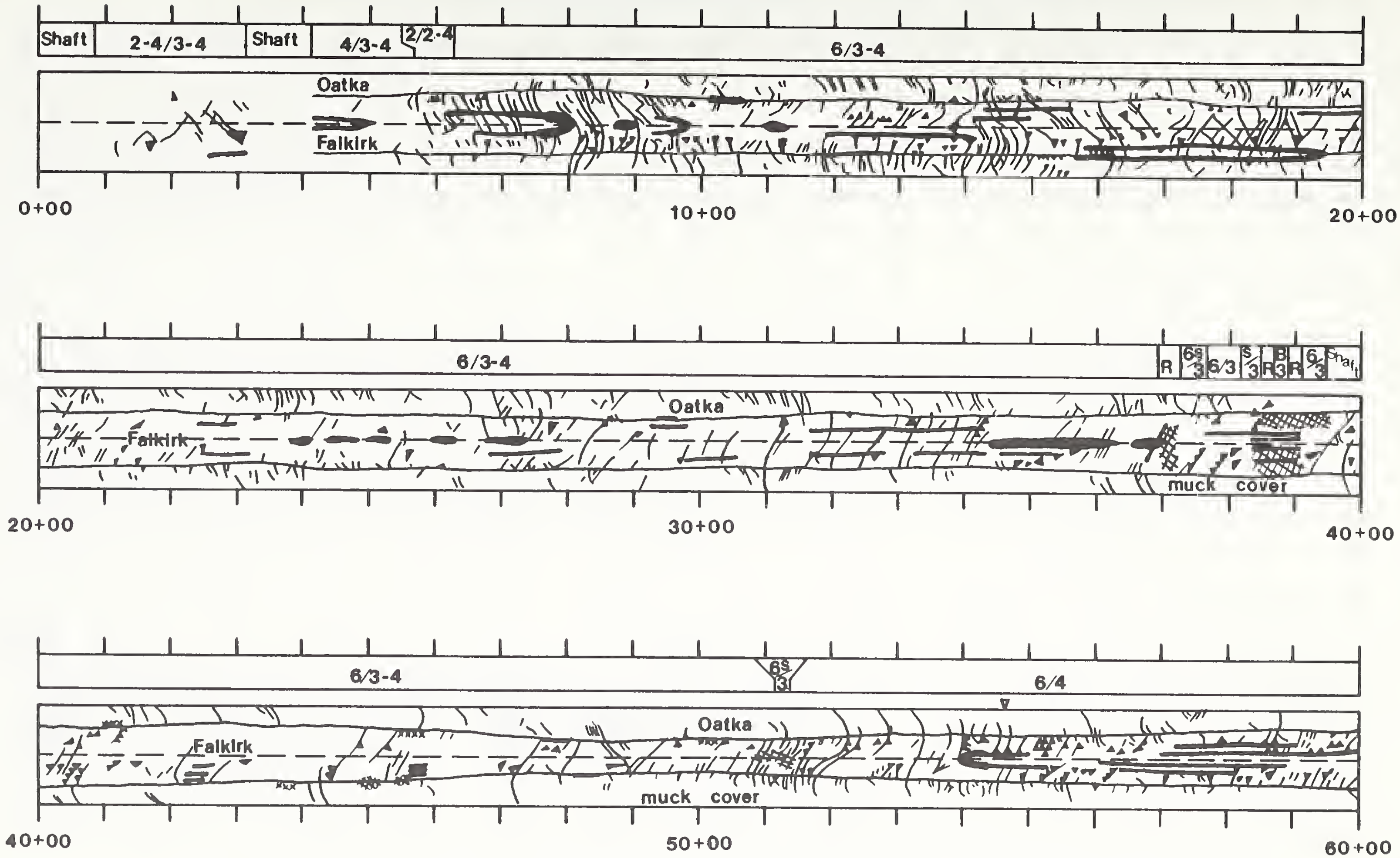


FIGURE A.8 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE C31 INBOUND TUNNEL, STATIONS 0+80 TO 60+00

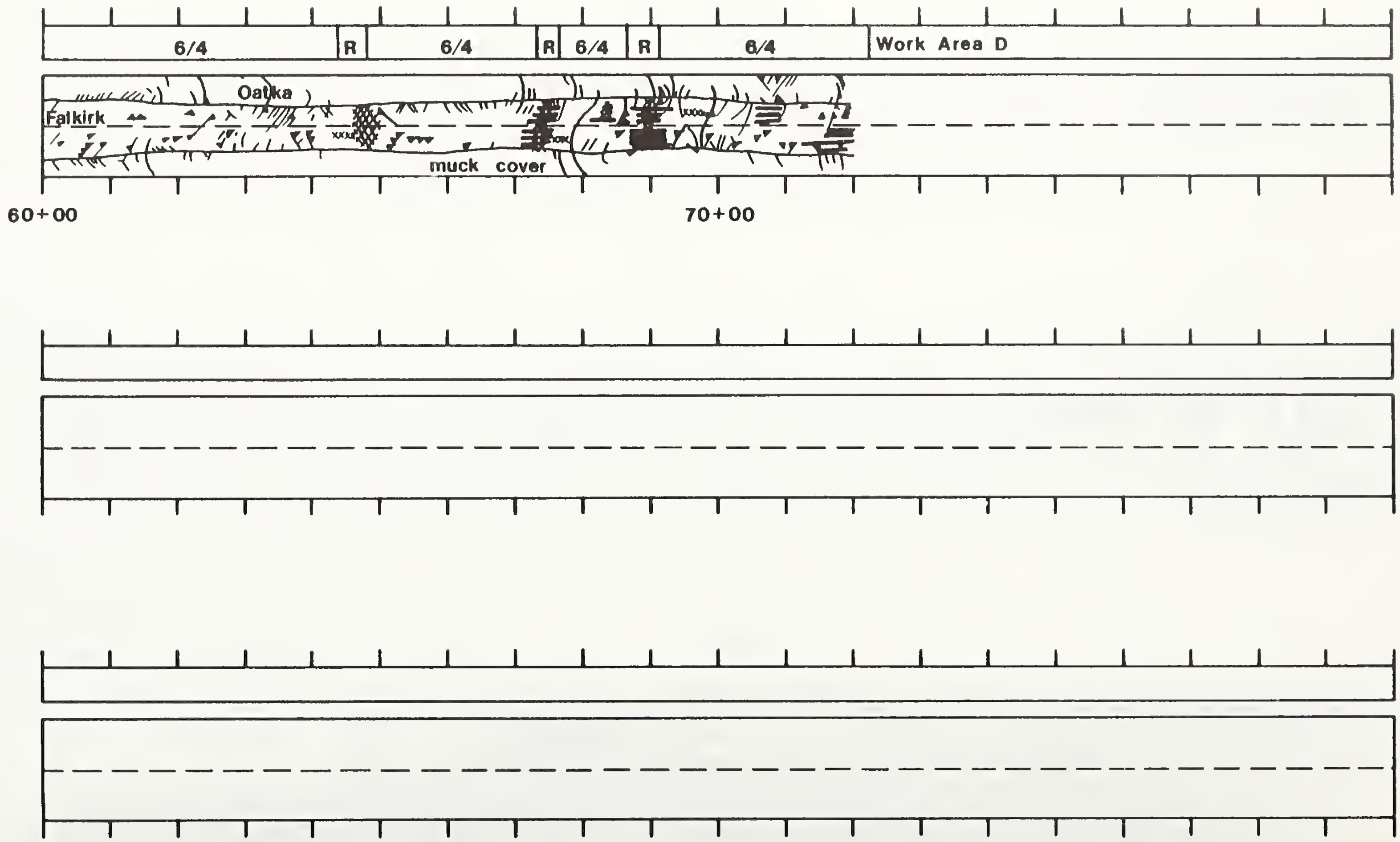


FIGURE A.9 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE C31 INBOUND TUNNEL, STATIONS 60+00 TO 72+20

tunnel intersects the shaft at Work Area D. The tunnel was bored in the Falkirk and Oatka Members of the Bertie Formation.

The C31 inbound tunnel was driven along a trend similar to that of the C31 outbound tunnel. The major difference between the two alignments is the radius of curvature of the horizontal curve at the northern end of the contract. The stratigraphic and discontinuity description included in Section A.4 for the outbound tunnel is generally valid as a description of the rock encountered in the inbound tunnel. Joint frequency was lower, however, in the inbound tunnel. For muck of the tunnel length, muck covered the tunnel walls below springline, obscuring details on joint frequency and condition in the Oatka Member.

A.6 TUNNEL WALL GEOLOGY AND SUPPORT FOR THE CULVER-GOODMAN TUNNEL

Figures A.10 through A.12 include tunnel wall geologic maps, descriptions and support notations for the sections corresponding to the Densmore and Goodman legs of the Culver-Goodman Tunnel. The spacing of the patterned support is not shown in Figure A.6, since the spacing of 3.6 to 4 ft (1.1 to 1.2 m) was uniform throughout the tunnel. Steel set spacings are not shown in the figure, but may be found in Appendix B. The tunnel walls were mapped from Station 4+00 to 169+93 along an uphill grade of 1.10 percent.

The Queenston Shale Formation is present below tunnel springline from Station 4+00 to approximately Station 11+50, where it dips below the invert. The Grimsby Formation is exposed above the Queenston, and from Station 11+50 to about 59+50, the tunnel is completely within the Grimsby Formation. In general, the joint spacing in the Queenston and Grimsby is greater than 20 ft (6.1 m), although in places the spacing is more than 100 ft (30.5 m). The most common vertical joint strikes at about N 30 degrees to 45 degrees E and, since the tunnel axis trend in N 38 degrees E, these joints are subparallel to the tunnel. Much of the overbreak that occurred in this tunnel crown. The second major joint set in the Queenston and Grimsby rock strikes at N 35 degrees to 50 degrees W and contains many normal faults. The joint set is oriented nearly perpendicular to the tunnel axis. Overbreak often develops where joints of the two sets intersect. The planes of the perpendicular joint set are generally within 20 degrees of

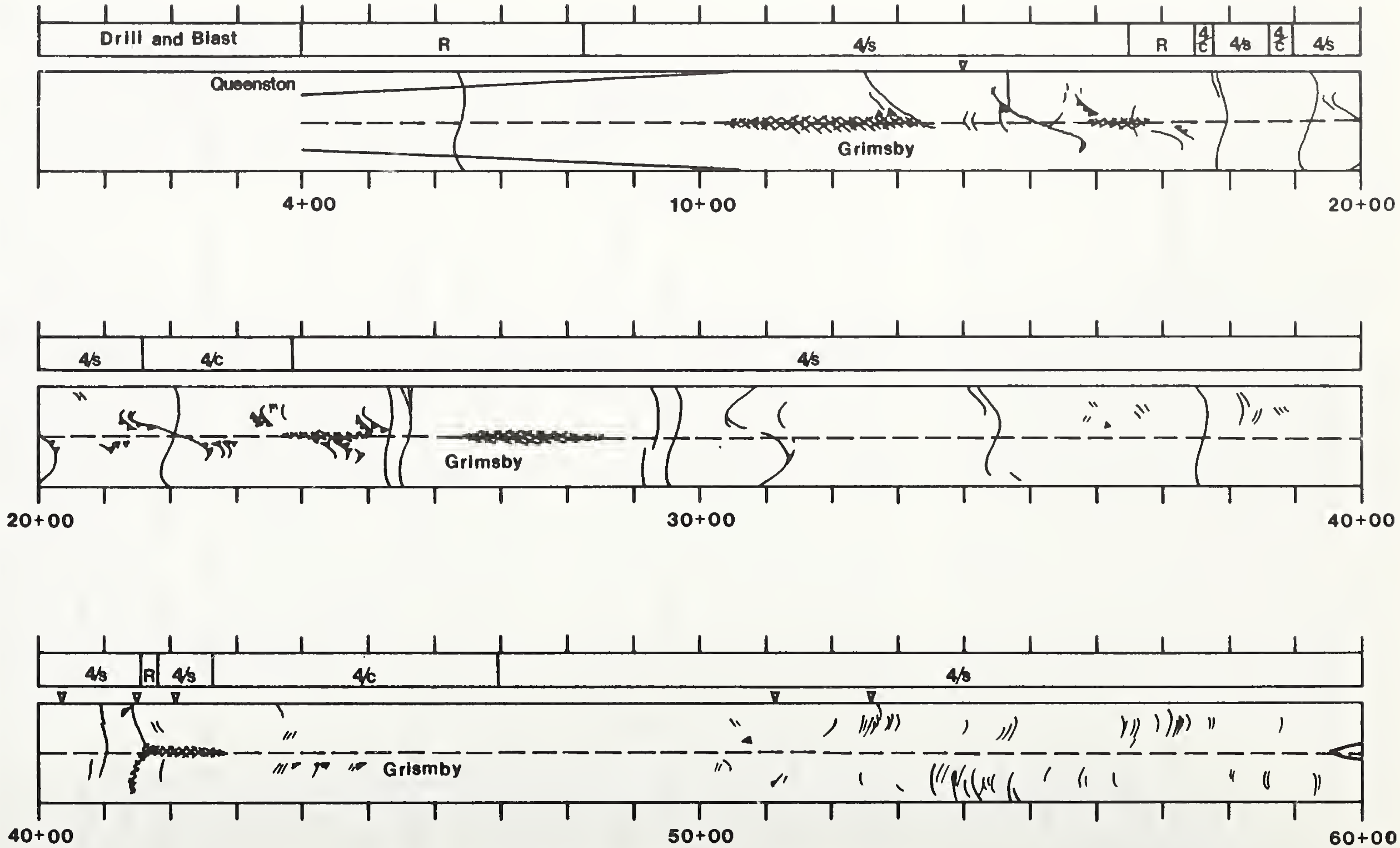


FIGURE A.10 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE CULVER-GOODMAN TUNNEL, STATIONS 4+00 TO 60+00

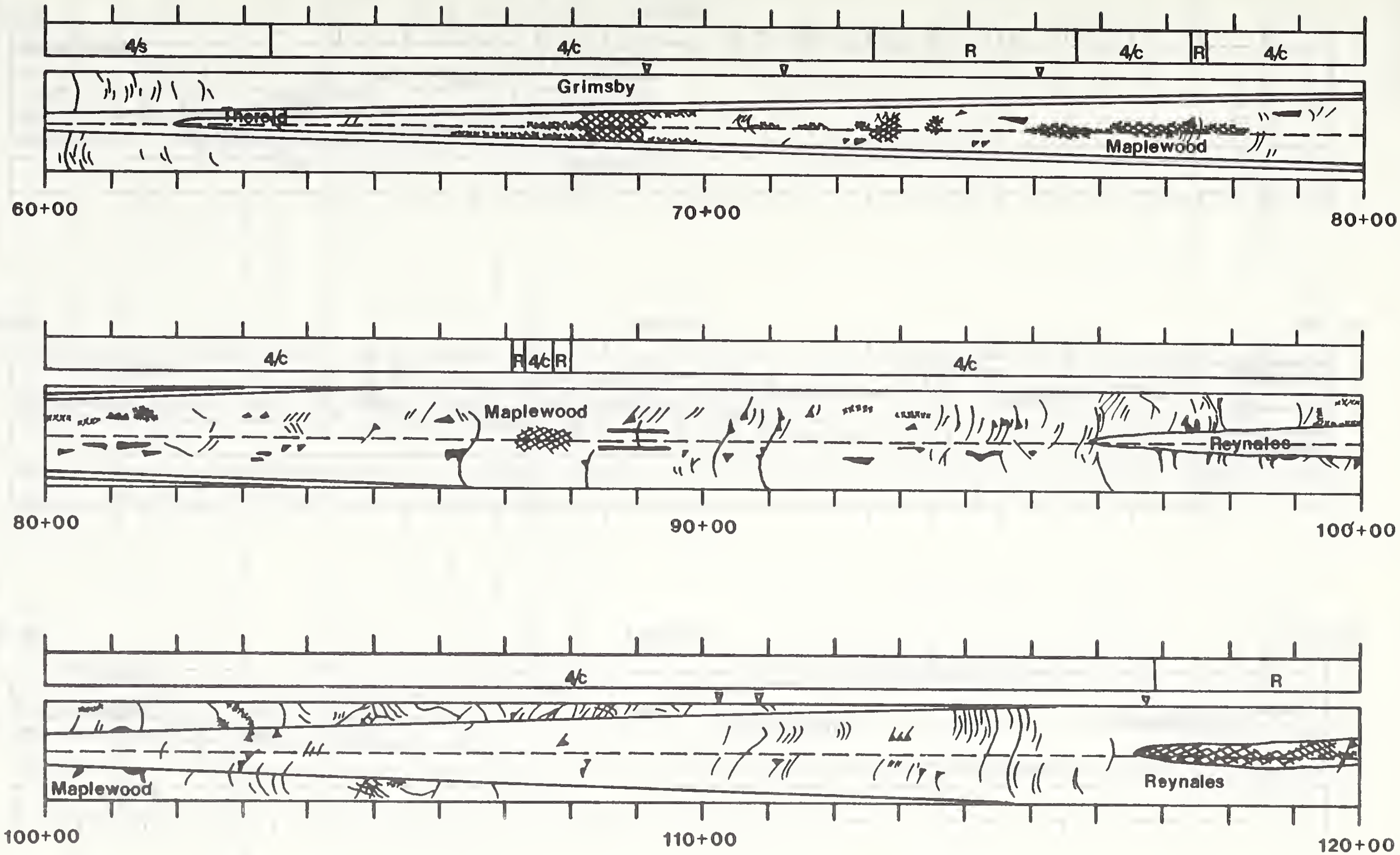


FIGURE A.11 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE CULVER-GOODMAN TUNNEL, STATIONS 60+00 TO 120+00

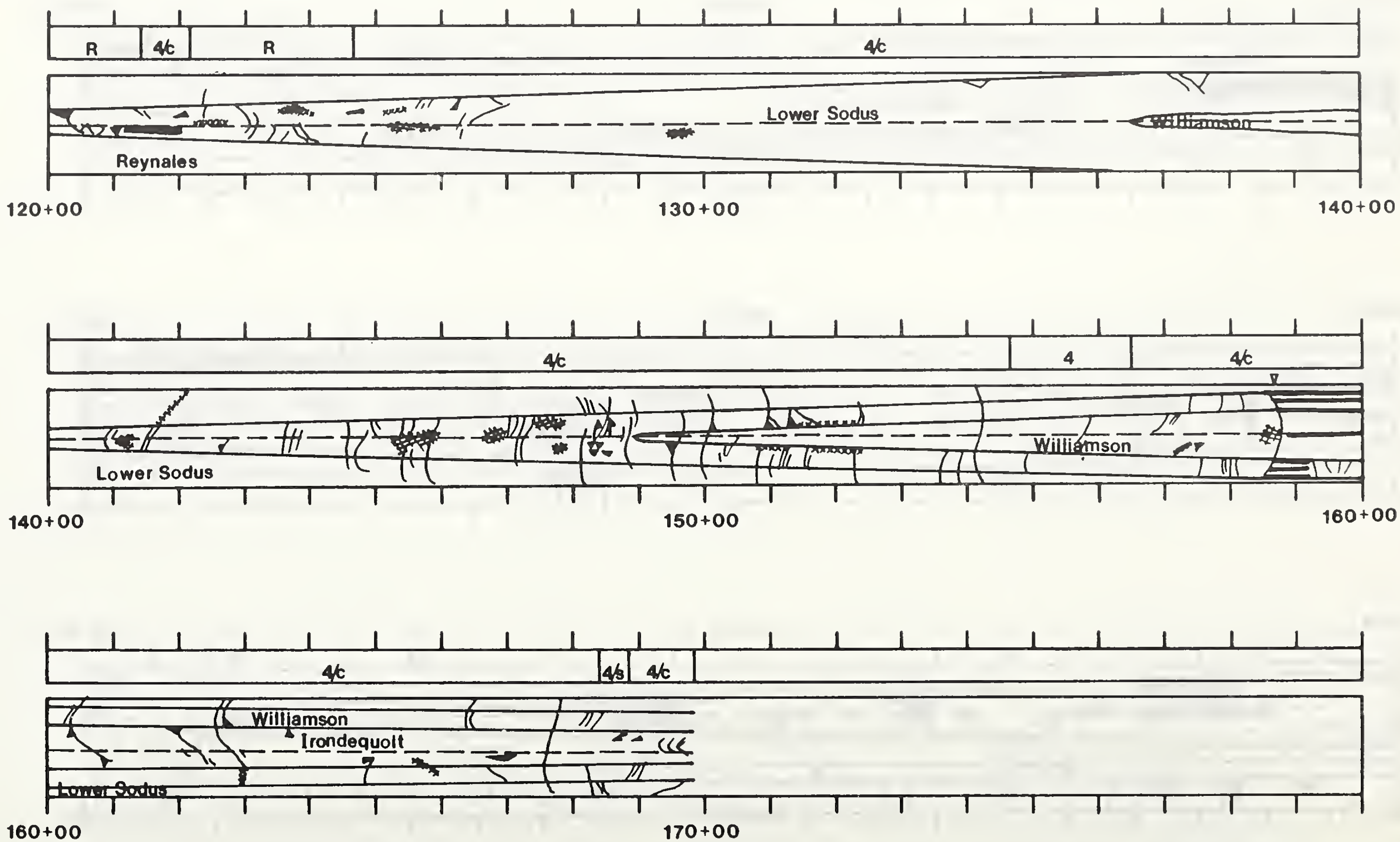


FIGURE A.12 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE CULVER-GOODMAN TUNNEL, STATIONS 120+00 TO 169+93

TABLE A.2 LOCATIONS AND OFFSETS FOR NORMAL FAULTS IN THE GRIMSBY SANDSTONE

APPROXIMATE LOCATION (STATION)	ESTIMATED OFFSET IN. (MM)
14+70	12 (305)
17+80	15 (381)
19+20	7 (178)
21+90	22 (559)
25+30 to 25+60	4 to 6 (102 to 152)
29+60	20 (508)
34+50	20 (508)
37+50	4 (102)
41+00	12 (305)
41+50	25 to 40 (635 to 1016)

the vertical. Table A.2 lists the locations of the normal faults mapped in the tunnel and the estimated offset that was observed for each. The rock along the fault planes is usually discolored and weathered. Generally, only a 1 to 2 in. thick zone (25 to 51 mm) of rock is disturbed, adjacent to the fault planes. A notable exception occurs at Station 41+50, where a zone of fault gauge, 6 to 12 in. (152 to 305 mm) thick, was observed. The faults are usually dry or are locations of minor seepage, less than 1 gal/min (4 liters/min).

The Thorold Sandstone appears in the tunnel crown at approximately Station 59+50, but this unit is only about 2 ft (0.6 m) thick. Beneath the Thorold is the Maplewood Shale, which is present in the tunnel from about Station 62+00 to 116+00. Joint frequency in the Maplewood is higher than that of the Grimsby, but the joints are usually discontinuous. Where they were closely spaced, spalling occurred, leaving a jagged edge to the bedding planes exposed in the tunnel wall. Due to the discontinuous nature of the joints, it is difficult to establish their orientation. Vertical and lower angle joints are present, with a strike generally within 30 degrees of north. Conchoidal fracture surfaces are common in the shale, and the fracture surfaces are usually moist. No seepage or water inflow was observed in the Maplewood Shale.

The Reynales Limestone is present in the tunnel from about Station 95+80 to 141+00. Joints in the Reynales are irregular in spacing, and many of the joints are confined to individual beds. The few joints that are more continuous are oriented approximately perpendicular to the tunnel axis, but no offsets were observed along these near vertical joints. Overbreak in the Reynales is generally associated with the intersection of bedding planes and joints in rock above springline. Bed thickness in the Reynales Limestone is usually 1 to 2 ft (0.3 to 0.6 m).

The lower Sodus Shale first appears in the tunnel at about Station 116+80, and the Williamson Shale first appears at about 136+70. These units are present throughout the rest of the tunnel. Most of the joints in these shales are discontinuous and occur in 1 to 2 ft (0.3 to 0.6 ft) lengths. These joint surfaces are often slickensided and are usually dry. Joints in the Williamson Shale are more often continuous than those in the Lower Sodus Shale. Two approximately orthogonal sets are present, which are nearly vertical and strike at N 60 to 75 degrees E and N 10 to 20 degrees W. Joint spacing varies from less than 1 ft (0.3 m) to more than 30 ft (9.1 m), and the joint planes are smooth, dry and unweathered. Overbreak in the Lower Sodus and Williamson Shales was associated with one of two apparent causes: 1) intersection of bedding planes and joints in the rock above springline, and 2) spalling resulting from the concentration of compressive stress in the crown because of stress redistribution under conditions of relatively high in-situ horizontal stress.

The Irondequoit Limestone first appears in the tunnel at about Station 149+00. Joints in this unit generally have the same orientation as those in the rock below, but many are discontinuous at the Irondequoit/Williamson contact. At approximately Station 158+70, about 20 in (510 mm) of offset were observed along a discontinuity which strikes about N 20 degrees W and dips about 30 degrees to the NE. This discontinuity is a reverse fault, and the fault plane cuts the Lower Sodus, Williamson and Irondequoit Formations. The rock within 6 to 12 in (152 to 305 mm) of the fault has been disturbed and a zone of clay-like gouge is present. The tunnel is generally dry in the Goodman leg, but some slow seepage was observed to enter the tunnel at the contact between the Irondequoit and Williamson Formations.

No significant amounts of combustable gas were encountered during eigher probe hole drilling or tunneling. At three locations in the Grimsby Sandstone, some gas inflow was noted, but the flow rate was very low.

Rock bolts were 8 ft (2.4 m) long steel reinforcing bars with a diameter 1.0 in (25 mm). All bolts were resin grouted along their full length. The bolts were placed at about 5 ft (1.5 m) circumferential spacing. Straps were 5 in (127 mm) wide, and were 0.25 in (6.4 mm) thick. Channel sections wer C 6 x 8.2 and were 16 ft (4.9 m) long, installed across the tunnel crown. Steel sets were W 6 x 25 sections, and each set was composed of four segments.

A.7 TUNNEL WALL GEOLOGY AND SUPPORT FOR THE EAST HEADING OF THE MAIN TUNNEL OF TARP CONTRACT 73-287-2H

Figures A.13 through A.16 include tunnel wall geologic maps, descriptions and support notations for the east heading of the main tunnel of TARP Contract 73-287-2H. The tunnel walls were mapped by personnel from Keifer & Associates, Inc., and the maps start at Station 185+83 and continue through the main tunnel to Station 409+68. The tunnel was bored mostly in the Romeo and Markgraf Members of the Joliet Formation, but rock of the Kankakee Formation is present below the Markgraf in the first 4,000 ft (1,219 m) of the east heading. The contact between the Joliet and Kankakee Formations is not distinct in the tunnel, and the location of this contact on the tunnel walls is not identified in Figure A.7.

There are two common vertical joint sets exposed in the tunnel. These sets strike at N 35 degrees to 50 degrees E and N 35 degrees to 55 degrees W, and are therefore approximately orthogonal to each other. The joint patterns shown in Figure A.7 vary along the tunnel primarily because of changing joint frequency and changing tunnel orientation.

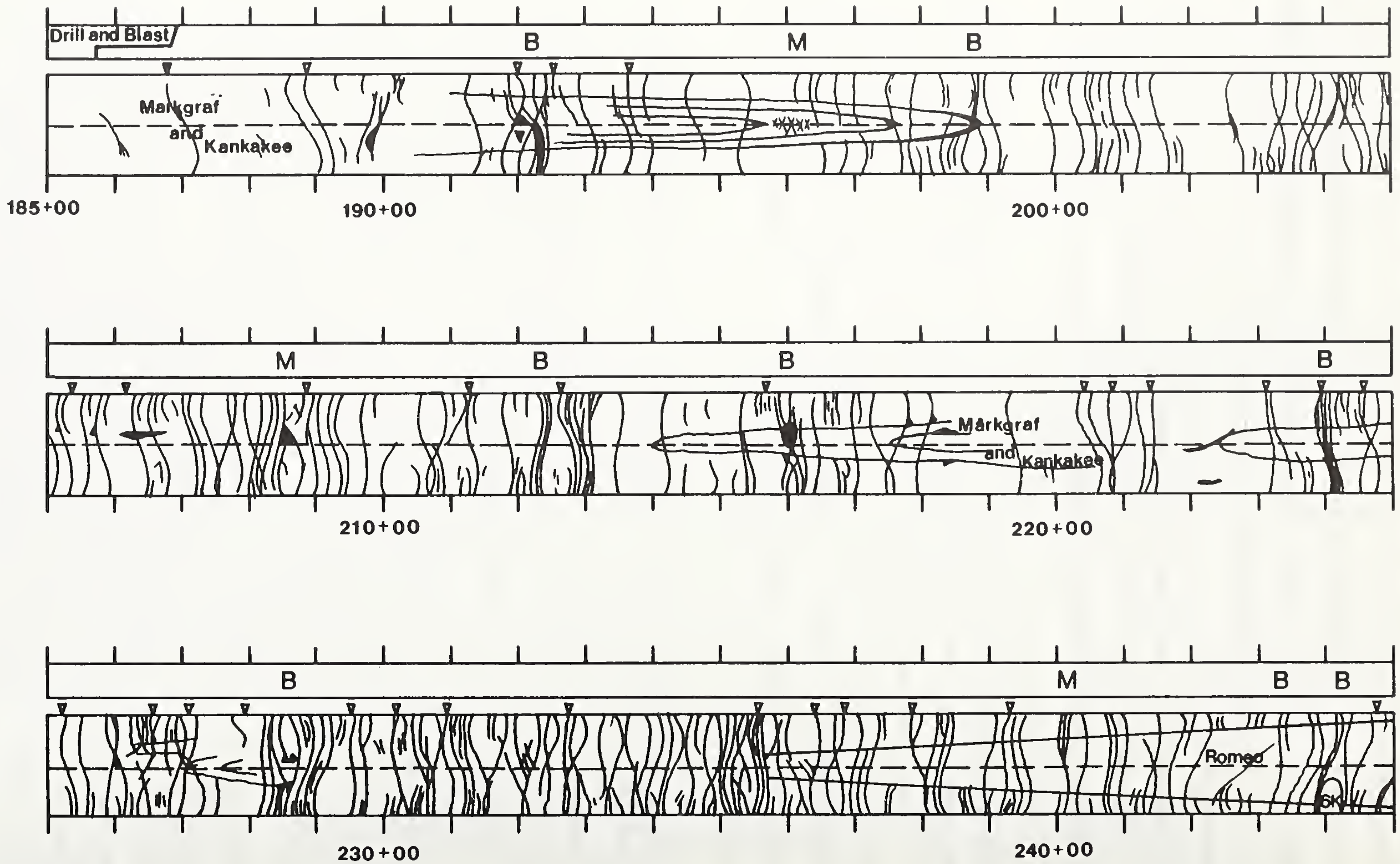


FIGURE A.13 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE EAST HEADING OF THE MAIN TUNNEL OF TARP CONTRACT 73-287-2H, STATIONS 185+83 TO 245+00

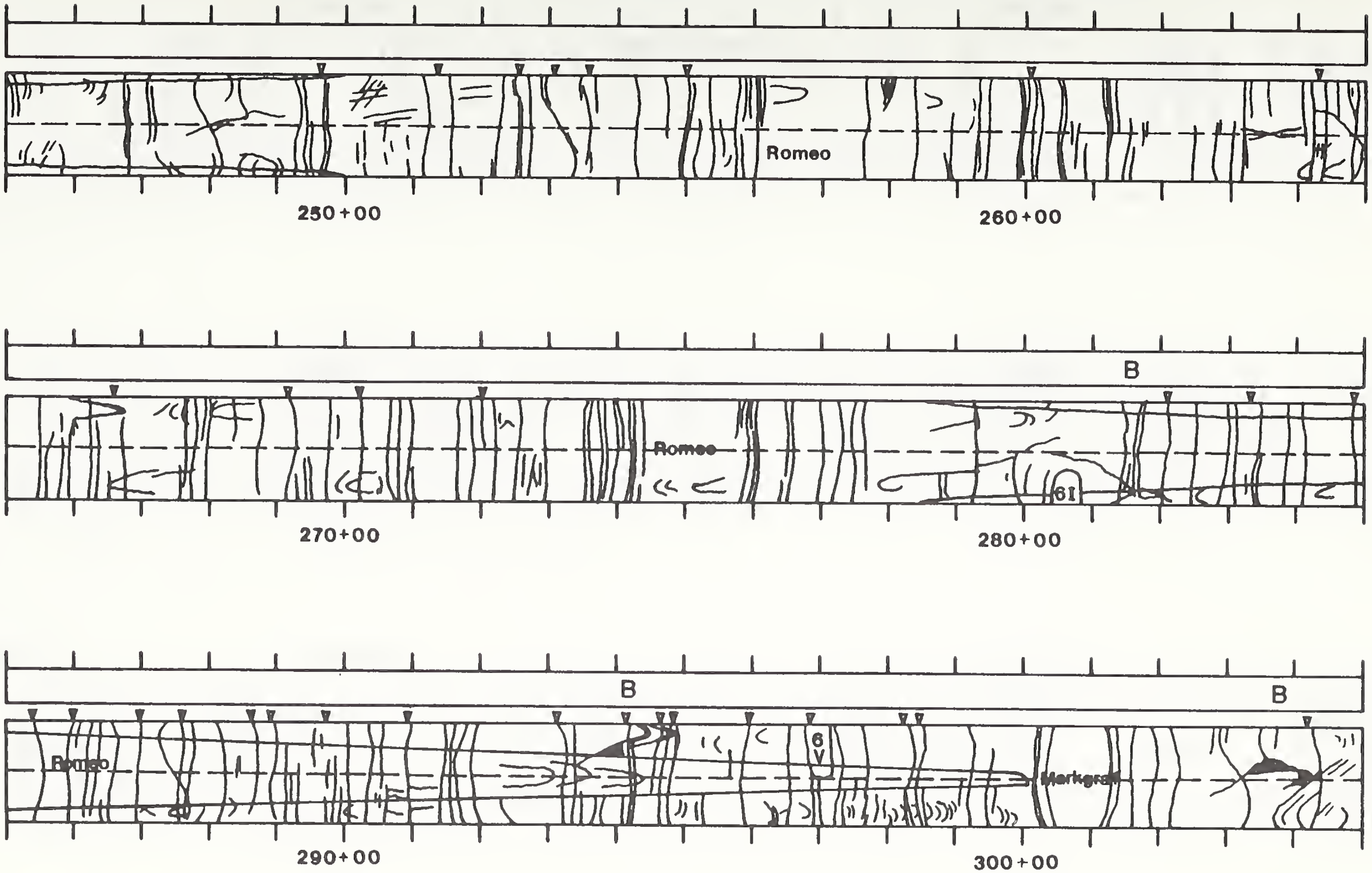


FIGURE A.14 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE EAST HEADING OF THE MAIN TUNNEL OF TARP CONTRACT 73-287-2H, STATIONS 245+00 TO 305+00

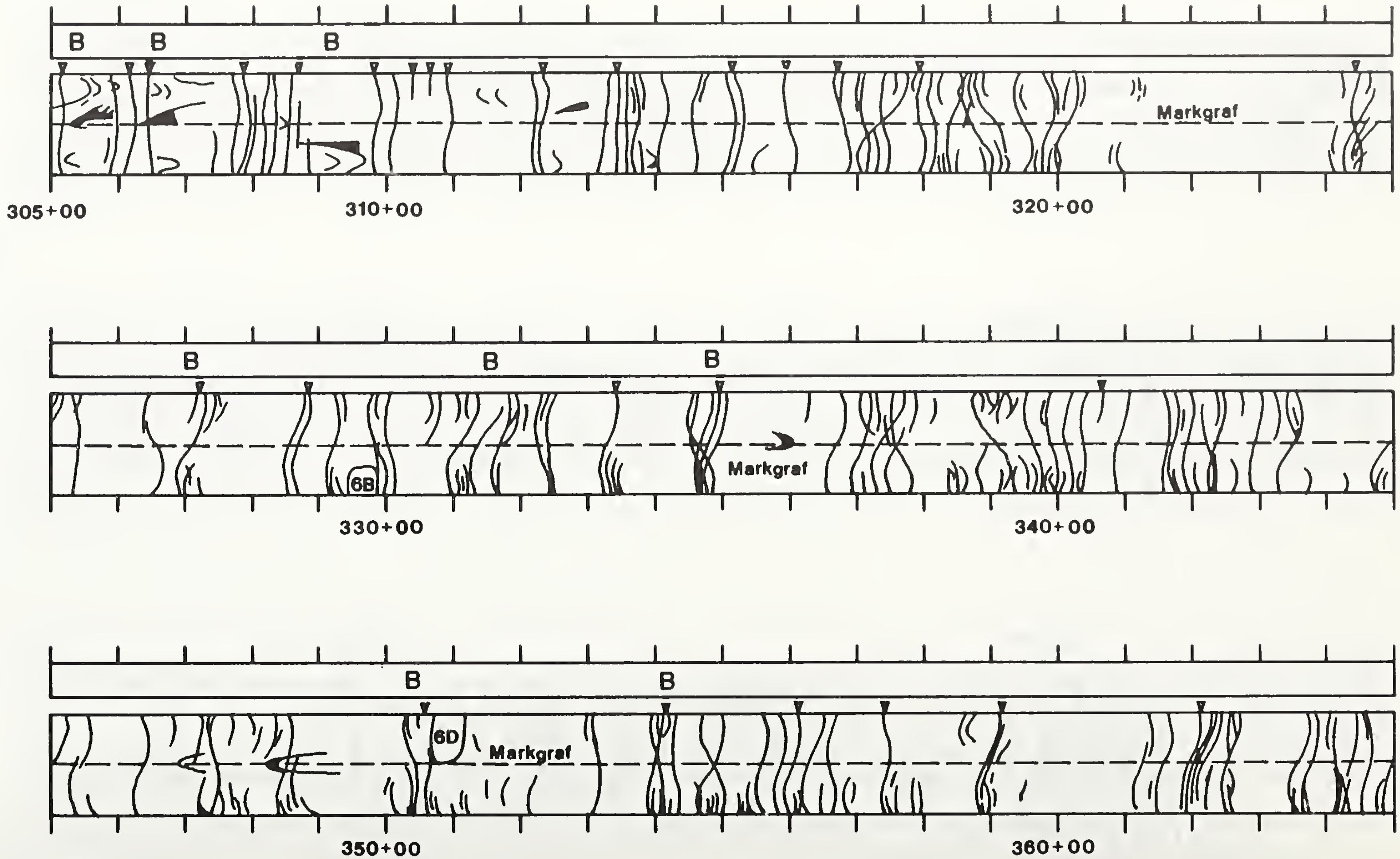


FIGURE A.15 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE EAST HEADING OF THE MAIN TUNNEL OF TARP CONTRACT 73-287-2H, STATIONS 305+00 TO 365+00

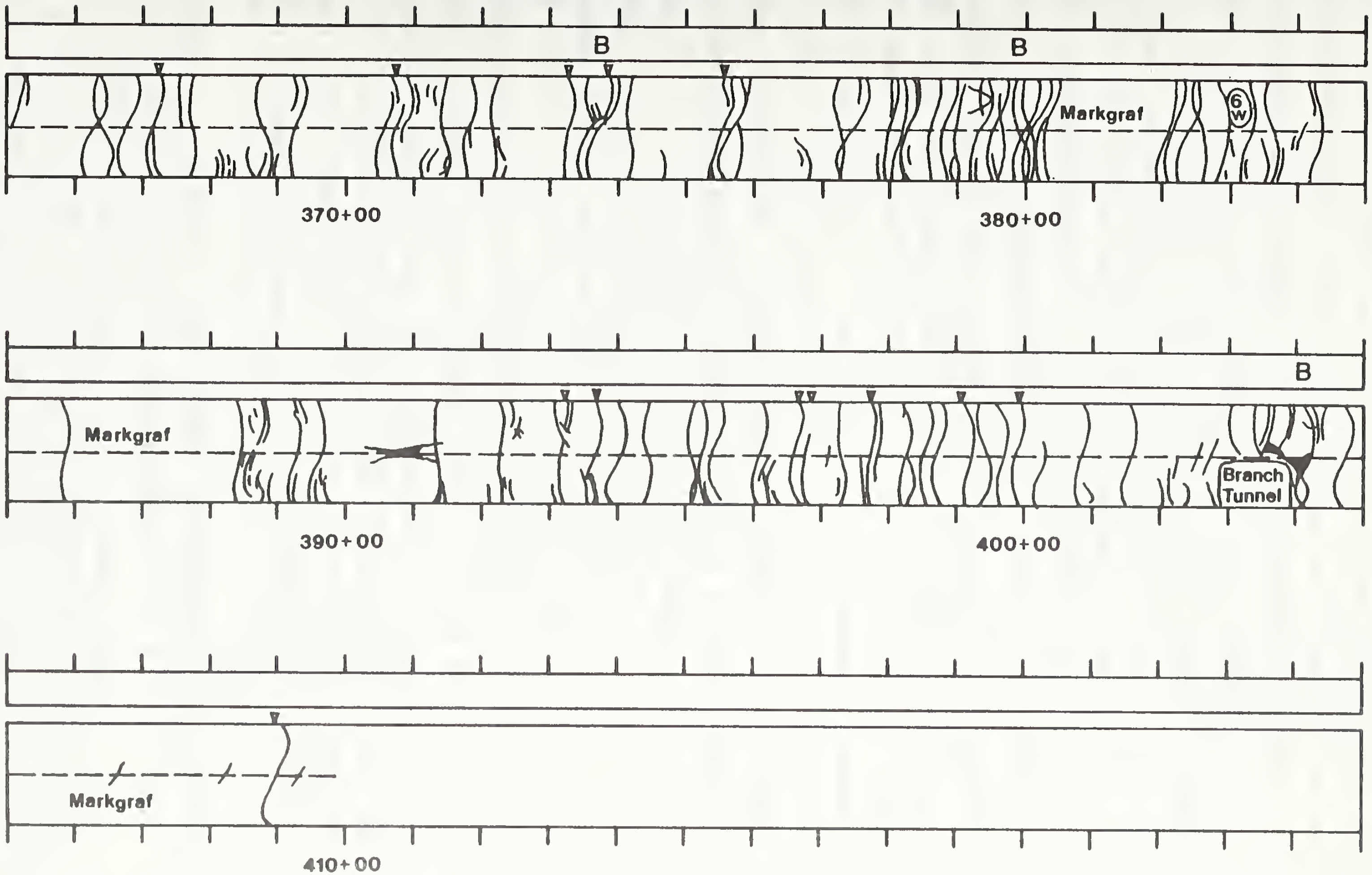


FIGURE A.16 GEOLOGIC MAPS, DESCRIPTIONS AND SUPPORT NOTATIONS FOR THE EAST HEADING OF THE MAIN TUNNEL OF TARP CONTRACT 73-287-2H, STATIONS 365+00 TO 409+68

The initial 5,600 ft (1,707 m) of the tunnel were driven along an approximate east-west trend, and the grade was downhill at 0.3 percent. This grade is similar to the apparent dip of the bedding planes so that the tunnel wall stratigraphy is relatively constant. An exception to this occurs at Station 235+50, where more than 10 ft (3 m) of offset is present along a discontinuity, bringing rock of the Romeo Member into the tunnel crown, and displacing the Kankakee Formation to a position below the tunnel invert. Between Stations 241+86 and 247+52, boring was around a 600 ft (183 m) horizontal curve, and from Station 24+52 to 313+37 the trend of the tunnel axis is approximately N 40° W. In this straight section, the tunnel was mined against the apparent bedding plane dip so that by Station 300+10, the Romeo Member was above the tunnel alignment. For the remainder of the tunnel, excavation was in the Markgraf Member. Between Stations 313+37 and 325+77, boring was around a 500 ft (152 m) radius horizontal curve. At this location, the tunnel grade changes from 0.3 to 0.05 percent downhill. The trend of the tunnel axis between Stations 325+77 and 409+68 is approximately due north.

Few joints are exposed in the first 600 ft (183 m) of the tunnel, but the joint frequency increases beyond this point. The most common joint set is oriented N 40° to 50° E and the average spacing between Stations 190+00 and 200+00 is 60 to 70 ft (18 to 21 m). In this same section, N 45° to 55° W joints are also present at an average spacing of 120 to 130 ft (37 to 40 ft). Water inflow is minor, mostly as slow drips from joint planes. Occasionally, rock near the joint planes is fractured, but the joint planes are generally smooth and some of the joints are open as much as 0.25 in. (6 mm). Overbreak in this tunnel section is usually associated with the intersection of bedding planes and the tunnel crown.

Between Stations 200+00 and 229+00, joint frequency of each set varies from 5 ft (1.5 m) to more than 100 ft (30 m). Joints striking N 40° to 55° E are most common, with an average spacing of 40 ft (12 m). Slow seepage occurs along many of these joints. Groups of joints striking N 35° to 50° W occur at several locations in this section, notably in the vicinity of Station 203+70, 208+30, and 228+70. Within these groups, joint spacing is 5 to 10 ft (1.5 to 3.0 m), and displacements of up to 10 in. (254 mm) were observed along these discontinuities. Minor amounts of water inflow occur along joint and bedding planes, and overbreak in this section is associated both with bedding plane and crown intersection and with intersecting joints and bedding planes.

Between Stations 229+00 and 241+86, the frequency of the northwest joints increases. The average spacing of these discontinuities is about 30 ft (90 m), but many joints are at 5 to 10 ft (1.5 to 3 m) spacings. Several of these joints show offsets of up to 12 in. (0.3 m). Joints striking approximately N 45° E are also present, but their frequency decreases along this tunnel section. Numerous discontinuous joints are also present. In places, the spacing of these joints is as small as 2 to 4 ft (0.6 to 1.2 m), and many terminate in bedding planes. Water inflow occurs mainly along the continuous vertical joints as slow drips or seepage.

With the change in tunnel orientation between Stations 241+86 and 247+52, the northwest striking joints are approximately parallel to the tunnel axis and the northeast striking joints are approximately perpendicular to the axis. Between Station 247+52 and the next curve at Station 313+37, the average joint spacing is greater than in the previous tunnel section. The parallel joints are poorly exposed, but some can be observed to extend over more than 200 ft (61 m) of tunnel. Spacing of this joint set is difficult to estimate. Spacing of the perpendicular joint set varies from 5 ft (1.5 m) to more than 100 ft (30 m), and the average spacing is 35 to 40 ft (11 to 12 m). Small amounts of water inflow occur along joints of both sets, and several of the joints are filled with clay. Many of the perpendicular joints are open, with separations up to 0.75 in. (19 mm). Displacements of up to 3 in. (76 mm) have occurred along several of the joint planes. Overbreak in this section is generally associated with intersecting joint planes, but the overbreak between Stations 303+00 and 307+00 is primarily associated with the parallel joint set.

The strike of the joint sets with respect to the tunnel axis changes at the curve between Stations 313+37 and 325+77. In the final leg of the tunnel, between Stations 325+77 and 409+68, the most common joint set strikes at N 35° to 55° W. The average spacing of joints is 60 to 70 ft (18 to 21 m), but in several areas the spacing is less than 5 ft (1.5 m). A few of these joints are open up to 0.75 in (19 mm).

Joints striking at N 25° to 45° E are also present. The spacing of discontinuities in this set is highly variable, but the average spacing is about 170 ft (52 m). Water inflow occurred mostly as minor leakage from joint planes, and most of the overbreak occurred at the intersections of bedding planes and the tunnel crown.

Most of the tunnel was excavated without initial rock support. Patterned support was not installed, and the most common type of support was isolated rock bolts. These bolts were 8 to 10 ft (2.4 to 3.0 m) long, steel reinforcing bars which were resin grouted along their full length. At several locations, steel mesh or straps were installed. Details concerning the type of mesh and size of straps were not available.

APPENDIX B DOWNTIME ANALYSIS OF TBM TUNNELING

B.1 GENERAL

Tunneling delays occur when changes in the construction environment cannot be accommodated with a continuous cycle of excavation, mucking and support. Accordingly, time must be spent to deal with the difficulty encountered. During this time, tunneling is restricted and the construction cycle is referred to as being "down." Downtime frequently occurs in response to factors that reflect geologic controls and construction procedure. Because good tunneling requires planning to minimize delay, it is of paramount importance to understand the causes of downtime and how they interrelate to affect tunneling performance.

As part of this study, the downtime records from operator's and inspector's reports were collected and reviewed to provide a summary of downtime causes for each of the tunnel drives. The tunnel excavation process was analyzed as a system affected by: 1) maintenance and repair of the TBM, 2) repair of the backup system including trailing gear, rail, shaft and surface mucking, and 3) ground conditions. Figure B.1 shows the TBM system and associated downtime sources in a diagrammatic form. Some causes of downtime could not be assigned to a specific category. A few either were not recorded or did not occur on a consistent basis for all jobs. Accordingly, a general category covering additional items was also developed and used in the main part of the report to summarize average downtime percentages for the entire job.

In this appendix, the downtime causes are summarized under 21 individual categories in histogram form. The method of plotting the data and the scale for tunnel stations is the same as that used in the plots of advance rate, utilization, availability, and penetration rate in Chapters 4 through 9. The downtime for each category is expressed as a percentage of the time during each shift of the tunnel drive.

In each of the following sections, the downtime for one of the tunnels under study is discussed in detail. Three figures of histograms showing the downtime percentages are provided for each tunnel section. Each figure summarizes the percentage downtimes for individual causes under one of the general categories shown in Figure B.1. All downtime

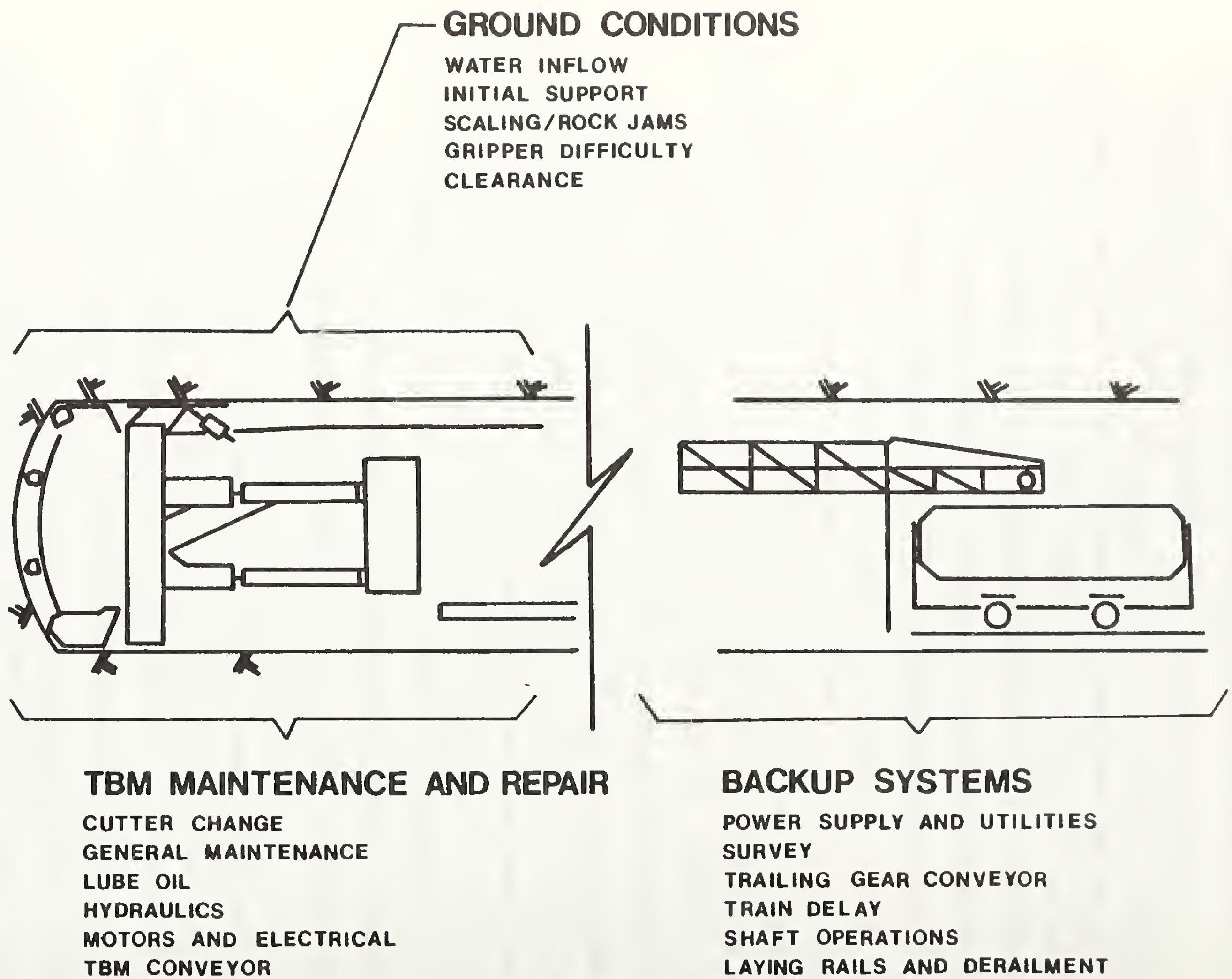


FIGURE B.1 SCHEMATIC DRAWING OF TBM EXCAVATION SYSTEM INCLUDING GENERAL LOCATIONS OF DELAYS IN VARIOUS DOWNTIME CATEGORIES percentages reported in the following sections are based on total shift time after the trailing gear was installed.

B.2 DOWNTIME RECORD FOR THE C11 OUTBOUND TUNNEL

Figures B.2, B.3, and B.4 summarize the downtimes for the C11 outbound tunnel as percentages of individual shift time for the general categories of TBM maintenance and repair, backup system repair, and ground conditions, respectively. The factors affecting the downtime in each of the categories summarized in Figures B.2 through B.4 are discussed under the headings that follow.

B.2.1 TBM Maintenance

Delays in this category, including general maintenance and repair of the lubricating oil system, amounted to 5.1 percent of the total shift time. Table B.1 summarizes the downtime causes, number of shifts affected by each cause, and the number of shift hours involved. General maintenance includes checking the torque on the cutter saddle bolts, cleaning and repair of the water nozzle system and normal maintenance of the TBM conveyor. Cutterhead checks were performed at the start of most shifts, and were often made concurrently with repairs to other parts of the excavation system. Most of the downtime on the lubricating oil system was caused by the pump, which was replaced twice during the project. The excavation system was down for one shift at Station 81+44 to install a piece of pipe between the TBM and the trailing gear. This pipe served as a brake on the trailing gear during downhill excavation.

B.2.2 Electric Systems

Delays in this category occurred during 37 shifts and resulted in a loss of 55 hours or 1.6 percent of the total shift time. In most of these cases, the notation on the reports was "power outage at the heading." Many of the problems appeared to have been caused by loose and broken wires in the TBM control panel. If methane were detected at the heading, the monitoring meter was wired to shut off power to the TBM. This occurred once. Many outages were caused by a defective arc welder on the trailing floor.

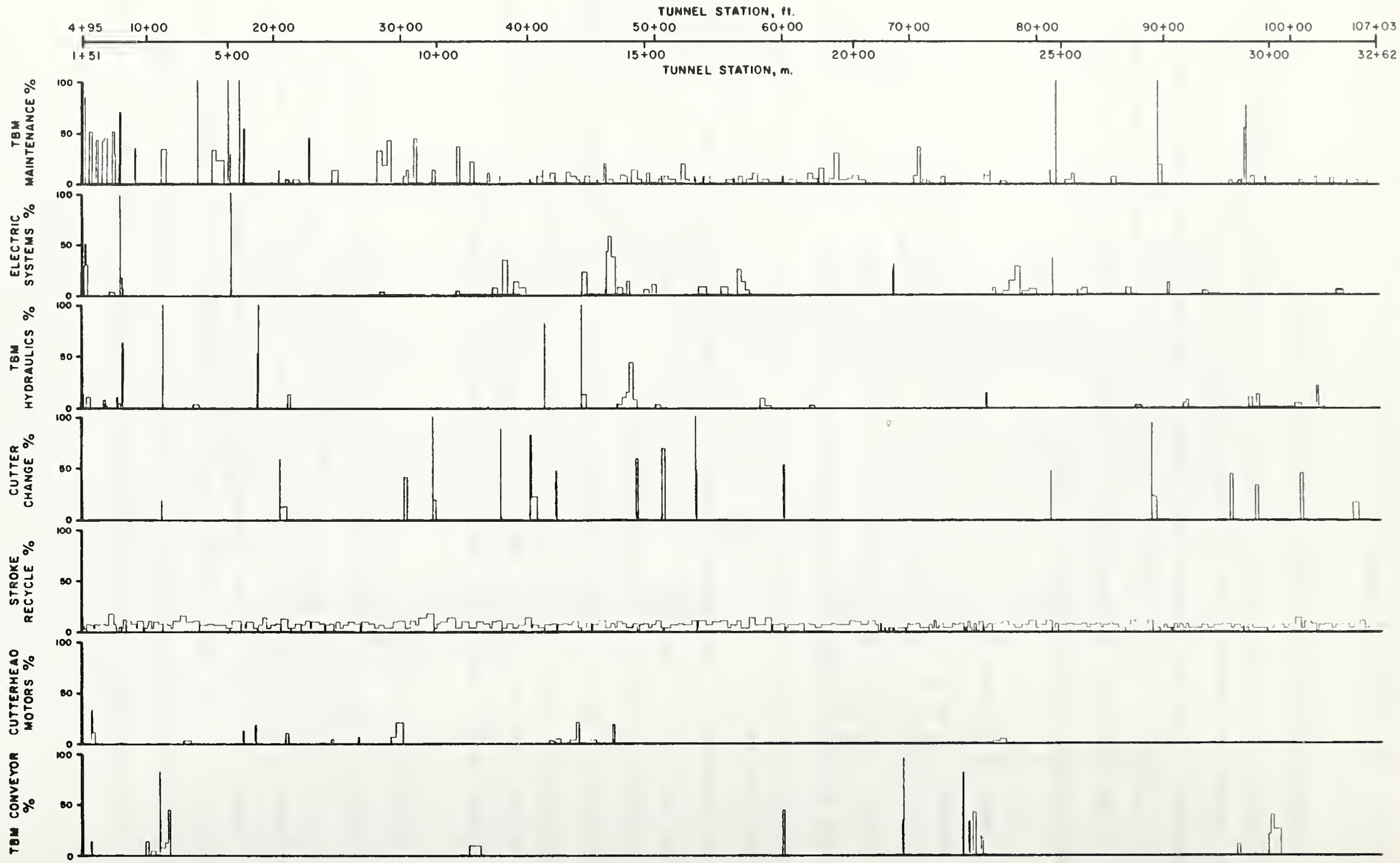


FIGURE B.2 SUMMARY OF TBM MAINTENANCE AND REPAIR DOWNTIME FOR THE C11 OUTBOUND TUNNEL

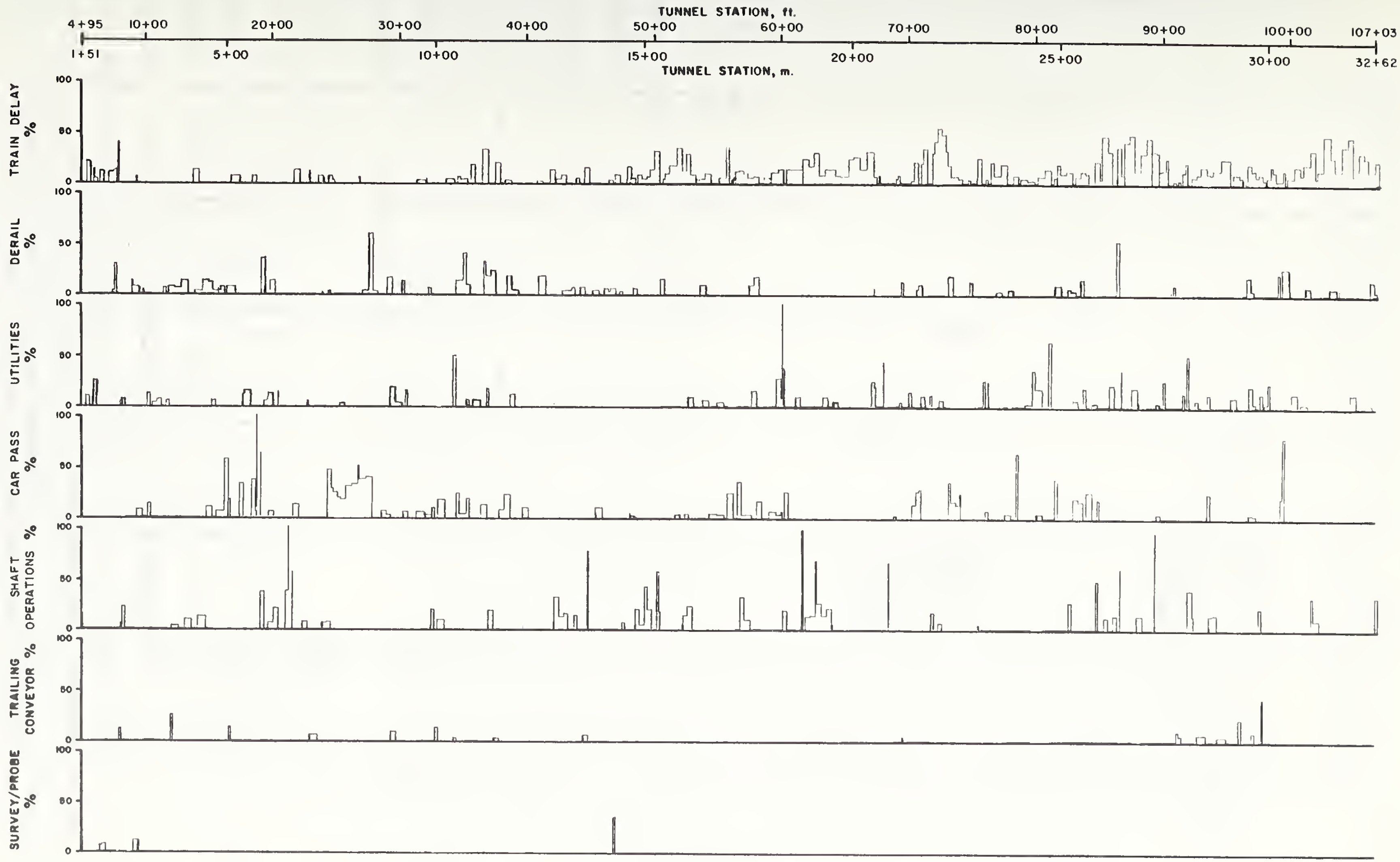


FIGURE B.3 SUMMARY OF BACKUP SYSTEM DOWNTIME FOR THE C11 OUTBOUND TUNNEL

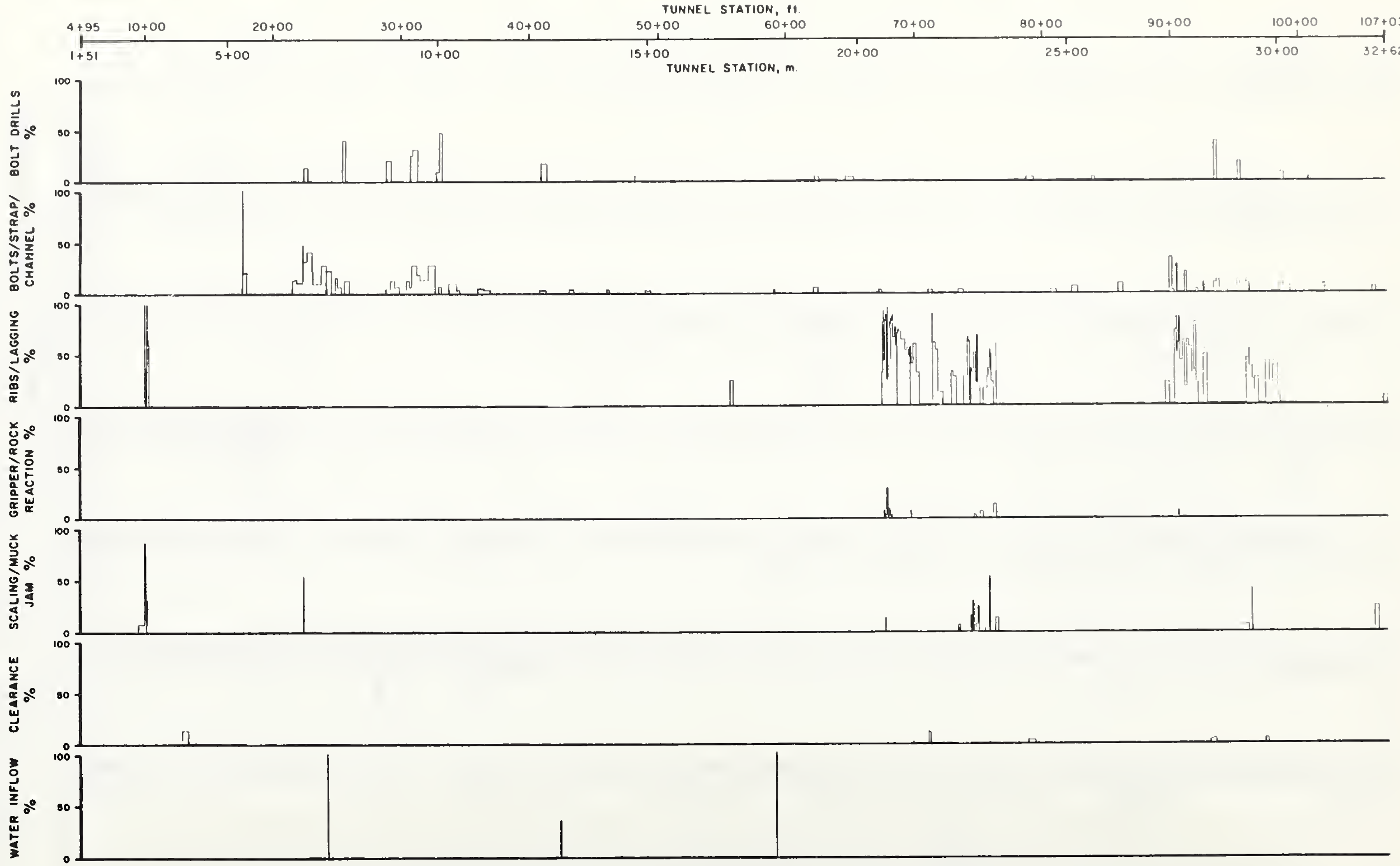


FIGURE B.4 SUMMARY OF GROUND CONDITION DOWNTIME FOR THE C11 OUTBOUND TUNNEL

TABLE B.1 SUMMARY OF DOWNTIME CAUSES, NUMBER OF SHIFTS, AND SHIFT HOURS ASSOCIATED WITH C11 OUTBOUND TBM MAINTENANCE

DOWNTIME CAUSE	NUMBER OF SHIFTS AFFECTED	NUMBER OF SHIFT HOURS INVOLVED
General Maintenance	22	66
Cutterhead Check	62	27
Lube Oil System	15	30
Install Pipe Brake	1	8
Total	100	131

B.2.3 TBM Hydraulics

Delays in this category amounted to 8.2 percent of the total shift time. Table B.2 summarizes the downtime causes, number of shifts affected by each cause and the shift hours required for repair. The right gripper cylinder developed leaks three times during the drive. To stop the leaks, the hydraulic oil was drained from the system and both gripper pads were bolted to the tunnel walls for support during repair. To gain access to the cylinder, the TBM conveyor belt inside the main beam had to be removed. Repair of the gripper cylinder accounts for 90 percent of the downtime in this category.

B.2.4 Cutter Change

The tunneling system was down expressly for cutter changes 17 times involving 23 shifts. Table B.3 summarizes the location of cutter changes, number of cutters changed, and hours of downtime for the changes. Four cutters were changed while the excavation system was down for repairs to other system components. The time required for these changes has not been included in the downtime hours listed in Table B.3. Twenty-four cutters were changed during maintenance at Shaft E,

TABLE B.2 SUMMARY OF DOWNTIME CATEGORIES, NUMBER OF SHIFTS, AND SHIFT HOURS ASSOCIATED WITH C11 OUTBOUND TBM HYDRAULICS

DOWNTIME CAUSE	NUMBER OF SHIFTS AFFECTED	NUMBER OF SHIFT HOURS INVOLVED
General Maintenance	10	11
Rear Supports	2	8
Grippers	37	254
Cutterhead Side Supports	4	6
Thrust Cylinders	1	1
Total	54	280

TABLE B.3 SUMMARY OF CUTTER CHANGES, TUNNEL LOCATIONS, NUMBER OF SHIFTS, AND HOURS OF DOWNTIME FOR THE C11 OUTBOUND TUNNEL

LOCATION	NUMBER OF CUTTERS CHANGED	NUMBER OF SHIFTS WITH CUTTER CHANGE DOWNTIME	DOWNTIME HOURS
Before Shaft E	24	13	59
At Shaft E (53+03)	24	—	—
After Shaft E	15	10	32
Total	63	23	91

but the time loss at this location has been included in the category of "shaft downtime" in Chapter 4. A total of 2.6 percent of the shift time was required to change cutters at other locations in the tunnel.

B.2.5 Stroke Recycle

Downtime due to recycling the thrust cylinders required a fairly steady 3.9 percent of the total shift time. There were a total of 2,297 restroke cycles, at an average of 4.32 ft (1.32 m) per cycle. Where steel support was used in weathered and jointed rock, reset times were often greater than 10 minutes. In sections where the rock required only minimal support, the reset time was often less than 3 minutes.

B.2.6 Cutterhead Motors

Downtime in this category was caused by difficulty with the air clutch system or with motors overheating. Sixteen shifts were affected by time losses because of cutterhead motor repair, amounting to 0.3 percent of the total shift time.

B.2.7 TBM Conveyor

Downtime in this category was caused by repair and splicing of the conveyor belt. Rips often developed when rock blocks became wedged in the main beam and clogged the conveyor. The belt was removed and replaced twice. Nineteen shifts were affected by TBM conveyor downtime, and time loss amounted to 1.5 percent of the total shift time.

B.2.8 Train Delay

This category was used when an absence of muck cars at the heading was recorded without a specific reason for the delay. Downtime because of lack of cars occurred during 162 shifts, and for 80 of these the delays were one hour or more. Delays increased with increasing distance between the heading and Shaft F. In total, 183 hours, or 5.4 percent of the total shift time, were spent waiting for an empty muck train.

B.2.9 Derailment

There were 86 derailments during tunnel excavation. Table B.4 summarizes the derailment locations, number of incidents, and downtime hours required to reset the train. The most time consuming individual derailments were those that occurred between the trailing floor and Shaft F, but the majority of the incidents occurred near or at the car pass. Many of the derailments at Shaft F were caused, in part, by muck build-up at the rollover. Cleaning up after the derailments and putting the train back on line required 1.9 percent of the total shift time.

B.2.10 Utilities

This category includes downtime for ventilation, air, water and track line installation and electric cable extension and loss of electricity. Table B.5 summarizes the number of shifts and downtime hours affected by utility supply. It should be noted that fan line rerouting through Shaft F was performed when the excavation system was down for other causes, and the time for this is not included in Table B.5. In general, utility downtime increased with increasing distance between the heading and Shaft F, and delays in this category amounted to 2.6 percent of the total shift time.

B.2.11 Car Pass

This category includes downtime primarily caused by repairs to the car pass assembly. When the car pushers were not operating, a locomotive had to be on the trailing floor to maneuver the muck cars and assemble the train. Repairs to the car pass system directly affected 75 shifts, but many more shifts were indirectly affected by slow mucking when the car pass system was down. A total 120 hours, or 3.5 percent of the total shift time, was directly associated with car pass assembly repairs.

B.2.12 Shaft Operations

Downtime in this category was caused by repairs to the mucking system at Shaft F. Table B.6 summarizes the mucking system components, number of shifts affected, and hours of downtime because of component repair. A total of 71 shifts was involved in mucking system repair. Many problems at the rollover were associated with muck accumulations in the mechanism. The rollover also experienced electrical problems and the drive belt had to be replaced once. The conveyors were down with a

TABLE B.4 SUMMARY OF DERAILMENTS, LOCATIONS, AND HOURS OF DOWNTIME FOR THE C11 OUTBOUND TUNNEL

DERAILMENT LOCATION	NUMBER OF DERAILMENTS	DOWNTIME HOURS
Trailing Floor	57	41
Tunnel	5	9
Shaft F	9	6
Unspecified Location	15	10
Total	86	66

TABLE B.5 SUMMARY OF UTILITY SERVICES, NUMBER OF SHIFTS, AND HOURS OF DOWNTIME FOR THE C11 OUTBOUND TUNNEL

SERVICE	NUMBER OF SHIFTS AFFECTED	DOWNTIME HOURS
Fan Line	28	26
Air, Water and Electric Lines	30	24
Surface Power	3	9
Rail	19	28
Total	74[a]	87

[a]During 6 shifts, work was performed on more than one utility service.

TABLE B.6 SUMMARY OF SYSTEM COMPONENTS, NUMBER OF SHIFTS, AND SHIFT HOURS ASSOCIATED WITH SURFACE MUCKING EQUIPMENT REPAIR FOR THE C11 OUTBOUND TUNNEL

COMPONENT	NUMBER OF SHIFTS AFFECTED	DOWNTIME HOURS
Rollover/Shaker/ Grizzly	20	18
Conveyors	32	59
Bucket Elevator	23	152
Total	71[a]	229

[a]During 4 shifts, repairs were made on more than one surface mucking system component.

variety of problems including muck jams, torn belts, and electrical repairs. Bucket elevator repairs caused the greatest delay in this category. Six shifts were required for repair when a railroad tie became jammed in the elevator, and 11 shifts were required for repairs after shaft flooding. In total, shaft mucking system repairs accounted for 6.7 percent of the shift time.

B.2.13 Trailing Conveyor

Downtime for repairs to the trailing floor conveyor occurred during 17 shifts. Repair of belt tears and conveyor belt adjustments accounted for 13 of these incidents. The conveyor motor was replaced once, a bearing on a return roller was replaced once, and two repairs were required on the flap gate and chute at the car pass end of the belt. In total, 0.5 percent of the shift time was involved with trailing conveyor repair.

B.2.14 Survey/Methane Probe

The contractor was not required to drill a methane probe hole on this project. Delays caused by resetting the laser occurred two times; all other resets were performed while the excavation system was in operation. Downtime because of dust interfering with the laser and target system was not included in this category. In total, 4 hours, or 0.1 percent of the total shift time, were required for laser resets.

B.2.15 Bolt Drills

Downtime for repair of the rock bolt drills occurred during 16 shifts. In addition to general repairs and hydraulic hose replacements, the platform control cylinders were damaged twice and the right drill platform had to be replaced. The hydraulic motor for the drill controls also had to be replaced once. A total of 0.6 percent of the shift time was required for bolt drill repair.

B.2.16 Bolt/Strap/Channel Installation

Rock bolts and straps were used on this project. Where bolting alone was required for rock support, little downtime was accumulated. Strap placement required extra time at several locations. In total, excavation was delayed by bolt and strap installation for 59 hours, or 1.7 percent of the shift time.

B.2.17 Ribs/Lagging

Steel sets were installed in ten sections of the tunnel. Table B.7 summarizes the steel set locations, number of sets, set spacing, and total downtime hours used in the steel set erection. The times listed include any downtime spent placing lagging between the steel ribs. Two sets were also installed at the end of the tunnel to facilitate the removal of the trailing floor. The delays amounted to 380 hours over 97 shifts, or 11.3 percent of the shift time.

B.2.18 Gripper/Rock Reaction

Blocky rock and springline overbreak caused problems when the gripper pads could not make firm contact with the side wall. In such cases, timber cribbing often was used to allow the grippers to sustain the

TABLE B.7 SUMMARY OF LOCATIONS, SPACINGS, AND DOWNTIME HOURS ASSOCIATED WITH STEEL SET INSTALLATION FOR THE C11 OUTBOUND TUNNEL

STATIONS WITH STEEL SET SUPPORT	NUMBER OF STEEL SETS	SPACING OF STEEL SETS ft	m	DOWNTIME HOURS
9+59 - 10+00	11	4	1.2	20
66+90 - 69+90	75	4	1.2	184
70+99 - 71+67	15	4-5	1.2-1.5	18
72+63 - 73+04	9	5	1.5	5
73+74 - 74+70	23	4-5	1.2-1.5	30
75+30 - 76+12	17	5	1.5	24
89+52 - 91+28	55	3-4	0.9-1.2	64
92+22 - 92+42	5	5	1.5	8
95+71 - 96+51	17	5	1.5	15
97+15 - 98+25	23	5	1.5	12
Total	250			380

reaction as the TBM was thrust forward. Eleven shifts were affected by this problem, covering 0.2 percent of the total shift time.

B.2.19 Scaling/Muck Jam

In areas of blocky rock, large pieces of rock often became jammed in the mucking system. Most commonly, this occurred at the head of the TBM conveyor in the main beam. Occasionally, rock falls occurred behind the heading, and loose rock had to be scaled from the crown. A total of 37 hours, or 1.1 percent of the shift time, was required to remove rock jams and to scale loose rock.

B.2.20 Clearance

Advance of the trailing sleds through steel supported sections resulted in some components jamming against or snagging on the supports. This problem was most noticeable for the ventilation equipment. A total of 3 hours, or 0.1 percent of the shift time, was required for clearance.

B.2.21 Water Inflow

Significant water infiltration occurred once in the outbound tunnel near Station 24+00. Excavation was stopped for one shift to pump the 18 in. (457 mm) depth of water that accumulated at the heading. Water from the inbound tunnel flooded parts of the outbound tunnel, but the outbound TBM was not affected. Removing the water and getting the mucking system back in operation required 13 shifts. In total, 15 shifts were affected by pumping water and subsequent clean-up amounting to 3.4 percent of the shift time.

B.3 DOWNTIME RECORD FOR THE C11 INBOUND TUNNEL

Figures B.5, B.6 and B.7 summarize the downtimes for the C11 outbound tunnel as percentages of individual shift time for the general categories of TBM maintenance and repair, backup system repair, and ground conditions, respectively. The factors affecting the downtime in each of the categories summarized in Figures B.5 through B.7 are discussed under the headings that follow.

B.3.1 TBM Maintenance

Downtimes in this category cover both general maintenance and repair of the lubricating oil system amounting to 2.3 percent of the total shift time. Table B.8 summarizes the downtime causes, number of shifts affected by each cause, and the number of shift hours involved. Cutterhead checks were performed at the start of most shifts, and were often made concurrently with repairs to other parts of the excavation system. Most of the downtime on the lube oil system was caused by failure of pressure valves and hoses.

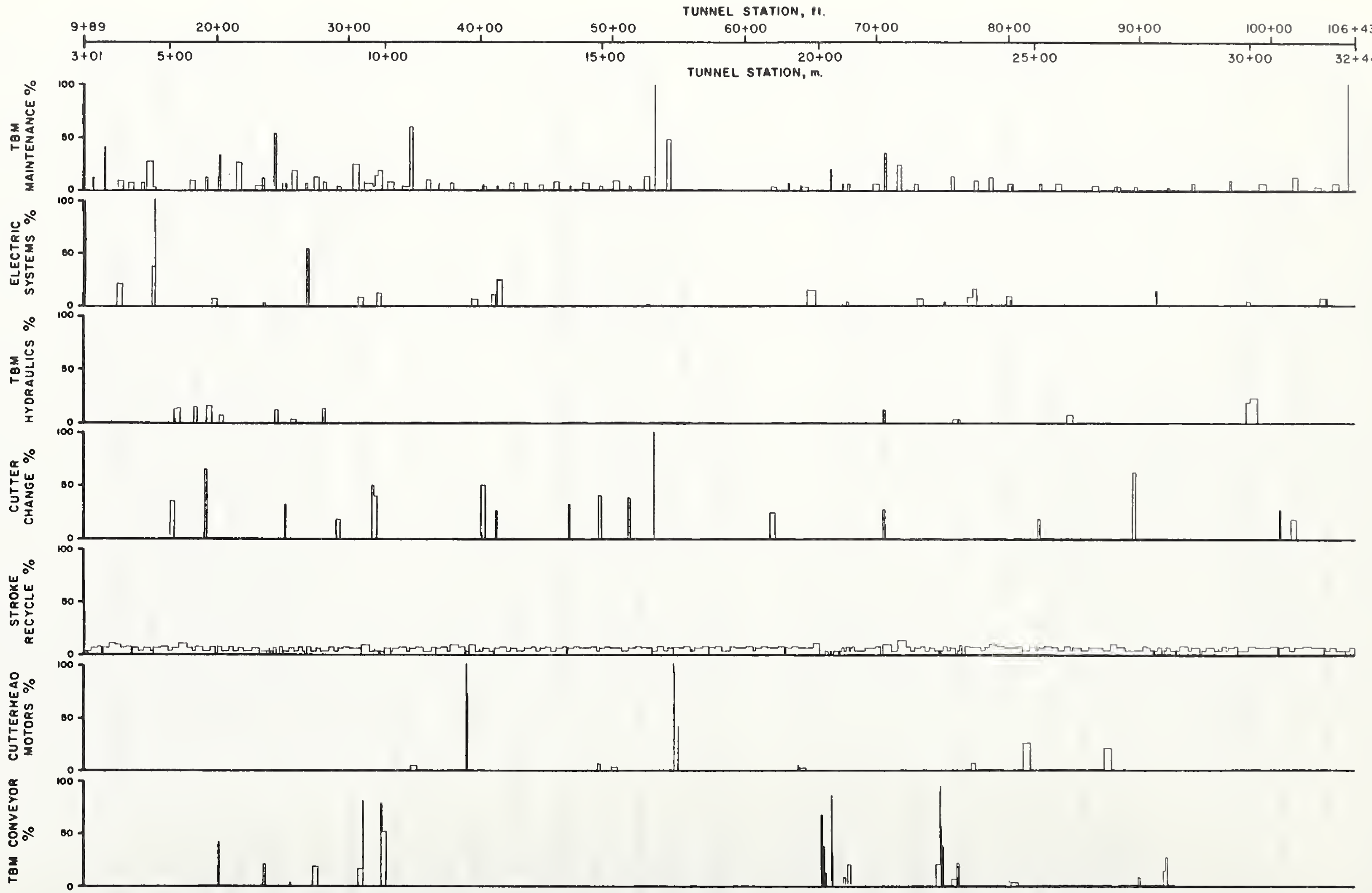


FIGURE B.5 SUMMARY OF TBM MAINTENANCE AND REPAIR DOWNTIME FOR THE C11 INBOUND TUNNEL

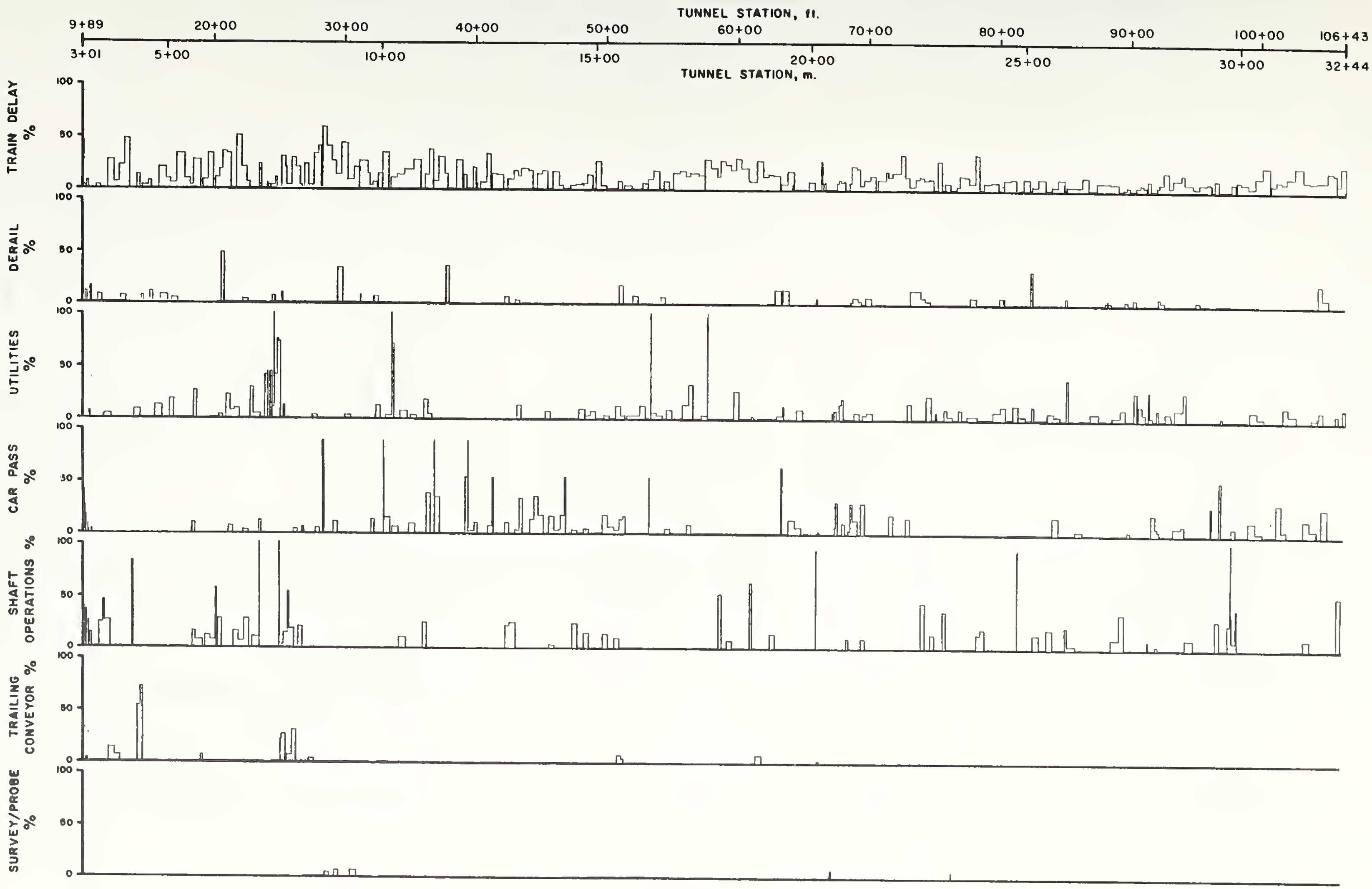


FIGURE B.6 SUMMARY OF BACKUP SYSTEM DOWNTIME FOR THE C11 INBOUND TUNNEL

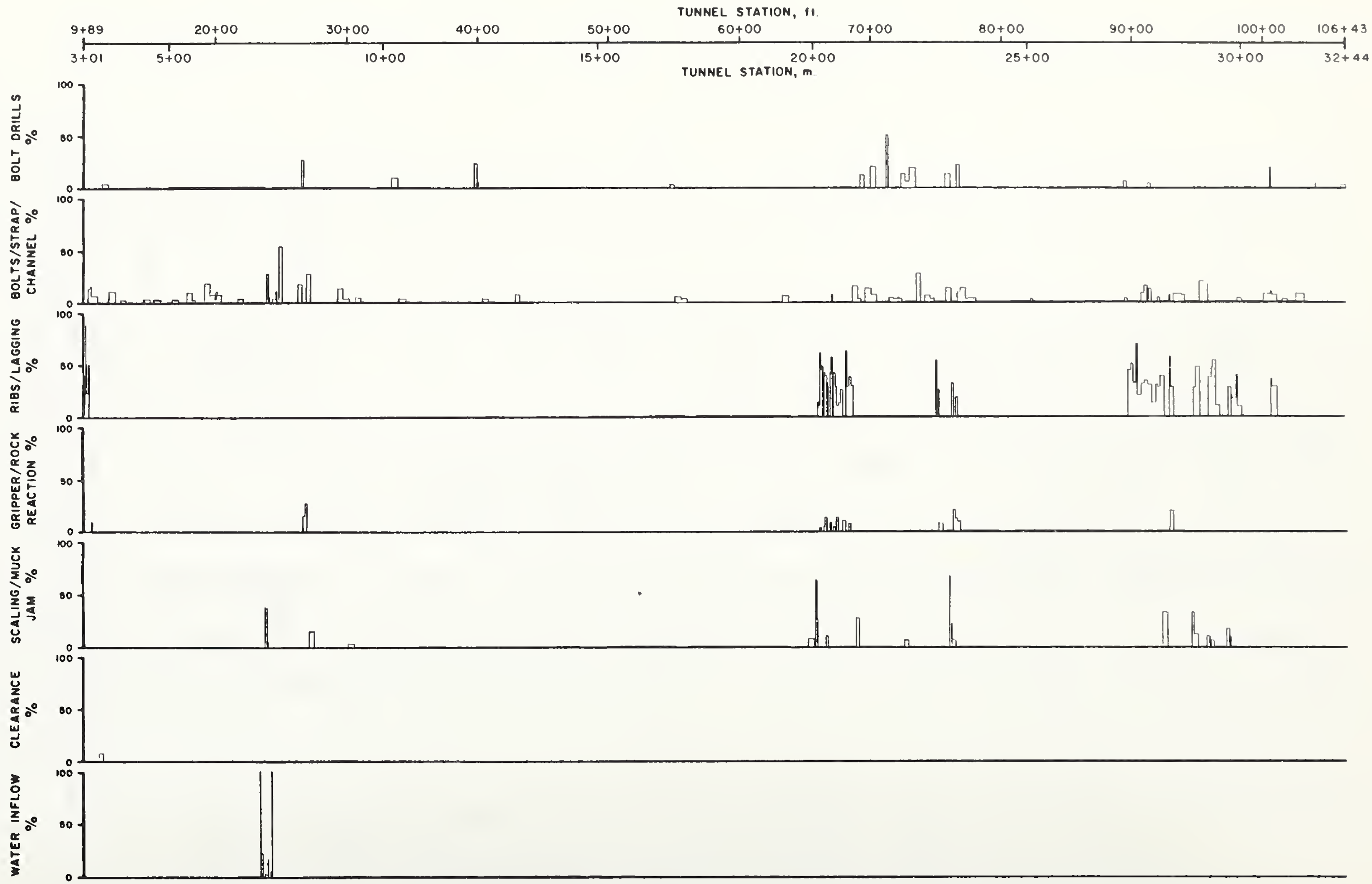


FIGURE B.7 SUMMARY OF GROUND CONDITION DOWNTIME FOR THE C11 INBOUND TUNNEL

TABLE B.8 SUMMARY OF DOWNTIME CAUSES, NUMBER OF SHIFTS, AND SHIFT HOURS ASSOCIATED WITH C11 INBOUND TBM MAINTENANCE

DOWNTIME CAUSE	NUMBER OF SHIFTS AFFECTED	NUMBER OF SHIFT HOURS INVOLVED
General Maintenance	17	32
Cutterhead Check Only	52	26
Lube Oil System	9	10
Total	78	68

B.3.2 Electric Systems

Delay in this category resulted in a loss of 37 hours, or 1.3 percent of the total shift time. A total of 21 shifts was affected. In most of these cases, the problem was indentified as power loss at the heading. Downtime was also caused by transformer repair and modification of the wiring on the electrical panel.

B.3.3 TBM Hydraulics

Delays in this category amounted to 0.4 percent of the total shift time. A total of 13 shifts was affected and the most frequent downtime cause was repair or replacement of hydraulic hoses and pressure valves. A total of 12 hours was involved in these repairs.

B.3.4 Cutter Change

The tunneling system was down expressly for cutter changes 16 times involving 25 shifts. Table B.9 summarizes the location of cutter changes, number of cutters changed, and hours of downtime for the changes. Three cutters were changed while the excavation system was down for repairs to other components, and the time for these changes is not included in Table B.9. Thirty-one cutters were changed during

TABLE B.9 SUMMARY OF CUTTER CHANGES, TUNNEL LOCATIONS, NUMBER OF SHIFTS, AND HOURS OF DOWNTIME FOR THE C11 INBOUND TUNNEL

LOCATION	NUMBER OF CUTTERS CHANGED	NUMBER OF SHIFTS WITH CUTTER CHANGE DOWNTIME	DOWNTIME HOURS
Before Shaft E	18	12	36
At Shaft E (53+04)	31	—	—
After Shaft E	11	7	15
Total	60	19	51

maintenance at Shaft E, but the time loss at this location has been included in the category of "shaft downtime" in Chapter 5. A total of 1.7 percent of the total shift time was required to change cutters at other locations in the tunnel.

B.3.5 Stroke Recycle

Downtime due to recycling the thrust cylinders required a fairly steady 3.5 percent of the total shift time. There were a total of 2,142 restroke cycles, at an average of 4.51 ft (1.37 m) per cycle. Where steel support was used in weathered and jointed rock, reset times were often greater than ten minutes. In sections where the rock required only minimal support, the reset time was often less than three minutes.

B.3.6 Cutterhead Motors

Downtime in this category amounted to 39 hours, 1.3 percent of the total shift time, and 85 percent of this time was spent removing faulty motors and installing repaired ones. The TBM mined 25 percent of the tunnel with only five motors operating. Additional problems included difficulty with the air clutch system, motors overheating, and loose bolts on the motor mounts.

B.3.7 TBM Conveyor

Downtime in this category was caused by repair and splicing of the belt and repair of the flashing at the cutterhead end of the main beam. The belt was removed and replaced five times. Rips often developed when rock blocks became wedged in the main beam. A total of 74 hours or 2.5 percent of the total shift time was required for repairs during 26 shifts.

B.3.8 Train Delay

This category was used when a specific reason for absence of muck cars at the heading was not cited. Downtime due to lack of cars occurred during 199 shifts, and for 87 of these the delays were one hour or more. During the first 7,450 ft (2,271 m) of the drive, both the inbound and outbound TBMs on the C11 Contract were operating and in competition for the use of the Shaft F mucking equipment. This, in part, caused the delays to be greater early in the inbound tunnel. Delays were less for the final 2,760 ft (841 m) of the tunnel. A total of 215 hours, or 7.3 percent of the total shift time, was spent waiting for an empty muck train.

B.3.9 Derailment

There were 48 derailments during the tunnel excavation. Table B.10 summarizes the derailment locations, number of incidents, and downtime hours required to reset the train. The majority of the incidents occurred near or at the car pass. Many of the derailments at Shaft F were caused, in part, by muck buildup at the rollover. Cleaning up after derailments and putting the train back on line required 1.2 percent of the total shift time.

B.3.10 Utilities

This category includes downtime for ventilation, air, water and track line installation and electric cable extension and loss of electricity. Table B.11 summarizes the number of shifts involved and downtime hours for utility supply. One shift was required to reroute the fan line through Shaft F. Most of the downtime because of rail installation and surface power loss occurred early in the drive, in the

TABLE B.10 SUMMARY OF DERAILMENTS, LOCATIONS, AND HOURS OF DOWNTIME FOR THE C11 INBOUND TUNNEL

DERAILMENT LOCATION	NUMBER OF DERAILMENTS	DOWNTIME HOURS
Trailing Floor	36	26
Tunnel	2	1
Shaft F	6	6
Unspecified Location	4	2
Total	48	35

TABLE B.11 SUMMARY OF UTILITY SERVICES, NUMBER OF SHIFTS, AND HOURS OF DOWNTIME FOR THE C11 INBOUND TUNNEL

SERVICE	NUMBER OF SHIFTS AFFECTED	DOWNTIME HOURS
Fan Line	31	25
Air, Water, and Electric Lines	51	38
Surface Power	9	29
Rail	22	50
Total	96[a]	142

[a]During 17 shifts, work was performed on more than one utility service.

water inflow area near Station 24+00. Sediment, carried into the tunnel by the water, was deposited in the invert in thicknesses up to 2 ft (0.6 m). This material had to be removed and the track relaid. Downtime because of fan, air, water, and electric line installation generally increased with increasing distance between the heading and Shaft F, and amounted to 4.8 percent of the total shift time.

B.3.11 Car Pass

This category includes downtime primarily caused by repairs to the car pass assembly. The full car pusher was inoperative for two tunnel sections, from Station 28+20 to 32+81 and from 37+61 to 38+50. The empty car pusher was also inoperative twice, between Stations 33+50 and 36+72, and from 38+50 to 41+10. In these sections, a locomotive had to be on the trailing floor to maneuver the muck cars and assemble the train. The car pass main drive chain was replaced once and the bearings on the car pass truck were replaced twice. Both full and empty muck car pusher motors were also replaced. Repairs to the car pass system directly affected 81 shifts, but more shifts were indirectly affected by slow mucking when the car pass was down. A total of 121 hours, or 4.1 percent of the total shift time, was directly associated with car pass repairs.

B.3.12 Shaft Operations

Downtime in this category was caused by repairs to the mucking system in Shaft F. Table B.12 summarizes the mucking system components, number of shifts affected, and hours of downtime caused by component repair. A total of 77 shifts was involved in mucking system repair. The rollover drive motor was replaced once, and three conveyor motors burned out and had to be replaced. The conveyor belts were torn many times and had to be repaired, and three bearings on the conveyors had to be replaced. The bucket elevator chain guide rails had to be repaired or replaced four times and 12 damaged buckets were replaced during 11 shifts of downtime shortly after the water inflow zone. In total, shaft mucking system repairs amounted to 9.0 percent of the total shift time.

TABLE B.12 SUMMARY OF SYSTEM COMPONENTS, NUMBER OF SHIFTS, AND SHIFT HOURS ASSOCIATED WITH SURFACE MUCKING EQUIPMENT FOR THE C11 INBOUND TUNNEL

COMPONENT	NUMBER OF SHIFTS AFFECTED	DOWNTIME HOURS
Rollover/Shaker/Grizzly	13	20
Conveyors	40	70
Bucket Elevator	26	173
Unspecified	1	1
Total	77[a]	264

[a]During 3 shifts, repairs were made to more than one surface mucking system component.

B.3.13 Trailing Conveyor

Downtime for repairs to the trailing floor conveyor occurred during 16 shifts. Repair of belt tears and conveyor belt adjustments accounted for many of these incidents, and the flap gate, muck hopper, and conveyor motor also required repair. In total, 21 hours, or 0.7 percent of the total shift time, were involved with trailing conveyor repair.

B.3.14 Survey/Methane Probe

The contractor was not required to drill a methane probe hole on this project. Delays caused by resetting the laser occurred four times; all other resets were performed while the excavation system was in operation. Downtime due to dust interfering with the laser and target system was not included in this category. In total, 2 hours or 0.1 percent of the total shift time were required for laser resets.

B.3.15 Bolt Drills

Downtime for repairs of the rock bolt drills occurred during 17 shifts. Most of the downtime was caused by ruptured water or hydraulic lines. The right bolt drill was replaced once. A total of 20 hours, or 0.7 percent of the total shift time, were required for bolt drill repair.

B.3.16 Bolt/Strap/Channel Installation

Rock bolts and straps were used on this project. Where bolting alone was required for rock support, little downtime was accumulated. Strap placement required extra time at several locations. Sixty-one shifts were affected and excavation was delayed for bolt and strap installation for 42 hours, or 1.4 percent of the total shift time.

B.3.17 Ribs/Lagging

Steel sets were installed in ten sections of the tunnel. Table B.13 summarizes the steel set locations, number of sets, set spacing, and total downtime hours used in steel set erection. The times listed include any downtime spent placing lagging between the steel ribs. The delays amounted to 164 hours over 68 shifts, or 5.5 percent of the total shift time.

B.3.18 Gripper/Rock Reaction

Blocky rock and springline overbreak caused problems when the gripper pads could not make firm contact with the side wall. In such cases, timber cribbing often was used to allow the grippers to sustain a reaction as the TBM was thrust forward. Sixteen shifts were affected by this problem, and 15 hours, or 0.5 percent of the total shift time, were spent in placing timber support for the gripper pads.

B.3.19 Scaling/Muck Jam

In areas of blocky rock, large pieces of rock often became jammed in the mucking system. Most commonly, this occurred at the head of the TBM conveyor in the main beam. A total of 22 shifts was affected, and 36 hours, or 1.2 percent of the total shift time were required to remove the jams and to muck out the main beam.

TABLE B.13 SUMMARY OF LOCATIONS, SPACINGS, AND DOWNTIME HOURS ASSOCIATED WITH STEEL SET INSTALLATION FOR THE C11 INBOUND TUNNEL

STATIONS WITH STEEL SET SUPPORT	NUMBER OF STEEL SETS	SPACING OF STEEL SETS ft	SPACING OF STEEL SETS m	DOWNTIME HOURS
9+69 - 10+09	11	4	1.2	21
65+68 - 68+24	55	4-5	1.2-1.5	56
74+78 - 75+00	6	4	1.2	6
75+86 - 76+32	11	5	1.5	6
89+62 - 91+88	66	3-4	0.9-1.2	36
92+55 - 92+80	6	5	1.5	7
94+64 - 94+84	5	5	1.5	6
95+70 - 96+33	14	5	1.5	12
97+15 - 97+95	17	5	1.5	9
100+42 - 100+52	3	5	1,5	5
Total	194			164

B.3.20 Clearance

Advance of the trailing sleds through steel supported sections resulted in some components jamming against or snagging on the supports. This problem occurred once with the ventilation system and 0.5 hours were required for clearance.

B.3.21 Water Inflow

Significant water inflow occurred in the inbound tunnel between Stations 23+28 to 24+64 and from 25+92 to 27+27. Excavation was restricted or halted during 33 shifts while the water was removed and the rail line was reinstalled. Water depth reached a maximum depth of 8 ft (2.4 m) at the lowest point in the tunnel, but was 14 to 24 in. (0.36 to

0.61 m) at the heading. The water inflow also had an indirect effect on excavation by making it difficult to remove wet muck with the cutterhead buckets and the conveyor systems. In total, 174 hours or 5.9 percent of the total shift time were required for water inflow control and clean up.

B.4 DOWNTIME RECORD FOR THE C31 OUTBOUND TUNNEL

Figures B.8, B.9, and B.10 summarize the downtimes for the C31 outbound tunnel as percentages of individual shift time according to the general categories of TBM maintenance and repair, backup system repair, and ground conditions, respectively. The downtime analysis was made on the basis of shift reports from both the contractor and resident engineer. In all cases, the summation of the identified downtime and machine clock time was compared with the available shift time and the difference was assigned to the category of "other" as explained in Chapter 6. Factors affecting the downtime in each of the categories summarized in Figures B.8 through B.10 are discussed under the headings that follow.

B.4.1 TBM Maintenance

Delays in this category, including both general machine maintenance and repair of the lubricating oil system, amounted to 6.3 percent of the total shift time. Table B.14 summarizes the downtime causes, number of shifts affected by each cause, and the number of shifts involved. General maintenance includes checking the torque on the cutter saddle bolts, cleaning and repair of the cutterhead water spray system, greasing and checking the main bearing, and normal maintenance of the TBM conveyor and other systems. Cutterhead checks were made at the start of many shifts, and were often made during delays from other causes. Lubricating oil system delays often were caused by repairs of the oil pump. The motor for the pump was replaced once during the project.

B.4.2 Electric Systems

Delays in this category occurred during 28 shifts, and 4.5 percent of the total shift time was involved. At Station 30+08, the TBM was down for 24 hours, while repairs were made on the high voltage circuit breaker. At Station 31+91, excavation was stopped for 11 shifts after

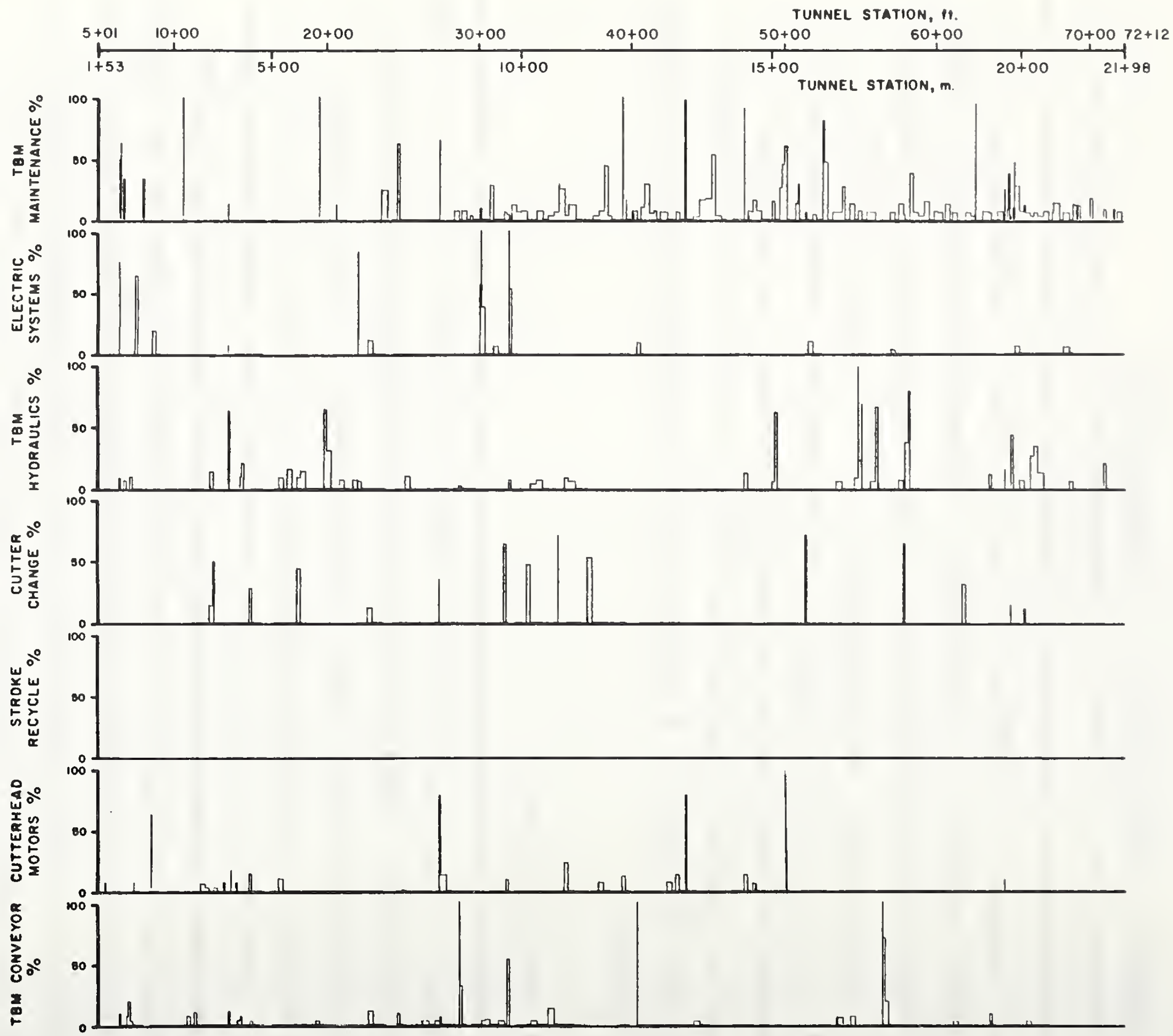


FIGURE B.8 SUMMARY OF TBM MAINTENANCE AND REPAIR DOWNTIME FOR THE C31 OUTBOUND TUNNEL

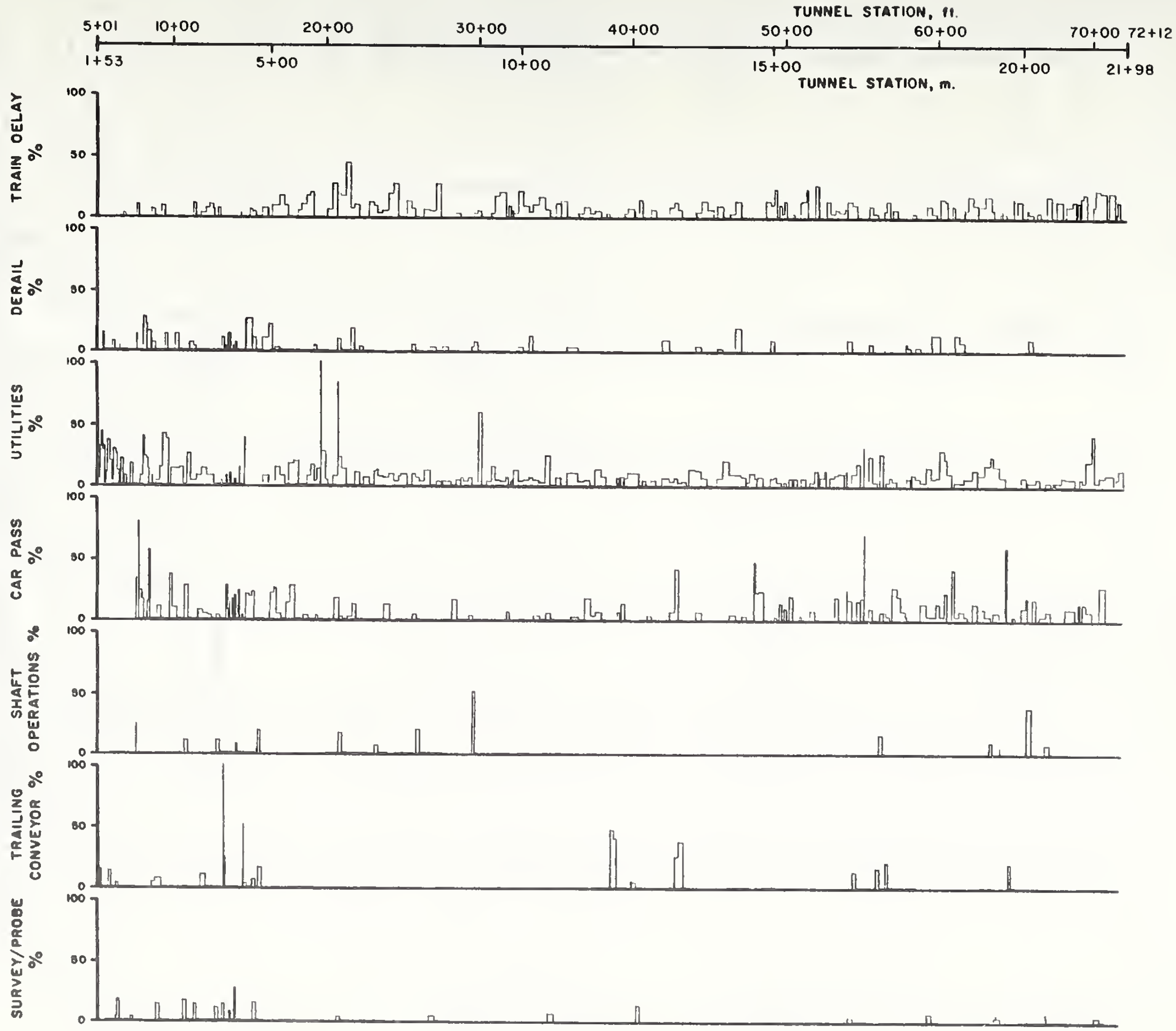


FIGURE B.9 SUMMARY OF BACKUP SYSTEM DOWNTIME FOR THE C31 OUTBOUND TUNNEL

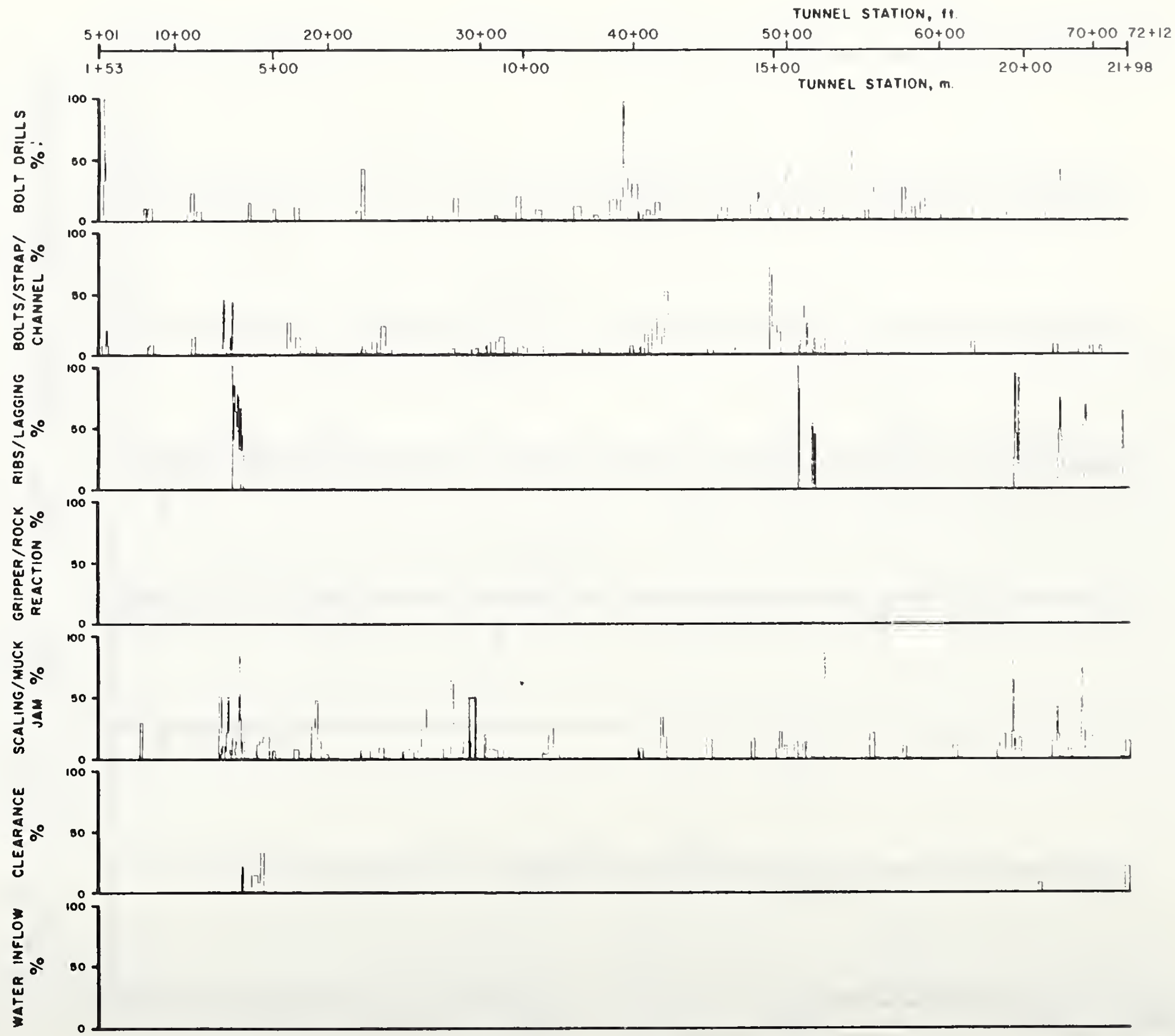


FIGURE B.10 SUMMARY OF GROUND CONDITION DOWNTIME FOR THE C31 OUTBOUND TUNNEL

TABLE B.14 SUMMARY OF DOWNTIME CAUSES, NUMBER OF SHIFTS, AND SHIFT HOURS ASSOCIATED WITH C31 OUTBOUND TBM MAINTENANCE

DOWNTIME CAUSE	NUMBER OF SHIFTS AFFECTED	NUMBER OF SHIFT HOURS
General Maintenance	33	81
Cutterhead Check Only	67	40
Lube Oil System	16	44
Total	111[a]	165

[a]During 5 shifts, repairs were performed in more than one maintenance category.

the transformer caught on fire. A total of 81 hours was required to remove and repair the transformer and to rewire the switch panel. A monitoring meter was wired so that the power to the TBM would be shut off, if methane were detected at the heading. Electrical faults in methane sensor caused power losses three times, and 13 hours were required to restore power to the heading.

B.4.3 TBM Hydraulics

Delays in this category amounted to 78 hours or 2.9 percent of the total shift time. Table B.15 summarizes the downtime causes, number of shifts affected by each hydraulic system component, and the shift hours required for repair. The lower right thrust cylinder broke off twice, at Stations 19+91 and 54+83. On the first occasion, the bolts on all four thrust cylinders were replaced. On the second occasion, all welds were reinforced. At Station 58+05, the center pin came out of one of the grippers and 9.0 hours were required to reinstall it.

B.4.4 Cutter Change

A total of 29 cutters was changed during the C31 outbound tunnel-

TABLE B.15 SUMMARY OF DOWNTIME CAUSES, NUMBER OF SHIFTS, AND SHIFT HOURS ASSOCIATED WITH C31 OUTBOUND TBM HYDRAULICS

DOWNTIME CAUSE	NUMBER OF SHIFTS AFFECTED	NUMBER OF SHIFT HOURS
General Maintenance	22	24
Rear Supports	0	0
Grippers	5	19
Cutterhead Side Supports	2	2
Thrust Cylinders	13	33
Total	42	78

ing, excluding replacements during scheduled maintenance at Station 39+33. A total of 1.8 percent of the total shift time was required for these changes. Information on cutter changes at Station 39+33 was not available.

B.4.5 Stroke Recycle

Downtime due to recycling the thrust cylinders could not be estimated from the shift reports. There were a total of 1,579 restroke cycles at an average of 4.31 ft (1.32 m) per cycle. The total percentage time spent on recycling is included under the category "other" in Chapter 6.

B.4.6 Cutterhead Motors

A total of 25 shifts included downtime for repairs of the cutterhead motors. This downtime amounted to 41 hours, or 1.5 percent of the total shift time. Most of this delay was because of air clutch line repairs. More than half of the tunnel was excavated with less than the full complement of six functioning motors.

B.4.7 TBM Conveyor

Downtime in this category was primarily caused by repairs to the conveyor belt, idler bearings, and muck transfer hopper at the cutterhead. The hopper often was plugged with rock blocks, and rips developed in the conveyor belt when these blocks were wedged inside the main beam. The conveyor belt was replaced once. Conveyor repairs were made during 37 shifts and the time loss amounted to 85 hours, or 3.2 percent of the total shift time.

B.4.8 Train Delay

This category was used when an absence of muck cars at the heading was recorded without a specific reason for the delay. Downtime due to lack of cars occurred during 128 shifts, and for 48 of these, the delays were one hour or more. In total, 104 hours, or 4.0 percent of the total shift time, were spent waiting for an empty muck train.

B.4.9 Derailment

There were 52 derailments during the tunnel excavation, most of these at unspecified locations. A total of 51 shifts was affected, and 35 hours, or 1.3 percent of the total shift time, were required to clean up after the derailments and to put the locomotive and cars back on line.

B.4.10 Utilities

This category includes downtime for ventilation, electric, water, air, and track line installation. Table B.16 summarizes the number of shifts involved and downtime hours required to supply each of these services. A total of 150 hours, or 5.7 percent of the total shift time, was required to supply these services.

B.4.11 Car Pass

Downtime in this category was primarily caused by repairs of the car pass mechanism. The car pass drive chain broke at least four times. A locomotive had to be on the trailing floor to position and advance the muck trains when the car pass was inoperative. Many of the individual reports indicate that the sliding track, rather than the empty or full

TABLE B.16 SUMMARY OF UTILITY SERVICES, NUMBER OF SHIFTS, AND HOURS OF DOWNTIME FOR THE C31 OUTBOUND TUNNEL

SERVICE	NUMBER OF SHIFTS AFFECTED	DOWNTIME HOURS
Fanline	150	84
Air, Water, and Electric Lines	24	43
Surface Power	4	4
Rail	26	19
Total	176[a]	150

[a]During 28 shifts, work was performed on more than one utility service.

car pusher, was the most frequent source of trouble. A total of 115 hours, or 4.4 percent of the total shift time, was associated with car pass assembly repairs.

B.4.12 Shaft Operations

Downtime in the shaft mucking system occurred during 13 shifts, and the main cable of the crane, which was used to lift the muck cars, was changed once. A total of 18 hours, or 0.7 percent of the total shift time, was required for shaft mucking system repairs.

B.4.13 Trailing Conveyor

Downtime for repairs of the trailing floor conveyor occurred during 20 shifts. The conveyor needed alignment four times and the front bearing was replaced once. The belt was torn at Station 13+21 and 24 hours were required to replace it. In total, 47 hours, or 1.8 percent of the shift time, were involved with the trailing conveyor repair.

B.4.14 Survey/Methane Probe

The contractor was not required to drill a methane probe hole on this project. Delays in this category were primarily caused by laser reset and laser and target adjustments. Parts of 17 shifts, amounting to 12 hours or 0.5 percent of the total shift time, were required for work on the TBM guidance system.

B.4.15 Bolt Drills

Downtime for repair of the rock bolt drills occurred during 71 shifts. Early in the drive, the right bolt drill was torn from its platform. Later in the tunnel, both the drill and rotation motor had to be replaced. Other delays were due to general repairs and the removal of drill rods that were stuck in bolt holes. A total of 89 hours, or 3.4 percent of the total shift time, was required for bolt drill repair.

B.4.16 Bolt/Strap/Channel Installation

Rock bolts and straps were used on this project. Downtime to install bolts and straps occurred during 54 shifts and excavation was delayed for a total of 55 hours, or 2.1 percent of the total shift time.

B.4.17 Ribs/Lagging

Steel sets were installed in seven sections of the tunnel. Table B.17 summarizes the steel set locations, number of sets, set spacing, and total downtime hours used in steel set erection, including time spent placing timber lagging between the steel ribs. The delays amounted to 208 hours over 46 shifts, or 7.9 percent of the total shift time. Between Stations 64+26 and 64+62, crown overbreak was extensive and 33 hours were used to fill voids above the tunnel.

B.4.18 Gripper/Rock Reaction

When the TBM was first installed, its gripper pads were positioned directly on the drill-and-blast surfaces of the tunnel. In this area, the springline overbreak was frequently large enough so that timber cribbing was needed to sustain a reaction between the machine and tunnel wall. A total of 93 hours was used to place the cribbing but because

TABLE B.17 SUMMARY OF LOCATIONS, SPACINGS, AND DOWNTIME HOURS ASSOCIATED WITH STEEL SET INSTALLATION FOR THE C31 OUTBOUND TUNNEL

STATIONS WITH STEEL SET SUPPORT	NUMBER OF STEEL SETS	SPACING OF STEEL SETS ft	m	DOWNTIME HOURS
13+40 - 14+18	21	4-5	1.2-1.5	70
50+08 - 50+33	6	5	1.5	14
51+18 - 51+35	4	5-6	1.5-1.8	8
64+26 - 64+62	8	5	1.5	71
67+19 - 67+34	4	5	1.5	15
68+86 - 69+01	4	5	1.5	17
71+30 - 71+55	6	5	1.5	13
Total	53			208

this delay occurred before the trailing gear was assembled, the downtime was not included in the calculations in Chapter 6. After the trailing gear was constructed, problems with springline overbreak and gripper reaction were negligible.

B.4.19 Scaling/Muck Jam

In areas of jointed and weathered ground, large pieces of rock often became jammed in the mucking system. Occasionally, rock falls occurred behind the face, and loose rock had to be scaled from the crown. Table B.18 summarizes the muck jam locations and scaling incidents, number of shifts, and hours of delay associated with these activities. For three shifts, muck jams occurred more than once. A total of 140 hours, or 5.3 percent of the total shift time, was required to remove rock jams and to scale loose rock.

TABLE B.18 SUMMARY OF MUCK JAM LOCATIONS AND SCALING INCIDENTS, NUMBER OF SHIFTS, AND HOURS OF DOWNTIME FOR THE C31 OUTBOUND TUNNEL

DOWNTIME CAUSE	NUMBER OF SHIFTS AFFECTED	NUMBER OF SHIFT HOURS INVOLVED
Muck Jams		
Cutterhead	2	1
Muck Hoppers	22	22
TBM Conveyor	18	30
Trailing Conveyor	3	2
Unspecified Location	15	12
Scaling	32	73
Total	92	140

B.4.20 Clearance

Advance of the trailing floor equipment through steel supported sections often resulted in components jamming against or snagging on the steel ribs. This most often occurred with the trailing gear ventilation system. During seven shifts, a total of nine hours, or 0.3 percent of the total shift time, was required to either adjust the trailing gear components or reposition the steel sets.

B.4.21 Water Inflow

There were no recorded incidents of water infiltration causing delay in the C31 outbound tunnel.

B.5 DOWNTIME RECORD FOR THE C31 INBOUND TUNNEL

Figures B.11, B.12, and B.13 summarize the downtimes for the C31 inbound tunnel as percentages of individual shift time for the general categories of TBM maintenance and repair, backup system repair, and ground conditions, respectively. The downtime analysis was performed in the same manner as that for the C31 outbound tunnel, discussed in secion B.4 of this appendix. The factors affecting the downtime in each of the categories summarized in Figures B.11 through B.13 are discussed under the headings that follow.

B.5.1 TBM Maintenance

Contributing downtimes in this category cover both general maintenance of the TBM and repair of the lubricating oil system, amounting to 9.1 percent of the total shift time. Table B.19 summarizes the downtime causes, number of shifts affected by each cause, and the number of shift hours involved. At Station 9+63, six shifts were required to repair cracked gage cutter saddles. At Station 12+31, grizzly bars were installed over the TBM conveyor hopper to stop blocks from entering the main beam conveyor. These bars were repeatedly jammed with muck, however, and were removed at Station 14+89. Near Station 64+64, a crack developed in the TBM main beam and six shifts were required for repair. Cutterhead checks were performed at the start of most shifts, and were often made concurrently with repairs to other parts of the excavation system. Most of the downtime on the lubricating oil system was caused by seal oil pump problems.

B.5.2 Electric Systems

Delays in this category occurred during 42 shifts and resulted in the loss of 152 hours or 5.7 percent of the total shift time. The 2000 amp circuit breaker was tripped repeatedly and the transformer overheated many times before Station 56+37 when it burned out. Eleven shifts were required to replace the transformer, breakers, and wiring. At Station 66+88, the TBM control panel transformer failed and was replaced.

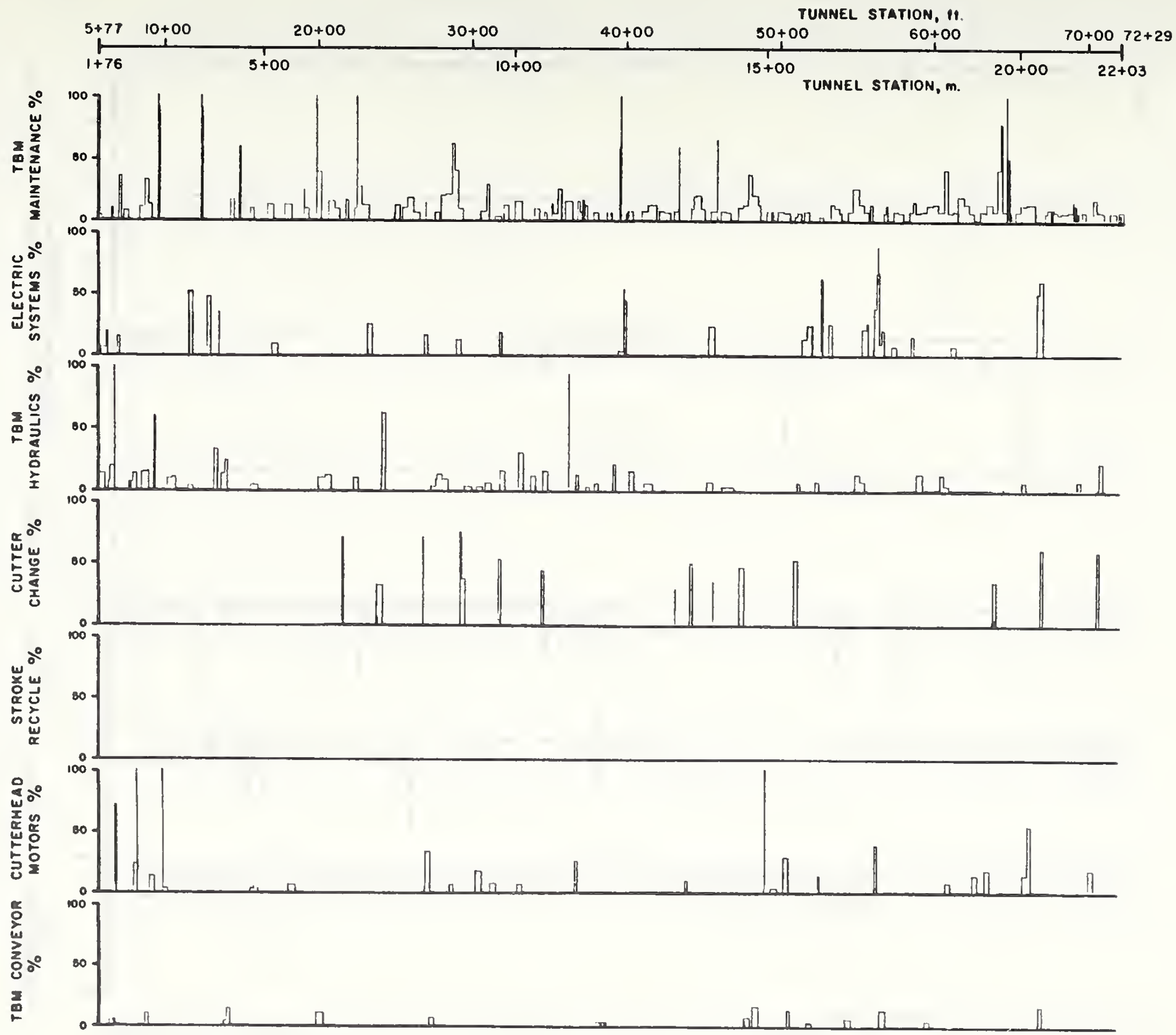


FIGURE B.11 SUMMARY OF TBM MAINTENANCE AND REPAIR DOWNTIME FOR THE C31 INBOUND TUNNEL

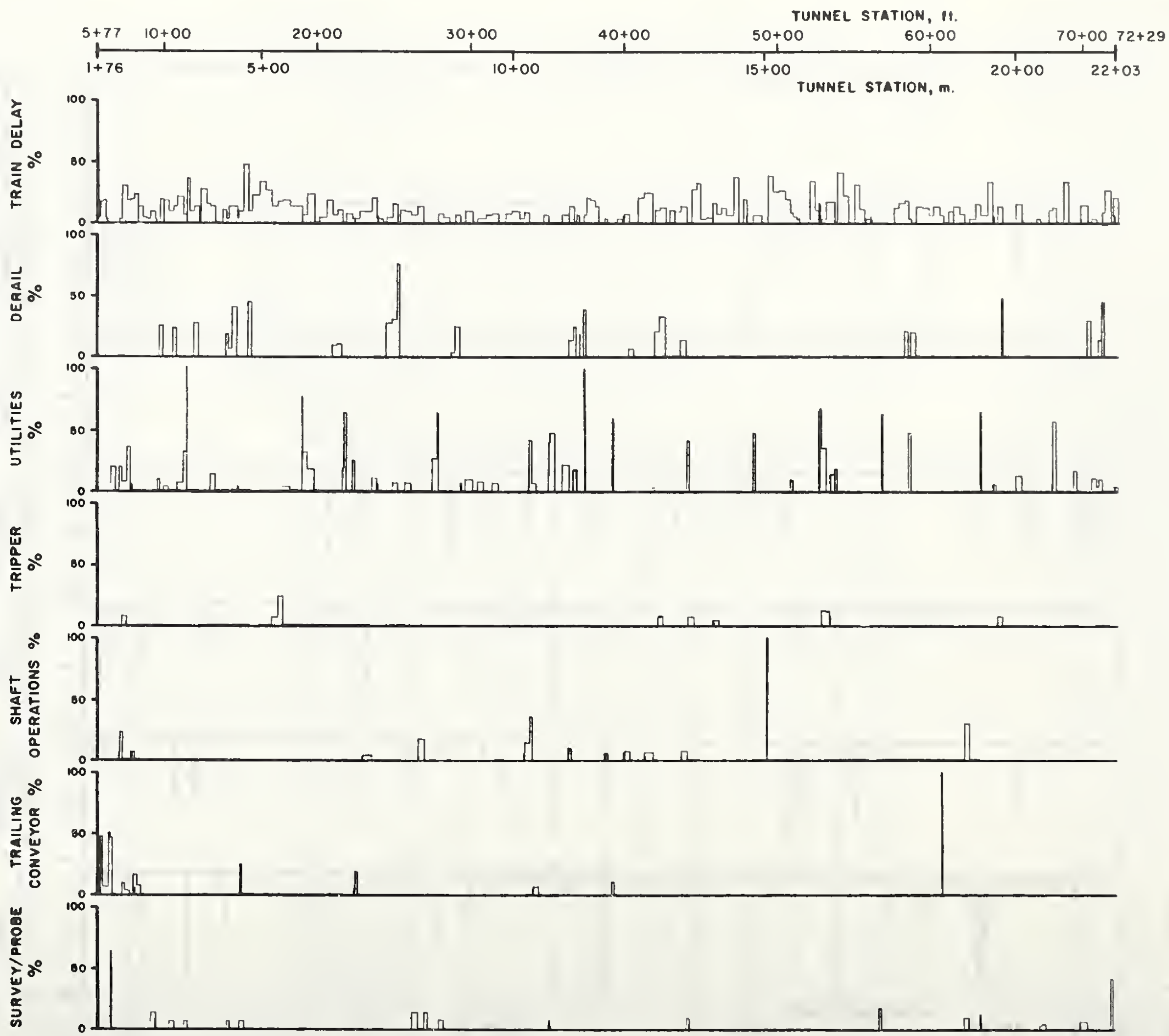


FIGURE B.12 SUMMARY OF BACKUP SYSTEM REPAIR DOWNTIME FOR THE C31 INBOUND TUNNEL

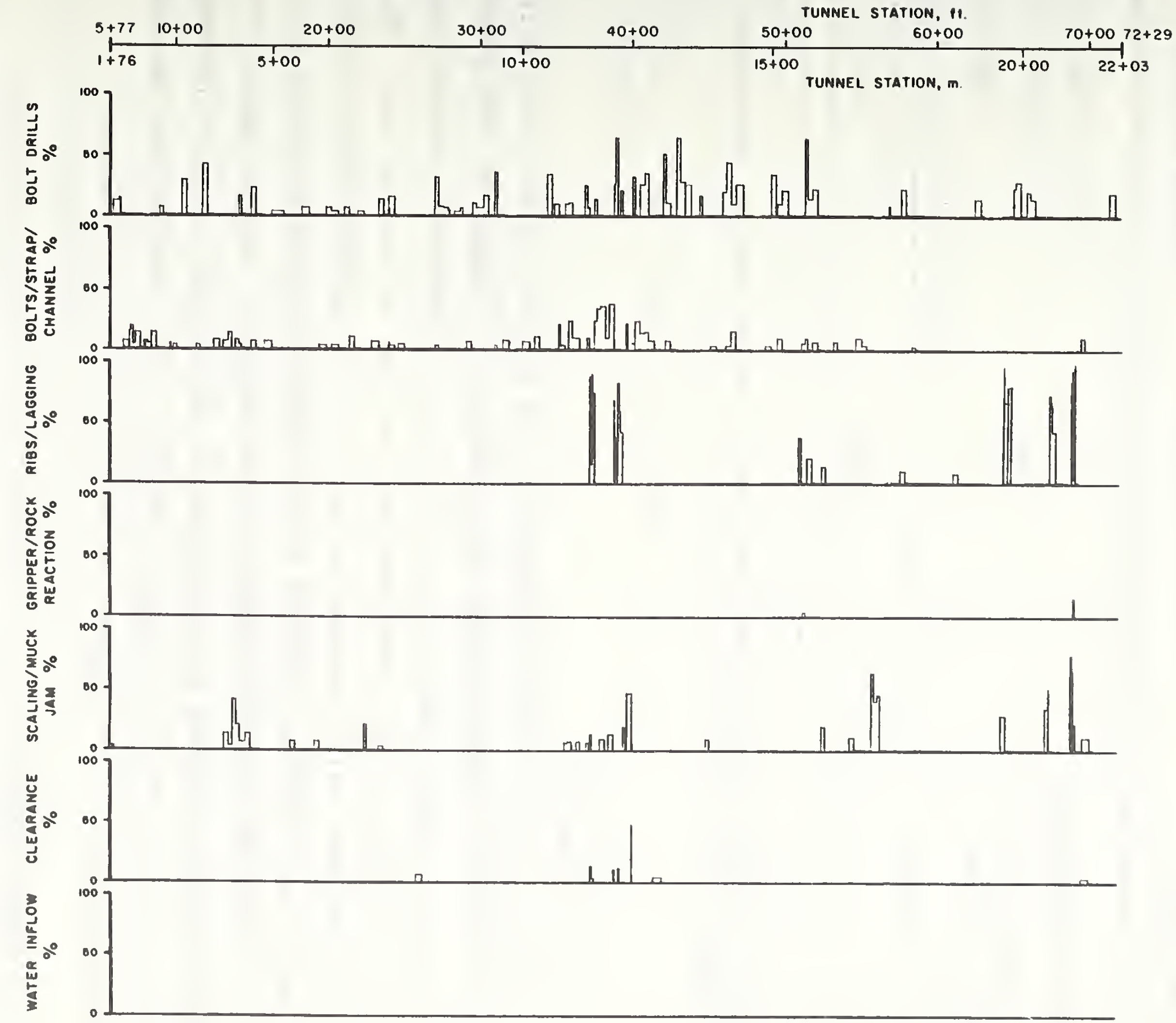


FIGURE B.13 SUMMARY OF GROUND CONDITION DOWNTIME FOR THE C31 INBOUND TUNNEL

TABLE B.19 SUMMARY OF DOWNTIME CAUSES, NUMBER OF SHIFTS, AND SHIFT HOURS ASSOCIATED WITH C31 INBOUND TBM MAINTENANCE

DOWNTIME CAUSE	NUMBER OF SHIFTS AFFECTED	NUMBER OF SHIFT HOURS INVOLVED
General Maintenance	36	135
Cutterhead Check Only	104	72
Lube Oil System	21	38
Total	146[a]	245

[a]During 15 shifts, repairs were performed in more than one maintenance category.

B.5.2 TBM Hydraulics

Delays in this category amounted to 5.3 percent of the total shift time. Table B.20 summarizes the downtime causes, number of shifts affected by each cause, and the the shift hours required for repair. The left side support on the cutterhead was torn off at Station 6+92. The cylinder had been fully extended to help the TBM maintain grade in an area where weak rock was present in the invert, and the connections at the pivot and the hydraulic piston failed during an advance cycle. Gripper repairs included faulty hydraulic valves and problems with the pin connections on both cylinders. Repair of the side support and the grippers account for 80 percent of the downtime in this category.

B.5.4 Cutter Change

A total of 52 cutters were changed during the C31 inbound tunneling. Thirty-two cutters were changed during maintenance at Shaft C, and the time loss required for these changes is listed under the category of "shaft downtime" in Chapter 7. A total of 2.5 percent of the total

TABLE B.20 SUMMARY OF DOWNTIME CAUSES, NUMBER OF SHIFTS, AND SHIFT HOURS ASSOCIATED WITH C31 INBOUND TBM HYDRAULICS

DOWNTIME CAUSE	NUMBER OF SHIFTS AFFECTED	NUMBER OF SHIFT HOURS INVOLVED
General Maintenance	23	23
Rear Supports	1	1
Grippers	18	23
Cutterhead Side Support	13	89
Thrust Cylinders	5	6
Total	57[a]	142

[a]During 3 shifts, repairs were made on more than one hydraulic component.

shift time was required to change the remaining 20 cutters at other locations in the tunnel.

B.5.5 Stroke Recycle

Downtime due to recycling of the thrust cylinders could not be estimated from the available records. There were a total of 1,742 re-stroke cycles, at an average of 3.81 ft (1.16 m) per cycle. The full stroke length of the thrust cylinders on this TBM was 4.0 ft (1.2 m).

B.5.6 Cutterhead Motors

Downtime in this category amounted to 93 hours, 3.5 percent of the total shift time, and occurred during 30 shifts. The TBM mined 48 percent of the tunnel with five motors operating, and 17 percent of the tunnel with only four motors on line. Most of the downtime was associated with burned out starter contacts. Several times, the 2000 amp breaker on the transformer was tripped.

B.5.7 TBM Conveyor

Downtime in this category was caused by repair of the belt, hydraulic fittings and rollers. A total of 11 hours or 0.4 percent of the total shift time was required for repairs during 21 shifts.

B.5.8 Train Delay

This category was used when a specific reason for absence of muck cars at the heading was not cited. Downtime due to lack of cars occurred during 149 shifts, and for 72 of these, delays were one hour or more. Delays were high early in the drive, in part because both the inbound and outbound TBMs on the C31 Contract were operating and in competition for the use of Shaft B mucking equipment. The outbound TBM completed its drive when the inbound TBM was at Station 33+90. Delays from Station 49+53 were, in part, caused by slow mucking at Shaft C. A total of 149 hours, or 5.6 percent of the total shift time, was spent waiting for an empty muck train.

B.5.9 Derailment

There were 30 derailments during the tunnel excavation, most of these at unspecified locations. Sixty percent of the incidents occurred in the first part of the drive, before Shaft C. Cleaning up after the derailments and putting the train back on line required 61 hours, or 2.3 percent of the total shift time.

B.5.10 Utilities

This category includes downtime for ventilation, air, water, and track line installation and electric cable extension and loss of electricity. Table B.21 summarizes the number of shifts involved and downtime hours for utility supply. Eighty percent of the time loss due to air, water, and electric lines was caused by electric cable extension. Cable delays occurred at a constant rate through the excavation, while delays associated with other utility services generally decreased with distance along the drive. The fan line was rerouted from Shaft B to Shaft C while the system was down for other reasons, and the time required is not included in Table B.21. Downtime due to fan, air, water,

TABLE B.21 SUMMARY OF UTILITY SERVICES, NUMBER OF SHIFTS AND HOURS OF DOWNTIME FOR THE C31 INBOUND TUNNEL

SERVICE	NUMBER OF SHIFTS AFFECTED	DOWNTIME CAUSE
Fan Line	27	31
Air, Water, and Electric Lines	32	101
Surface Power	0	0
Rail	7	6
Total	60[a]	138

[a]During 6 shifts, work was performed on more than one utility service.

rail, and electric lines amounted to 5.2 percent of the total shift time. There were no time losses due to surface power supply outage.

B.5.11 Tripper

Downtime to repair the tripper and other mechanical components of the muck loading system occurred during 11 shifts. Most of these cases involved repair of the tripper gear and deflecting chute, and the delays amounted to 11 hours, or 0.4 percent of the total shift time.

B.5.12 Shaft Operations

Downtime in this category was caused by repairs to the mucking system in Shaft B, and later in Shaft C. Twelve hours during nine shifts were involved in repairs. Also included in this category, is the time loss associated with moving the entire surface mucking operation to Shaft C, a move which required 18 shifts and 140 hours to complete. In total, work on the shaft and surface equipment amounted to 5.7 percent of the total shift time, of which 5.3 percent was required for the move to Shaft C.

B.5.13 Trailing Conveyor

Downtime for repairs of the conveyors on the trailing floor occurred during 16 shifts. The conveyor motor burned out twice early in the drive before an inching motor was installed to stop belt stalls. The transfer conveyor belt was replaced twice and the main belt was replaced once. In total, 31 hours, or 1.1 percent of the total time, were involved with conveyor repairs.

B.5.14 Survey/Methane Probe

The contractor was not required to drill a methane probe hole on this project. Delays caused by resetting the laser occurred during 17 shifts, and during three shifts repairs were made on the front laser target of the TBM. In total, 21 hours, or 0.8 percent of the total shift time, were required for laser resets and target repair.

B.5.15 Bolt Drills

Downtime for repairs of the rock bolt drills occurred during 61 shifts. Rotation motors were replaced twice and, toward the end of the drive, both drills were replaced. A total of 95 hours, or 3.5 percent of the total shift time, was required for bolt drill repair.

B.5.16 Bolt/Strap/Channel Installation

Rock bolts and straps were used on this project. Much of the downtime in this category occurred near Shaft C where the rock was fractured, in part, due to the drill-and-blast excavation for the shaft. Sixty-one shifts were affected by delays for bolt and strap installation, involving 46 hours, or 1.7 percent of the total shift time.

B.5.17 Ribs/Lagging

Steel sets were installed in six sections of the tunnel. Table B.22 summarizes the steel set locations, number of sets, set spacing, and total downtime hours used in steel set erection. The times listed include any downtime spent placing lagging between the steel ribs. The

TABLE B.22 SUMMARY OF LOCATIONS, SPACINGS, AND DOWNTIME HOURS ASSOCIATED WITH STEEL SET INSTALLATION OF THE C31 INBOUND TUNNEL

STATIONS WITH STEEL SET SUPPORT	NUMBER OF STEEL SETS	SPACING OF STEEL SETS ft	m	DOWNTIME HOURS
36+96 - 37+31	8	5	1.5	35
38+54 - 38+64	3	5	1.5	9
38+80 - 39+10	7	5	1.5	15
64+45 - 64+85	9	5	1.5	46
67+32 - 67+52	5	5	1.5	14
68+73 - 69+08	8	5	1.5	34
Total	40			153

delays amounted to 53 hours over 29 shifts, or 5.7 percent of the total shift time.

B.5.18 Gripper/Rock Reaction

At two places in the tunnel, springline overbreak caused problems when the gripper pads could not make firm contact with the tunnel wall, and timber cribbing was required to sustain a reaction. Two hours, or 0.1 percent of the total shift time, were required to place timber support for the gripper pads.

B.5.19 Scaling/Muck Jam

In areas of blocky rock, large pieces of rock often became jammed in the mucking system. Most commonly, this occurred in the hopper at the head of the TBM conveyor in the main beam or on the grizzly bars that were installed across the hopper mouth. Occasionally, rock falls occurred behind the heading, and loose rock had to be scaled from the

TABLE B.23 SUMMARY OF MUCK JAM LOCATIONS AND SCALING OCCURRENCES, NUMBERS OF SHIFTS, AND HOURS OF DOWNTIME FOR THE C31 INBOUND TUNNEL

DOWNTIME CAUSE	NUMBER OF SHIFTS AFFECTED	DOWNTIME HOURS
Muck Jams -		
Cutterhead	1	2
Grizzly Bars	8	11
Hoppers	6	7
Conveyors	6	22
Unspecified	2	1
Scaling	12	18
Total	35	61

crown. Table B.23 summarizes the locations of muck jams, the number of shifts involved with clearing muck jams and scaling loose rock from the TBM shield and tunnel walls, and the number of downtime hours required. A total of 61 hours, or 2.3 percent of the total shift time, was required to remove muck jams and to scale loose rock.

B.5.20 Clearance

Advance of the trailing sleds through steel supported sections resulted in some components jamming against or snagging on the supports. This problem was most noticeable for the ventilation equipment. A total of 8 hours, or 0.3 percent of the shift time, was required for clearance.

B.5.21 Water Inflow

There were no incidents of excavation delay associated with water inflow in this tunnel.

B.6 DOWNTIME RECORD FOR THE CULVER-GOODMAN TUNNEL

Figures B.14 through B.19 summarize the downtimes for the Culver-Goodman Tunnel as percentages of individual shift time. Figures B.14 and B.15 include downtimes for the general category of maintenance and repair, Figures B.16 and B.17 for backup system repair, and Figures B.18 and B.19 for ground conditions. Figures B.14, B.16, and B.18 cover the Densmore leg of the tunnel, Stations 3+98 to 85+71, and Figures B.15, B.17, and B.19 cover the Goodman leg of the tunnel, Stations 85+71 to 169+93. The factors affecting the downtime in each of the categories summarized in Figures B.14 through B.19 are discussed under the headings that follow.

B.6.1 TBM Maintenance

Contributing downtimes in this category cover both general TBM maintenance and repair of the lubricating oil system. Table B.24 summarizes the downtime causes, number of shifts affected by each cause, and the number of shift hours involved. Cutterhead checks were performed at the start of most shifts, and were often made concurrently with repairs to other parts of the excavation system. Most of the downtime on the lubricating oil system was caused by problems with the high pressure supply pump or the low pressure return pump. Each pump was replaced several times. The main bearing seal was changed during 14 shifts at Station 85+71, but the seal ring was not tight and, at Station 95+09, eight shifts were required to change the seal again. At Station 115+17, four shifts were required to replace a cutter saddle which was torn from the cutterhead. A total of 5.8 percent of the total shift time was required for repairs in this category.

B.6.2 Electric Systems

Delays in this category occurred during 38 shifts and resulted in a loss of 97 hours or 1.5 percent of the total shift time. In most cases, breakers in the TBM or main transformers were tripped and power to the TBM was shut off.

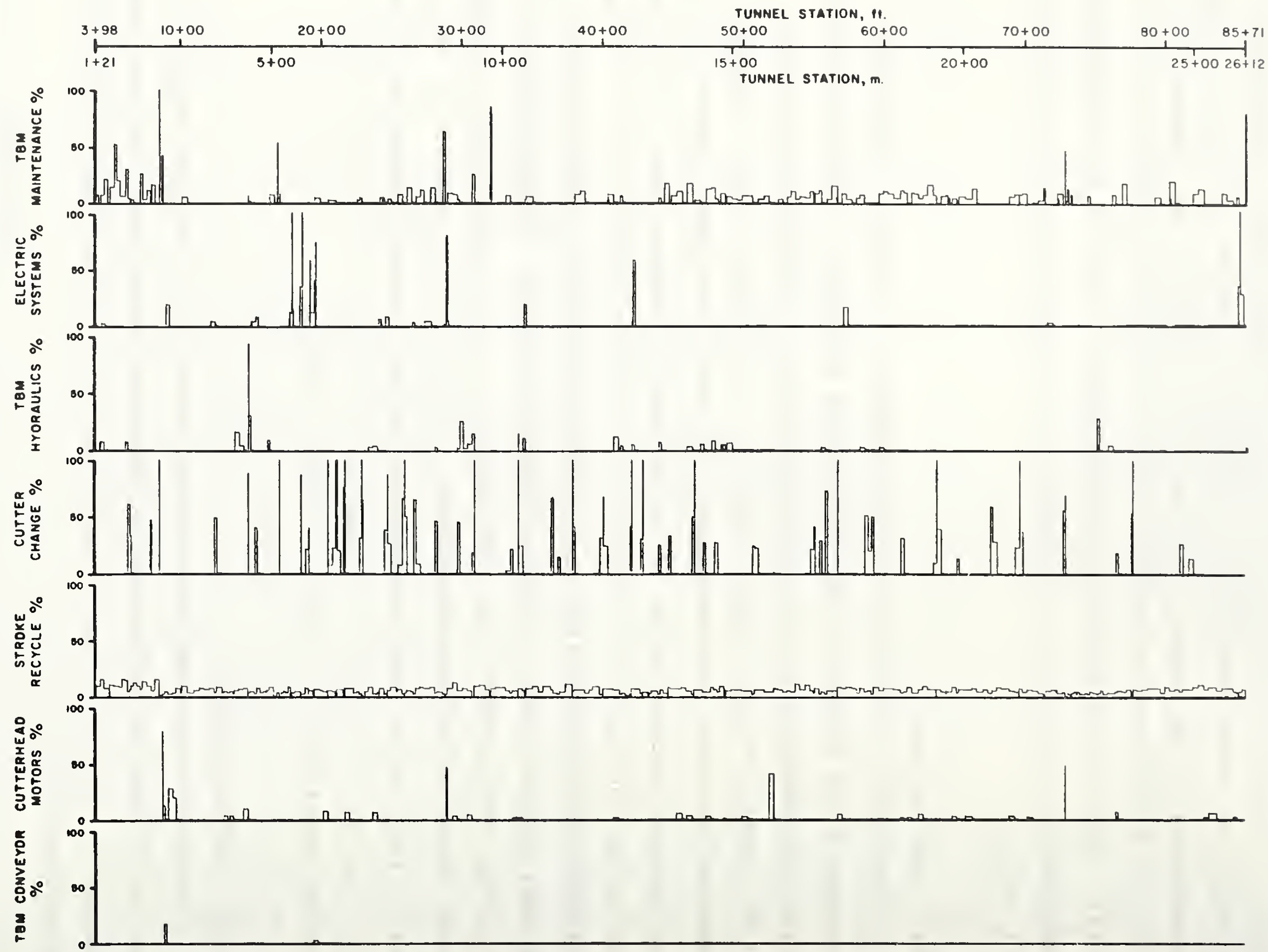


FIGURE B.14 SUMMARY OF TBM MAINTENANCE AND REPAIR DOWNTIME FOR THE DENSMORE LEG OF THE CULVER-GOODMAN TUNNEL

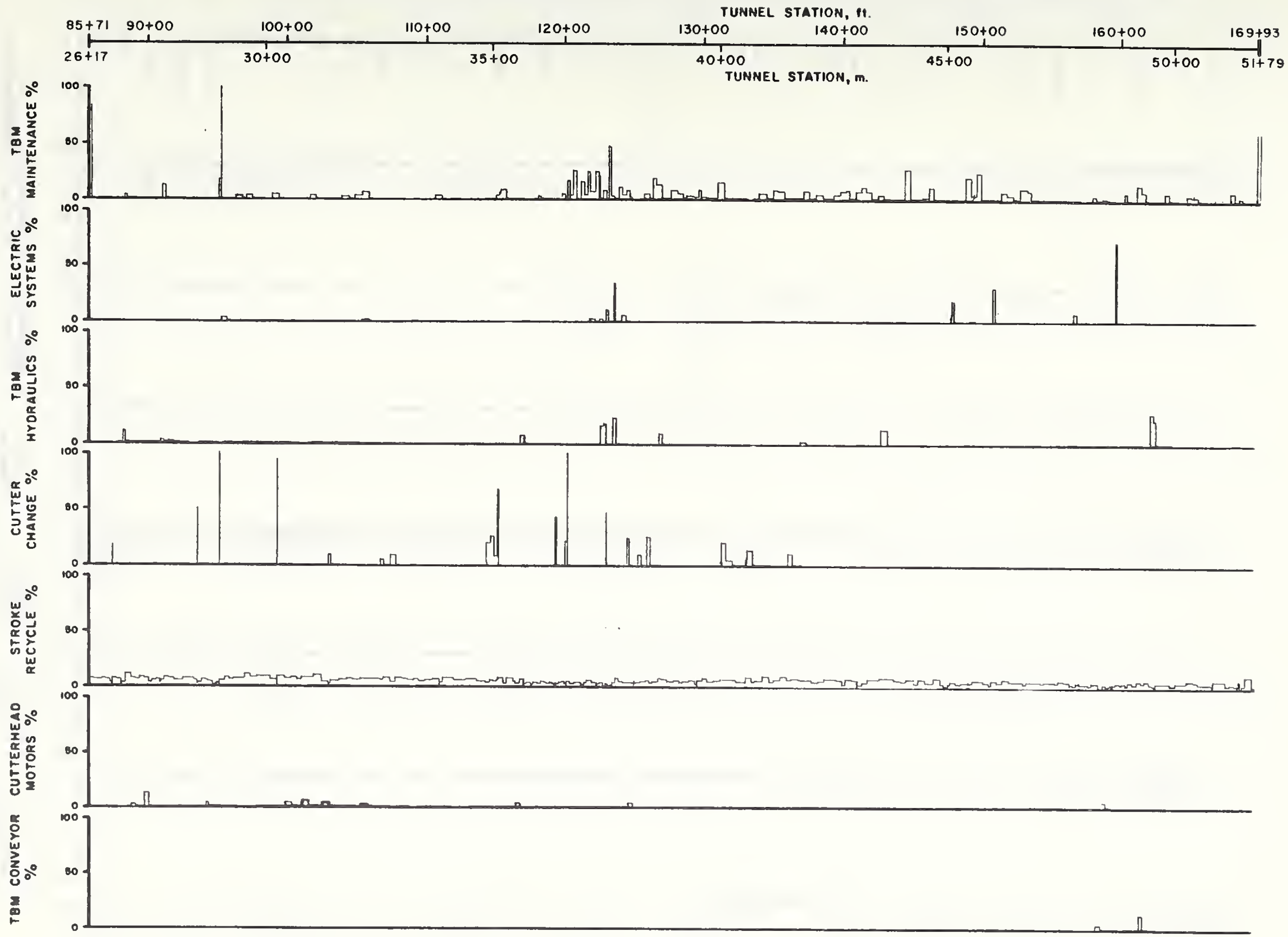


FIGURE B.15 SUMMARY OF TBM MAINTENANCE AND REPAIR DOWNTIME FOR THE GOODMAN LEG OF THE CULVER-GOODMAN TUNNEL

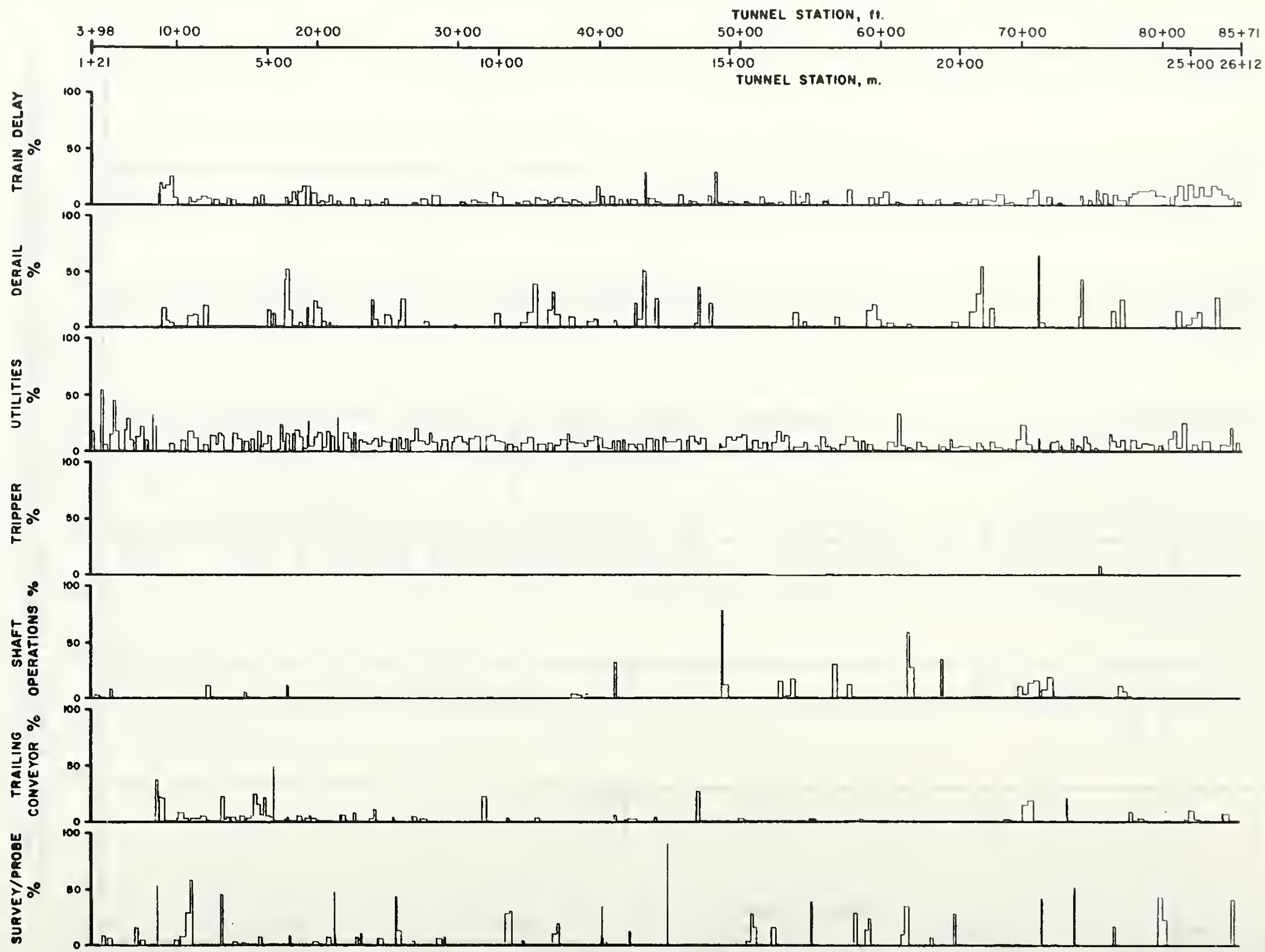


FIGURE B.16 SUMMARY OF BACKUP SYSTEM REPAIR DOWNTIME FOR THE DENSMORE LEG OF THE CULVER-GOODMAN TUNNEL

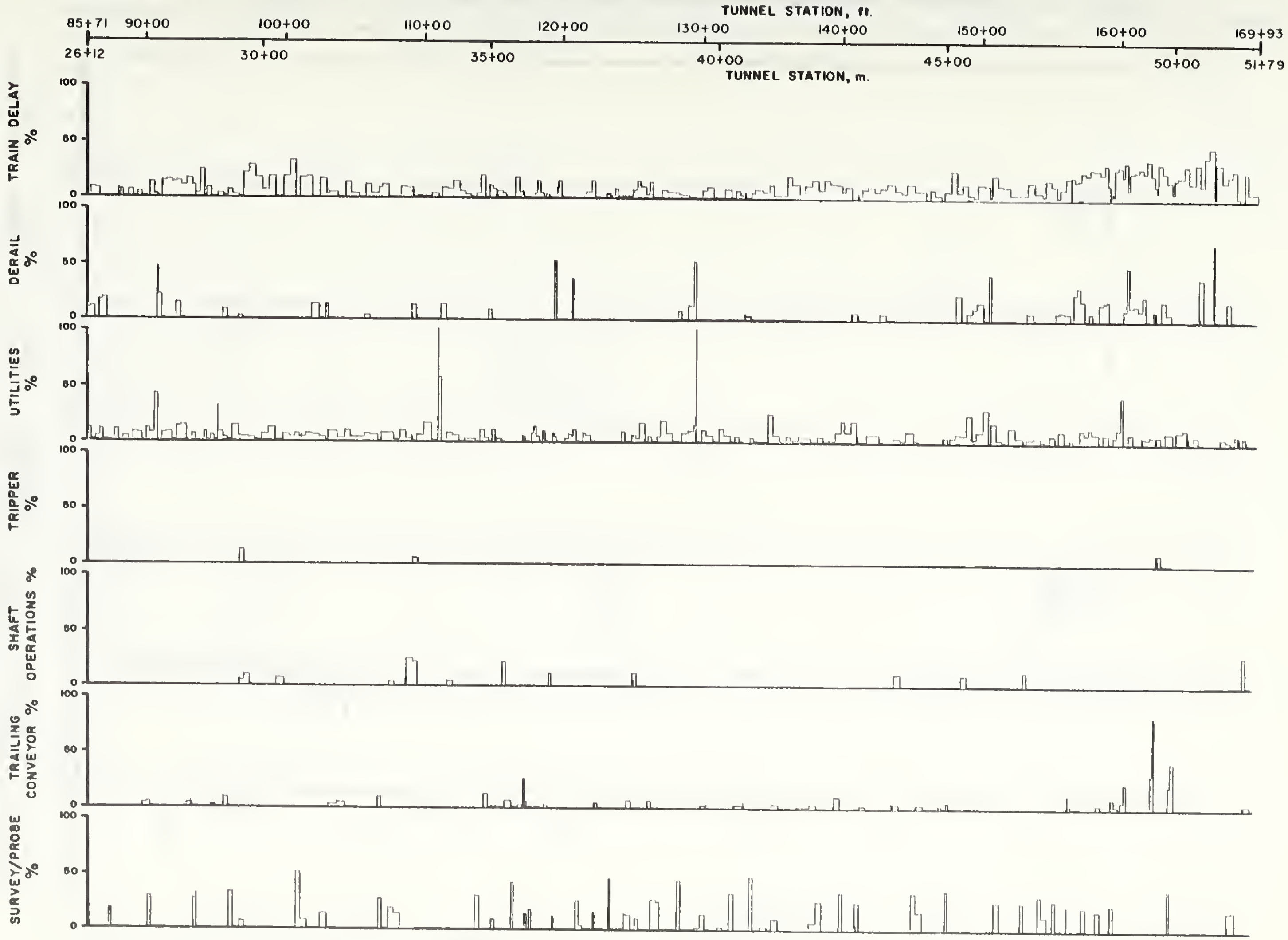


FIGURE B.17 SUMMARY OF BACKUP SYSTEM REPAIR DOWNTIME FOR THE GOODMAN LEG OF THE CULVER-GOODMAN TUNNEL

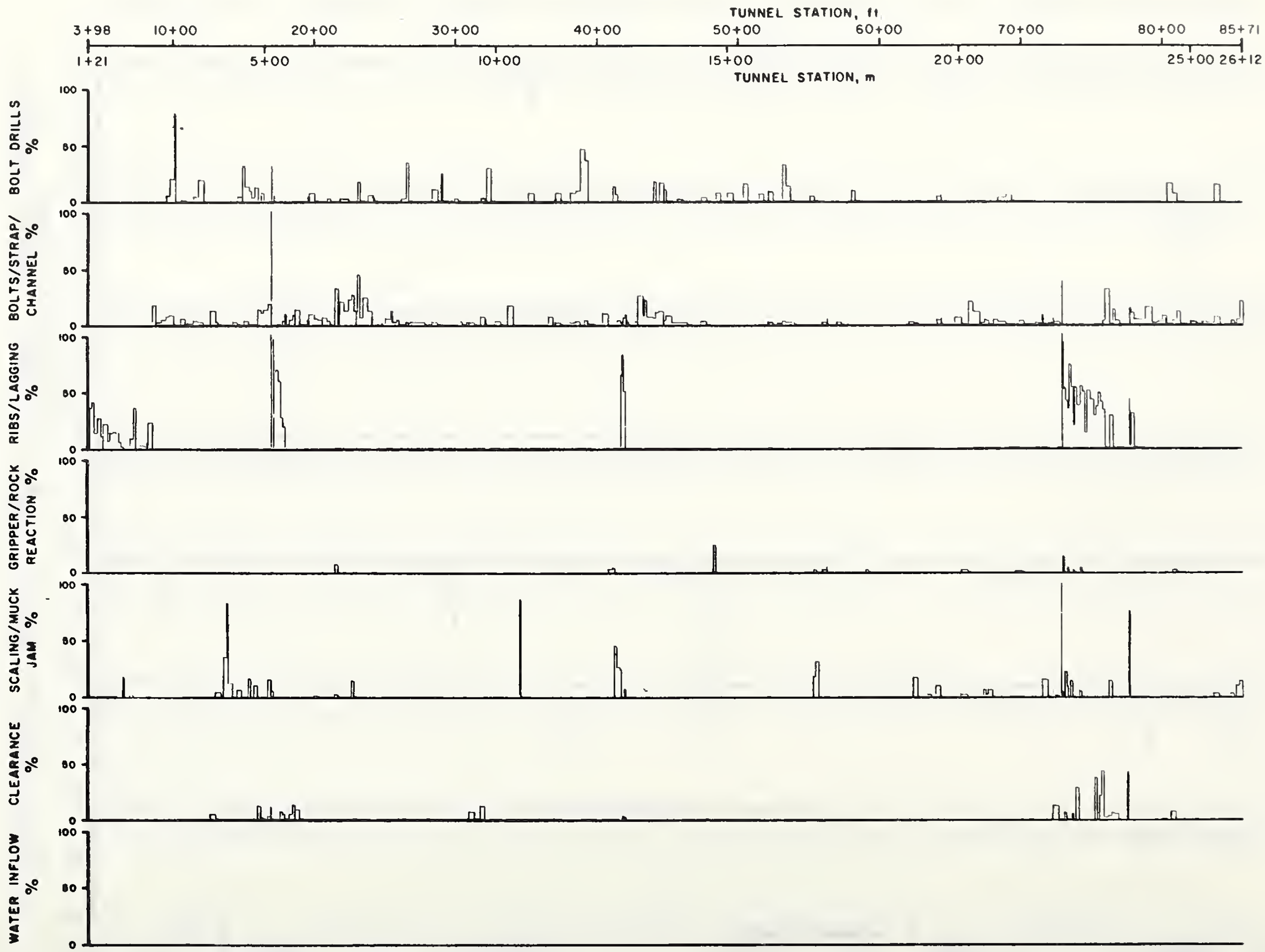


FIGURE B.18 SUMMARY OF GROUND CONDITION DOWNTIME FOR THE DENSMORE LEG OF THE CULVER-GOODMAN TUNNEL

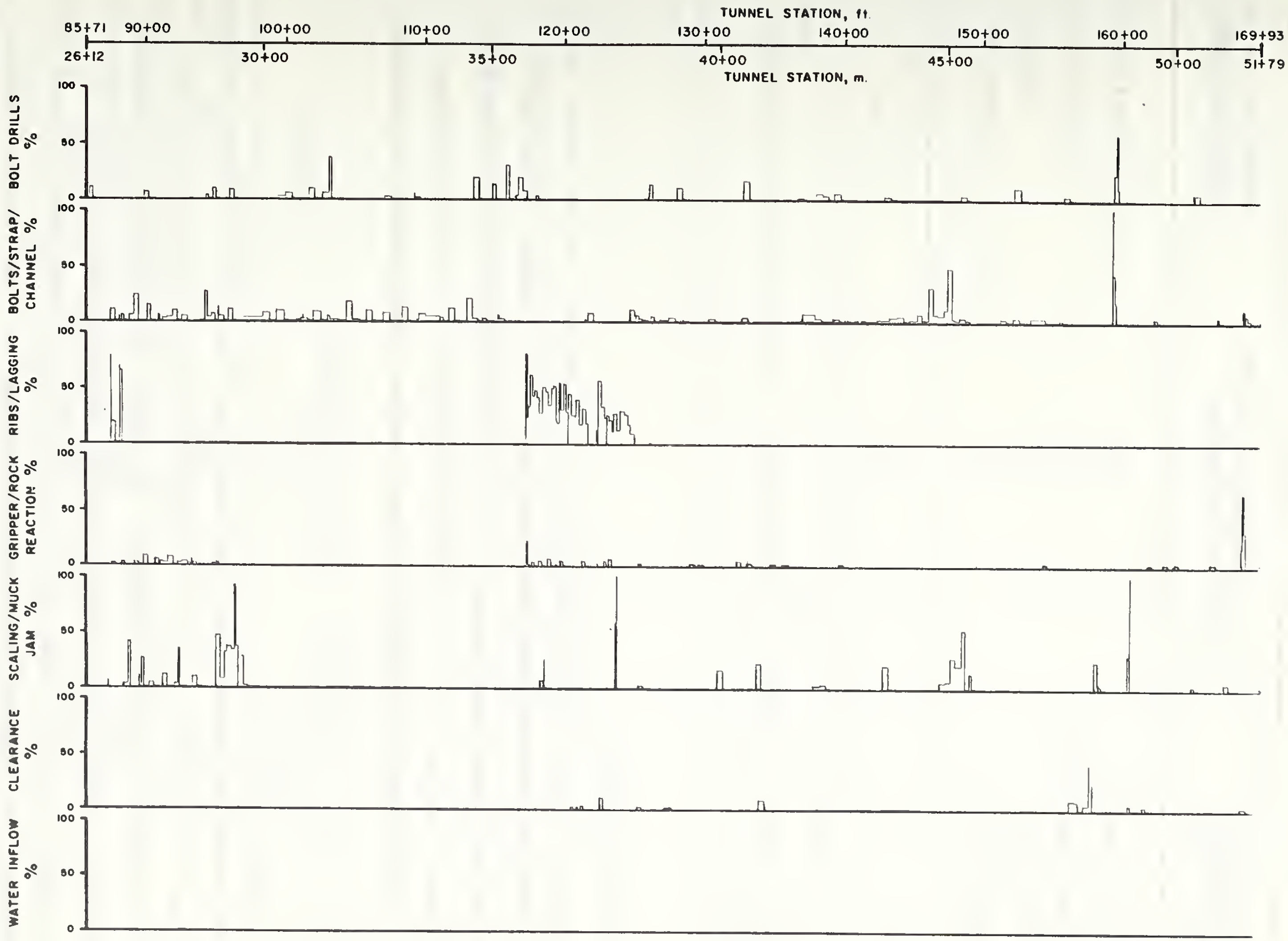


FIGURE B.19 SUMMARY OF GROUND CONDITION DOWNTIME FOR THE GOODMAN LEG OF THE CULVER-GOODMAN TUNNEL

TABLE B.24 SUMMARY OF DOWNTIME CAUSES, NUMBER OF SHIFTS, AND SHIFT HOURS ASSOCIATED WITH CULVER-GOODMAN TBM MAINTENANCE

DOWNTIME CAUSE	NUMBER OF SHIFTS AFFECTED	NUMBER OF SHIFT HOURS INVOLVED
General Maintenance	45	43
Cutterhead Check Only	143	72
Lube Oil System	41	24
Main Bearing Seal	22	264
Total	189[a]	403

[a]During 62 shifts, repairs were performed in more than one maintenance category.

B.6.3 TBM Hydraulics

Delays in this category amounted to 0.9 percent of the total shift time. Table B.25 summarizes the downtime causes number of shifts affected by each cause and the shift hours required for repair. Most of the gripper downtime was associated with repair of the leaf springs. Other repairs involved hydraulic lines, valves, and hydraulic cylinder pins.

B.6.4 Cutter Change

The tunneling system was down expressly for cutter changes 79 times involving 195 shifts. Table B.26 summarizes the location of cutter changes, number of cutters changed, and hours of downtime for changes. Twenty-eight cutters were changed during the Christmas shutdown at Station 48+14, but the time loss at this location has been included in the category of "holiday" downtime in Chapter 8. Four cutters before Station 85+71 and 17 cutters after Station 85+71 were changed while the excavation system was down for repairs on other system components. The

TABLE B.25 SUMMARY OF DOWNTIME CAUSES, NUMBER OF SHIFTS, AND SHIFT HOURS ASSOCIATED WITH CULVER-GOODMAN TBM HYDRAULICS

DOWNTIME CAUSE	NUMBER OF SHIFTS AFFECTED	NUMBER OF SHIFT HOURS INVOLVED
General Maintenance	7	5
Rear Supports	5	3
Grippers	17	13
Cutterhead Side Supports	7	7
Roof Support Cylinders	4	3
Thrust Cylinders	16	30
Total	53[a]	61

[a]During 3 shifts, repairs made on more than one hydraulic component.

TABLE B.26 SUMMARY OF CUTTER CHANGES, TUNNEL LOCATIONS, NUMBER OF SHIFTS, AND HOURS OF DOWNTIME FOR THE CULVER-GOODMAN TUNNEL

LOCATION	NUMBER OF CUTTERS CHANGED	NUMBER OF SHIFTS WITH CUTTER CHANGE DOWNTIME	DOWNTIME HOURS
Before 48+14	357	104	589
Holiday Shutdown (48+14)	28	—	—
48+14 to 85+71	241	51	283
85+71 to 169+68	184	40	216
Total	810	195	1,088

time required for these changes has not been included in Table B.26. A total of 16.5 percent of the shift time was required to change cutters at other locations in the tunnel.

B.6.5 Stroke Recycle

Downtime due to recycling the thrust cylinders required 3.5 percent of the total shift time. There were a total of 4,387 restroke cycles, at an average of 3.78 ft (1.15 m) per cycle. Where the tunnel was excavated in shale, the gripper pads often slipped and reset times of five to ten minutes were common. When excavating in other lithologies, the reset time was often less than 3 minutes.

B.6.6 Cutterhead Motors

Downtime in this category amounted to 42 hours, or 0.6 percent of the total shift time. The first 4868 ft (1484 m) of the tunnel were mined with six 150 hp (112 kW) motors. During six weekends between 10 January and 14 February 1980, these motors were exchanged for 200 hp (149 kW) motors. One motor was changed each week, and the stations of these changes are 52+66, 56+46, 61+16, 65+15, 69+99, and 72+74. Approximately 9.0 percent of the tunnel was mined with five operating motors. A total of 53 shifts included time losses due to cutterhead motor repair, with most of the delays occurring during excavation of the Densmore leg of the tunnel.

B.6.7 TBM Conveyor

Downtime in this category was caused by adjustment and splicing of the conveyor belt. Seven shifts were affected by conveyor downtime, and time loss amounted to 0.1 percent of the total shift time.

B.6.8 Train Delay

This category was used when a specific reason for absence of muck cars at the heading was not cited. Downtime due to lack of cars occurred during 317 shifts, and for 96 of these the delays were one hour or more. Delays generally increased with increasing distance between the heading and the portal. A total of 256 hours, or 3.9 percent of the total shift time, was spent waiting for an empty muck train.

TABLE B.27 SUMMARY OF DERAILMENTS, LOCATIONS, AND HOURS OF DOWNTIME FOR THE CULVER-GOODMAN TUNNEL

DERAILMENT LOCATION	NUMBER OF DERAILMENTS	DOWNTIME HOURS
Trailing Floor	49	58
Tunnel	19	22
Portal	29	42
Rollover	6	5
Unspecified Location	36	28
Total	139	155

B.6.9 Derailment

There were 139 derailments during the tunnel excavation. Table B.27 summarizes the derailment locations, number of incidents, and downtime hours required to reset the train. Many of the incidents occurred on or at the ramp to the trailing floor. Cleaning up after the derailments and putting the train back on line required 2.3 percent of the total shift time.

B.6.10 Utilities

This category includes downtime for ventilation, air, water, and track line installation and electric cable extension and loss of electricity. Table B.28 summarizes the number of shifts involved and downtime hours for utility supply. Three shifts were required to reroute the fan line through Shaft 9. The electric cable was extended in increments of approximately 1,000 ft (305 m), and each extension required 3.0 to 4.0 hours. Downtime due to fan, air, water, rail, and electric lines was generally constant through the drive, amounting to 4.9 percent of the total shift time.

TABLE B.28 SUMMARY OF UTILITY SERVICES, NUMBER OF SHIFTS, AND HOURS OF DOWNTIME FOR THE CULVER-GOODMAN TUNNEL

SERVICE	NUMBER OF SHIFTS AFFECTED	DOWNTIME CAUSE
Fan Line	182	131
Air, Water, and Electric Lines	255	171
Surface Power	8	11
Rail	15	19
Total	430[a]	332

[a]During 30 shifts, work was performed on more than one utility service.

B.6.11 Tripper

This category includes downtime for mechanical repairs on the trailing floor and tripper mechanism. These delays occurred during 49 shifts and amounted to 32 hours, or 0.5 percent of the total shift time. Ninety percent of this time loss was associated with repair of the tripper.

B.6.12 Portal Operations

Downtime in this category was caused by repairs on the mucking system at the portal. Table B.29 summarizes the mucking system components, number of shifts affected, and hours of downtime due to component repair. Seventy percent of the time loss was associated with the rollover, and the total delay in this category amounted to 0.8 percent of the shift time.

TABLE B.29 SUMMARY OF SYSTEM COMPONENTS, NUMBER OF SHIFTS, AND SHIFT HOURS ASSOCIATED WITH PORTAL MUCKING EQUIPMENT FOR THE CULVER-GOODMAN TUNNEL

COMPONENT	NUMBER OF SHIFTS AFFECTED	DOWNTIME HOURS
Rollover/Shaker	33	37
Stacking Conveyor	7	13
Other Components	5	2
Total	45	52

B.6.13 Trailing Conveyor

Downtime associated with the trailing floor conveyor occurred during 75 shifts. Repair of belt splices and conveyor belt adjustments accounted for many of these delays. Early in the drive, the main trailing conveyor was moved 10 in. (0.25 m) to one side of the trailing sleds to provide clearance for the locomotive on both sides of the double track for the full length of the trailing floor. As is shown in Figure B.17, trailing conveyor downtime also occurred near Station 160+00, where the belt was shortened while mining around a horizontal curve in the tunnel. In total, 1.2 percent of the shift time was involved with trailing conveyor repair. Little of this time was associated with repair of the bridge conveyor.

B.6.14 Survey/Methane Probe

The contractor was required to drill a methane probe hole on this project. Downtime to drill the hole and to make repairs on the drill occurred during 93 shifts and amounted to 236 hours, or 3.6 percent of the total shift time. Delays caused by resetting the laser occurred 31 times for 14 hours, or 0.2 percent of the total shift time.

B.6.15 Bolt Drills

Downtime for repair of rock bolt drills occurred during 94 shifts. Water needles, feed screws, and rotation motors were often replaced, and new or rebuilt drills were installed seven times. A total of 94 hours, or 1.4 percent of the shift time, was required for bolt drill repair.

B.6.16 Bolt/Strap/Channel Installation

Rock bolts, straps, and channels were used on this project. Table B.30 summarizes the support types, number of shifts, and downtime hours associated with delays for support installation. A majority of the downtime occurred in sections where channels were installed. In total, excavation was delayed for bolt, strap, and channel installation for 2.3 percent of the total shift time.

B.6.17 Ribs/Lagging

Steel sets were installed in nine sections of the tunnel. Table B.31 summarizes the steel set locations, number of sets, set spacing, and total downtime hours used in the steel set erection. The times listed include any downtime spent placing lagging between the steel ribs. Many of the steel sets installed between Stations 3+99 and 8+27 were placed while excavation was stopped to install utility lines and to lay track. Between Stations 72+48 and 75+61, more than 30 hours were required to scale loose rock before the steel sets and lagging could be installed. Between Stations 122+11 and 124+63, 16 hours were spent scaling loose rock. The downtime required for scaling is not included in Table B.31. Downtime required to install steel sets and to place lagging amounted to 336 hours over 107 shifts, or 5.1 percent of the shift time.

B.6.18 Gripper/Rock Reaction

The most common cause of downtime in this category was gripper pad slippage. Where the tunnel was excavated in shale, the spikes mounted on the gripper pads did not extend far enough into the muck-coated walls to develop the required reaction for TBM thrust. This was particularly true when mining in the Lower Sodus and Williamson Shales, where excavation was often stopped to wash the tunnel walls to remove the muck

TABLE B.30 SUMMARY OF SUPPORT TYPES, NUMBERS OF SHIFTS WITH DOWNTIME HOURS, AND HOURS OF DOWNTIME FOR THE CULVER-GOODMAN TUNNEL

SUPPORT TYPE	NUMBER OF SHIFTS AFFECTED	DOWNTIME HOURS
Bolts	39	25
Bolts and Straps	43	23
Channels	147	104
Total	229	152

TABLE B.31 SUMMARY OF LOCATIONS, SPACING, AND DOWNTIME HOURS ASSOCIATED WITH STEEL SET INSTALLATION FOR THE CULVER-GOODMAN TUNNEL

STATIONS WITH STEEL SET SUPPORT	NUMBER OF STEEL SETS	SPACING OF STEEL SETS ft	m	STEEL AND TIMBER DOWNTIME HOURS
3+99 - 8+27	87	4-6	1.2-1.8	38
16+56 - 17+50	21	5	1.5	55
41+52 - 41+64	4	4	1.2	16
72+48 - 75+61	65	5	1.5	90
77+28 - 77+48	5	5	1.5	9
87+08 - 87+18	3	5	1.5	7
87+77 - 87+96	5	5	1.5	11
116+89 - 121+39	91	5	1.5	84
122+11 - 124+63	51	5	1.5	26
Total	332			336

TABLE B.32 SUMMARY OF MUCK JAM LOCATIONS AND SCALING OCCURENCES, NUMBER OF SHIFTS AFFECTED, AND DOWNTIME HOURS FOR THE CULVER-GOODMAN TUNNEL

SCALING/MUCK JAM	NUMBER OF SHIFTS AFFECTED	DOWNTIME HOURS
Muck Jams		
Cutterhead Buckets	23	66
Cutterhead Hopper	8	12
Trailing Floor Conveyors	3	5
Tripper Hopper	5	1
Scaling		
Crown and Side Wall	64	98
Invert	8	18
Total	111	200

veneer. Gripper downtime also occurred at the end of the tunnel where a hole was excavated in the tunnel sidewall to facilitate the bull gear change performed after holing through. Timber cribbing had to be placed in this hole for gripper support as the machine mined past. Gripper delays amounted to 21 hours over 43 shifts, or 0.3 percent of the total shift time.

B.6.19 Scaling/Muck Jam

Where the tunnel was excavated in thinly bedded or highly jointed rock, rock falls often occurred and loose rock had to be scaled from the crown or picked up from the invert. Rock slabs falling on the TBM and trailing floor had to be broken up and removed. In areas of blocky rock, pieces of rock often became jammed in the mucking system. Table B.32 summarizes the muck jam locations and scaling incidents, number of shifts affected, and downtime hours. The most time-consuming muck jams occurred in the cutterhead buckets. Several times, muck became packed in the bucket openings and cutterhead motors overheated, tripping the breakers. In many places, crown rock overbreak developed after the TBM had mined through, and much of the scaling was done well behind the heading. A total of 200 hours, or 3.1 percent of the total shift time, was required to remove rock jams and to scale loose rock.

B.6.20 Clearance

Advance of the trailing sleds through steel supported sections resulted in some components jamming against or snagging on supports. This problem was most noticeable for the ventilation equipment. A total of 32 hours over 31 shifts, or 0.5 percent of the total shift time, was required for clearance.

B.6.21 Water Inflow

Downtime due directly to water inflow occurred only once in the Culver-Goodman Tunnel. At Station 71+32, water entered the tunnel from an alignment hole and excavation was stopped for one shift before the flow was controlled. Water inflow also exerted an indirect influence on progress when water accumulation near the portal contributed to a number of derailments.

B.7 DOWNTIME RECORD FOR THE CHICAGO TARP CONTRACT 73-287-2H

Figures B.20 through B.28 summarize the downtimes for the main tunnel between Stations 185+84 and 409+68 and the 125th Street Branch Tunnel of Chicago TARP Contract 73-287-2H. Downtimes are expressed as percentages of individual shift time. Figures B.20, B.21, and B.22 include downtime for the general category of TBM maintenance and repair. Figures B.23 through B.25 include backup system repair downtime, and Figures B.26 through B.28 include downtime in the general category of ground conditions. Downtime during weekend maintenance shifts has not been plotted in the histograms. The downtime analysis was performed using the contractor's shift reports. When the total of downtime delays and machine clock time did not equal the shift duration, the time difference between the two values was assigned to the category "other,"

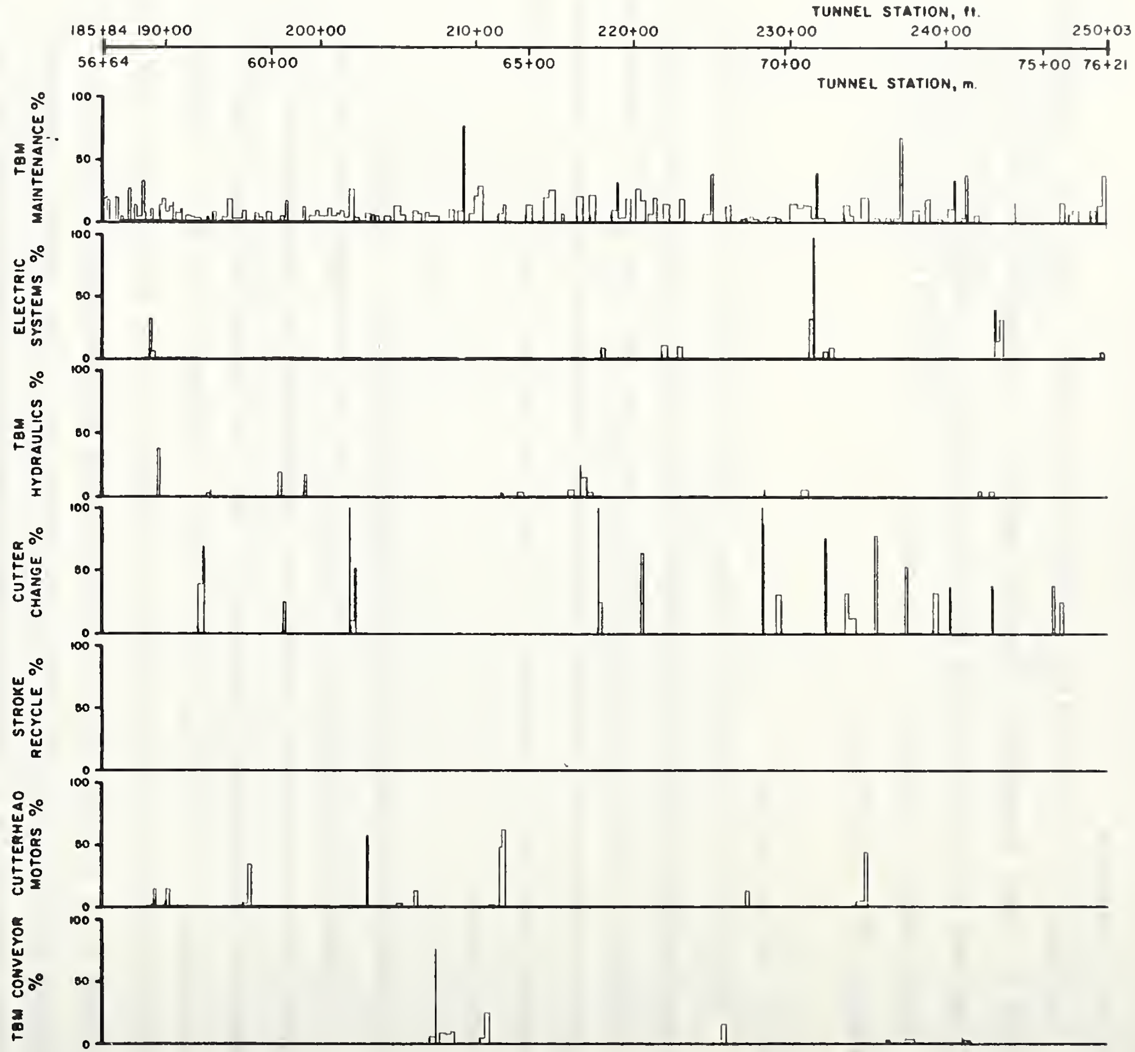


FIGURE B.20 SUMMARY OF TBM MAINTENANCE AND REPAIR DOWNTIME FOR TARP CONTRACT 73-287-2H, STATION 184+84 TO 250+03

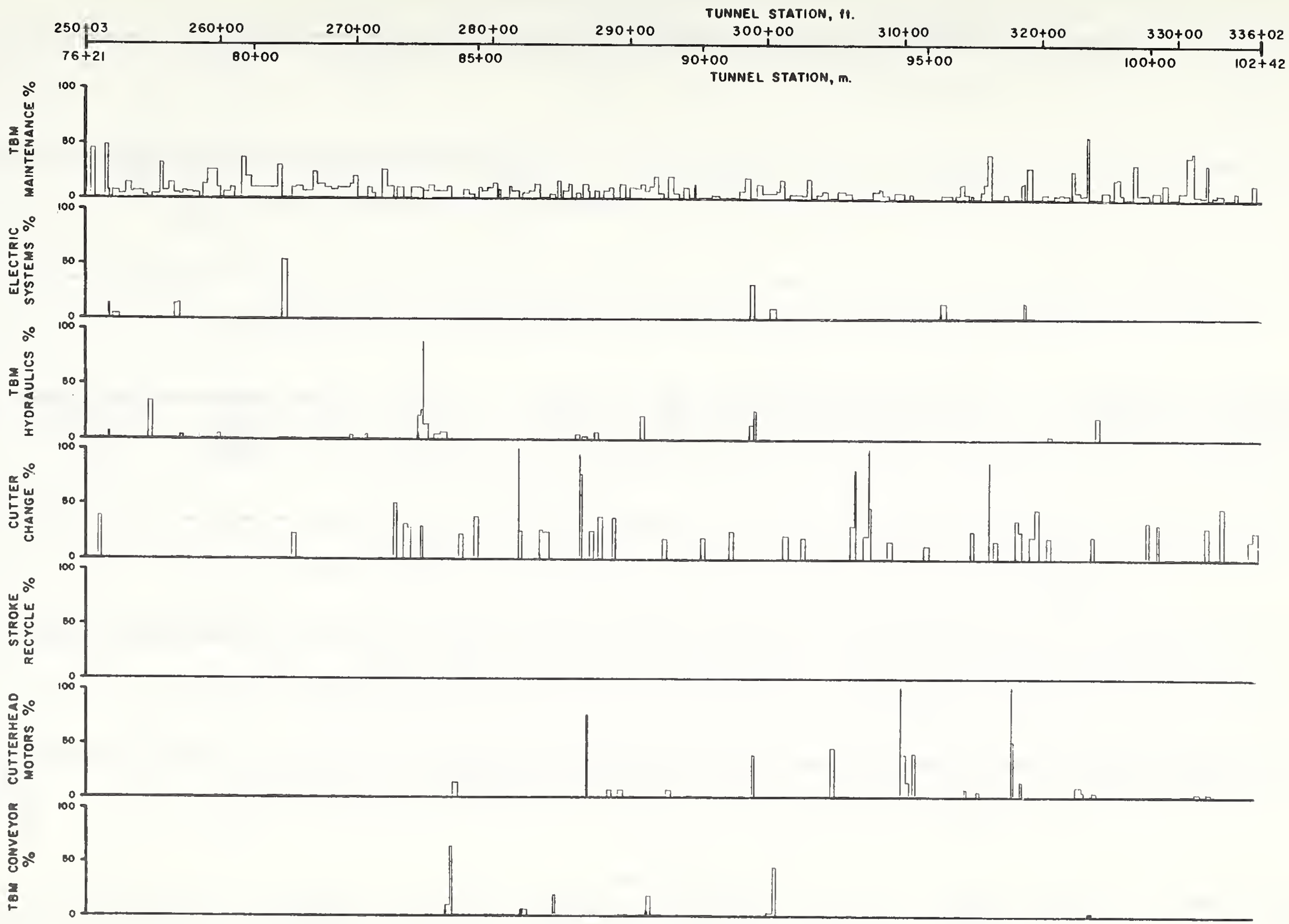


FIGURE B.21 SUMMARY OF TBM MAINTENANCE AND REPAIR DOWNTIME FOR TARP CONTRACT 73-287-2H, STATION 250+03 TO 336+02

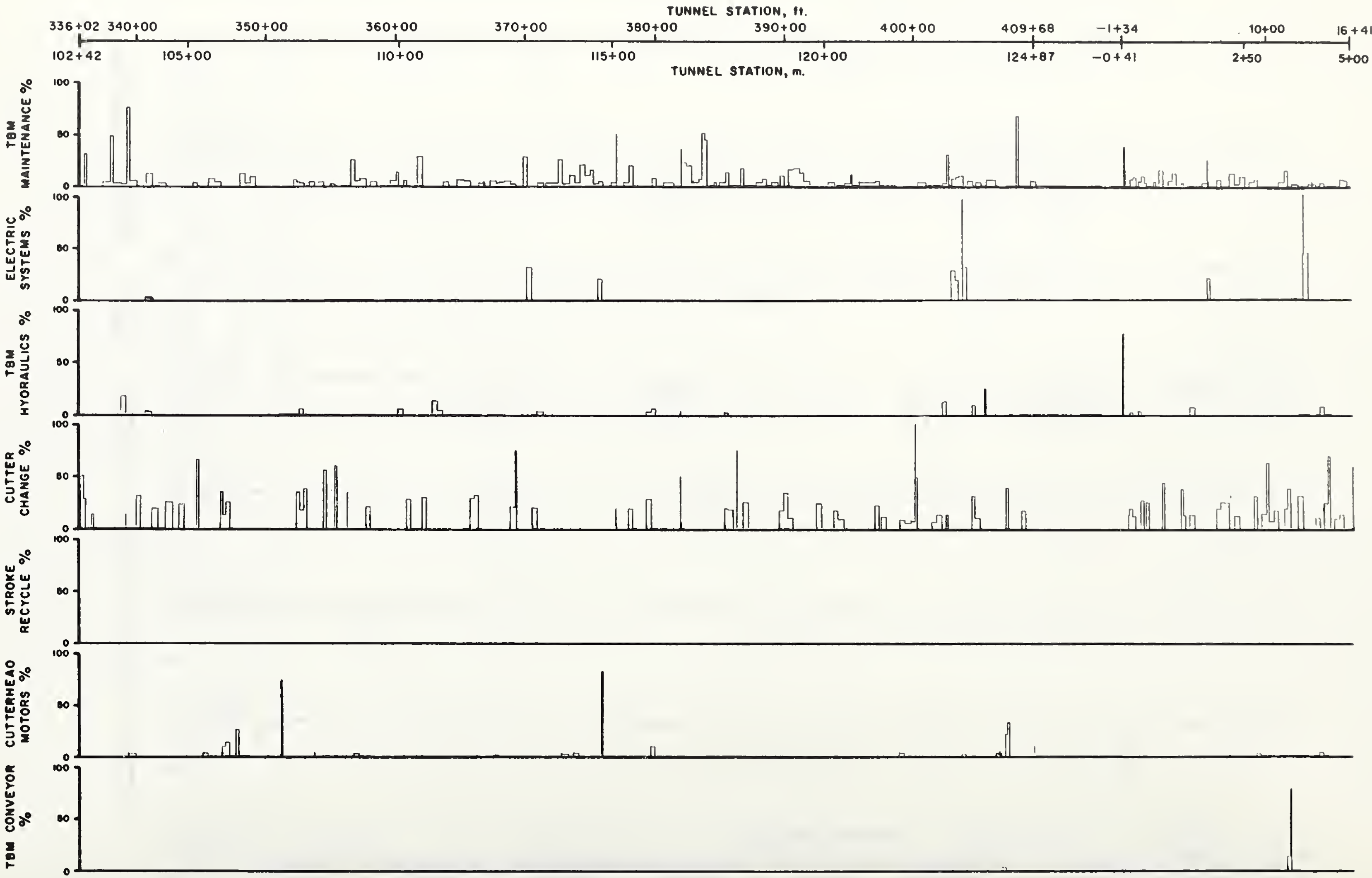


FIGURE B.22 SUMMARY OF TBM MAINTENANCE AND REPAIR DOWNTIME FOR TARP CONTRACT 73-287-2H, STATION 336+02 TO 409+68 AND THE 125th STREET BRANCH TUNNEL

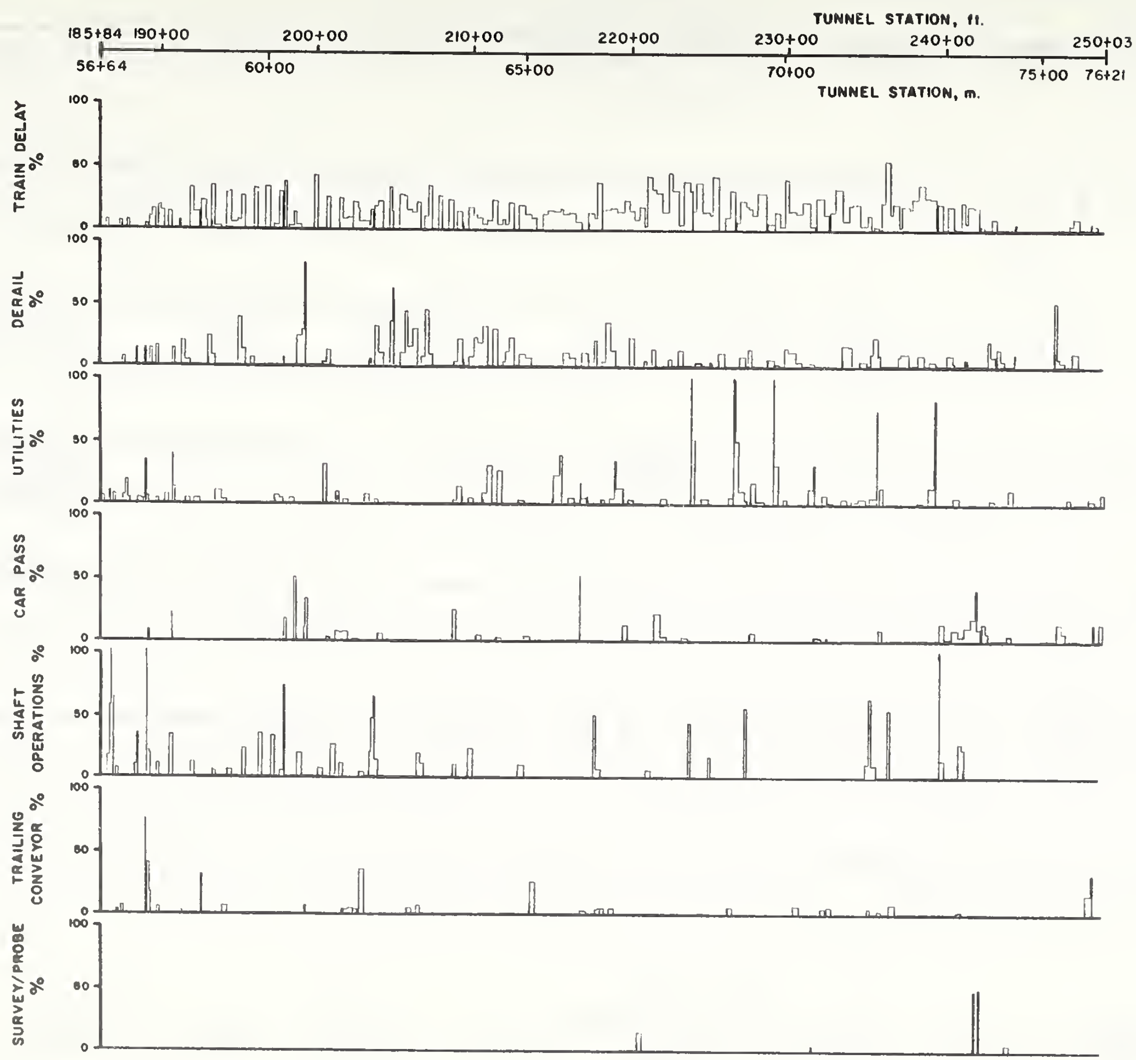


FIGURE B.23 SUMMARY OF BACKUP SYSTEM REPAIR DOWNTIME FOR TARP CONTRACT 73-287-2H, STATION 184+84 TO 250+03

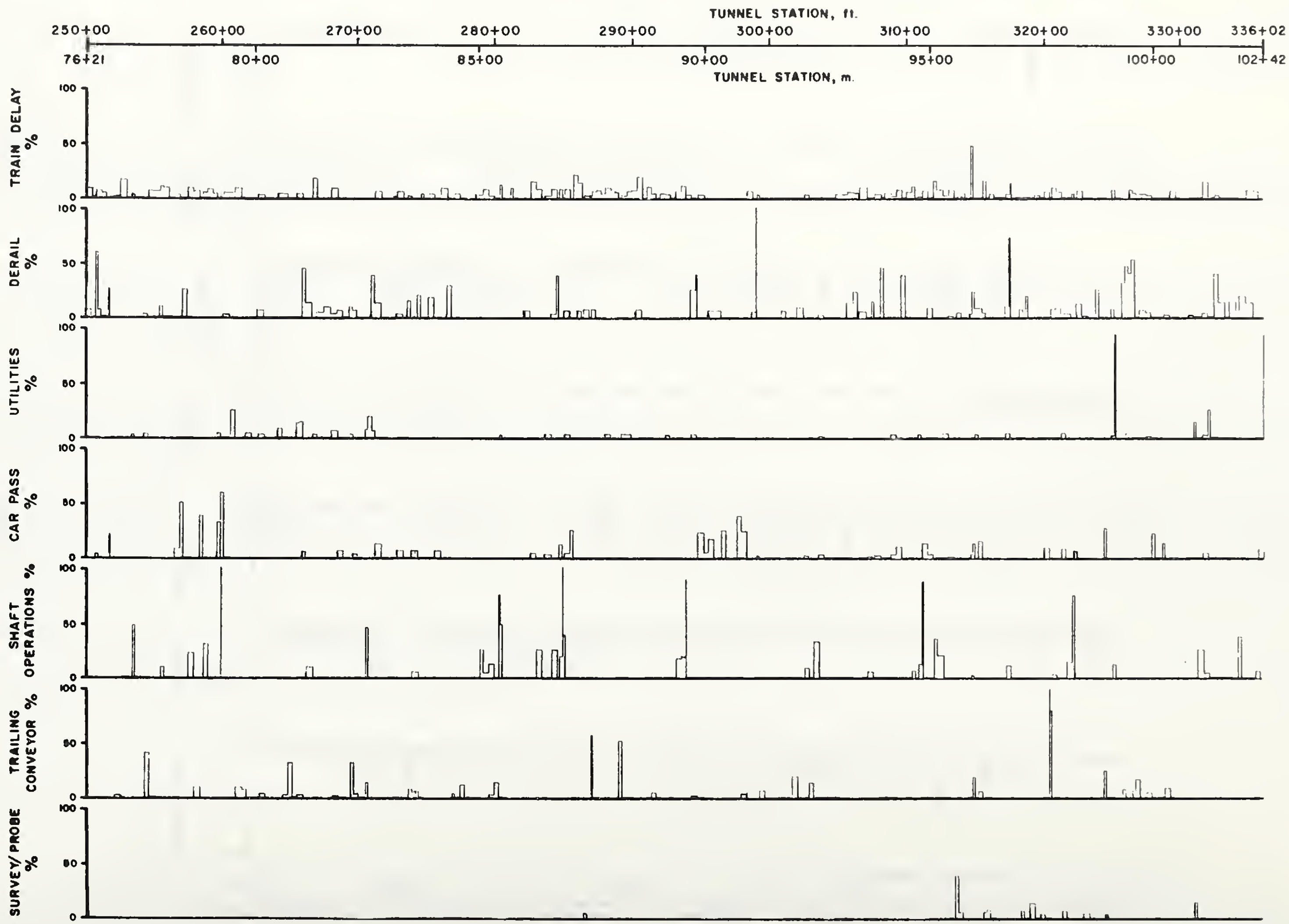


FIGURE B.24 SUMMARY OF BACKUP SYSTEM REPAIR DOWNTIME FOR TARP CONTRACT 73-287-2H, STATION 250+03 TO 336+02

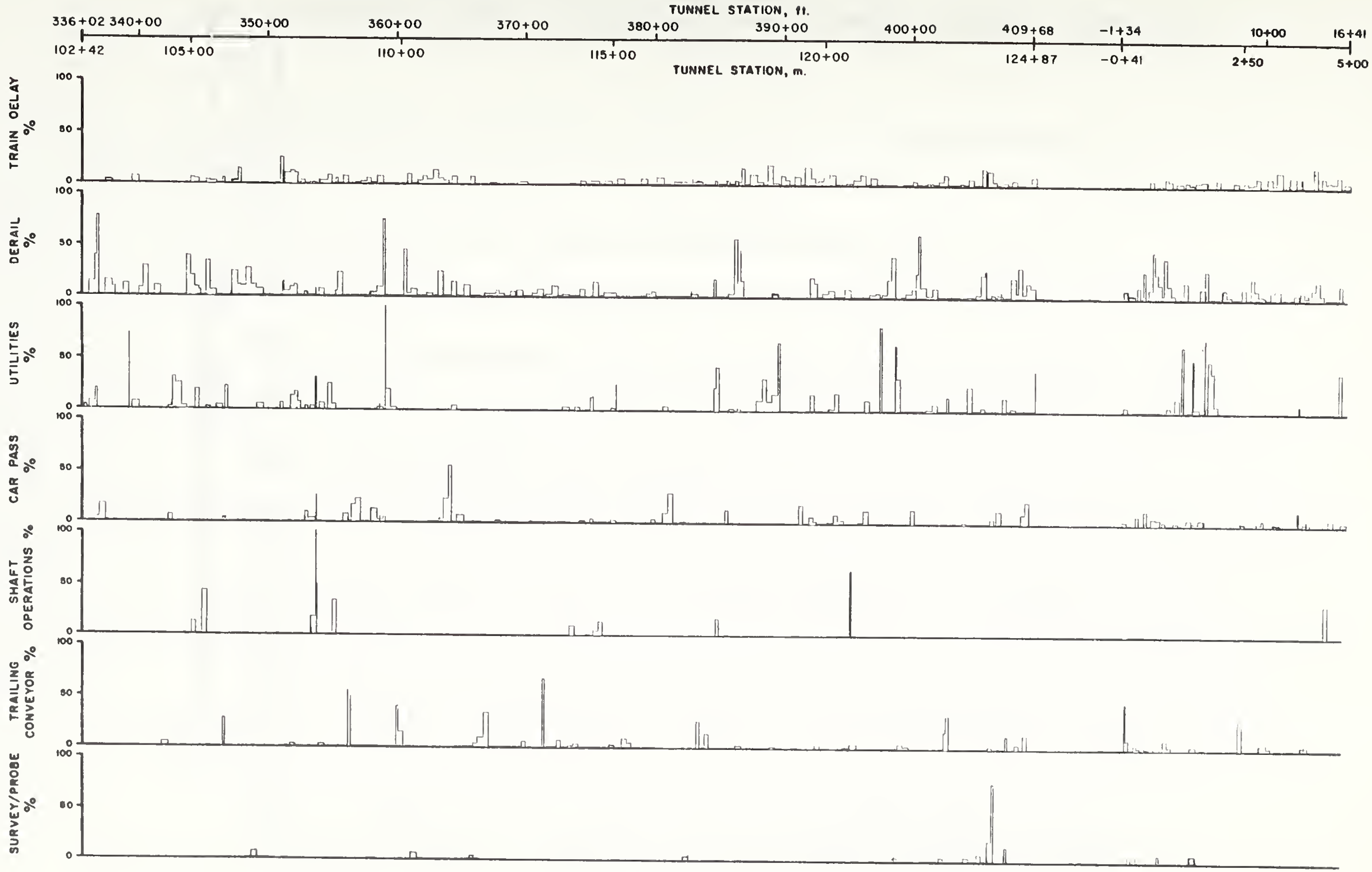


FIGURE B.25 SUMMARY OF BACKUP SYSTEM REPAIR DOWNTIME FOR TARP CONTRACT 73-287-2H, STATION 336+02 TO 409+68 AND THE 125th STREET BRANCH TUNNEL

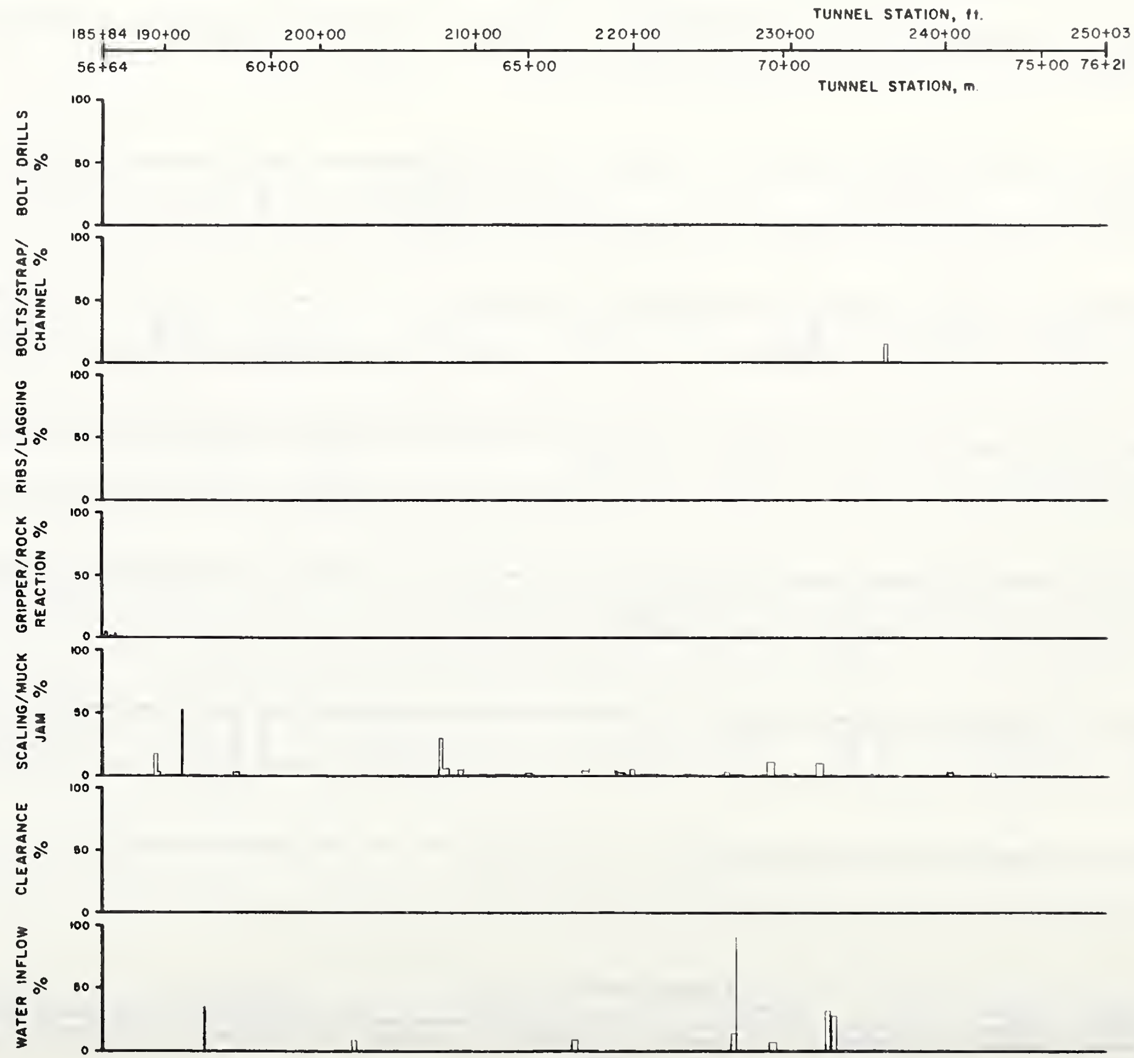


FIGURE B.26 SUMMARY OF GROUND CONDITION DOWNTIME FOR TARP CONTRACT 73-287-2H, STATION 184+84 TO 250+03

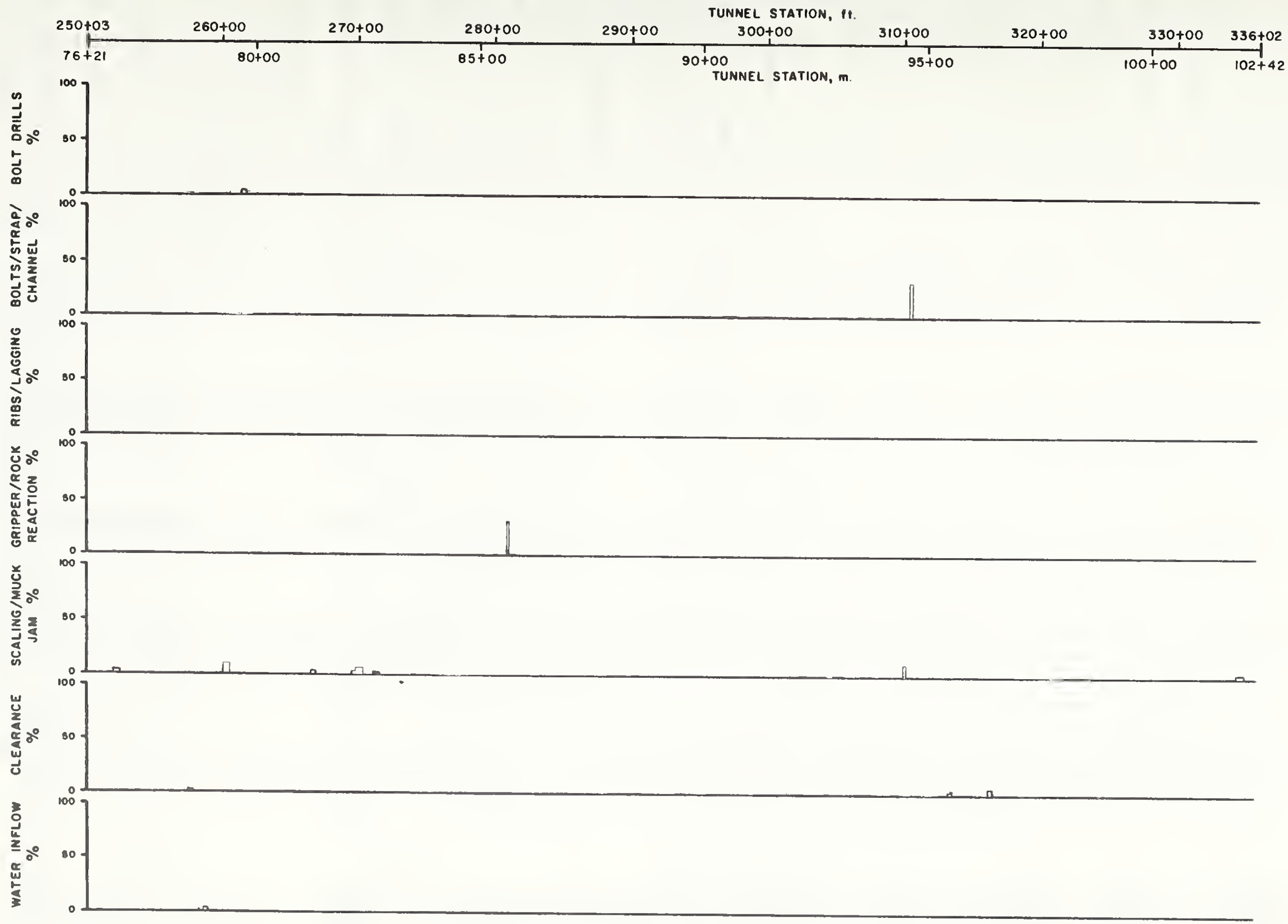


FIGURE B.27 SUMMARY OF GROUND CONDITION DOWNTIME FOR TARP CONTRACT 73-287-2H, STATION 250+03 TO 336+02

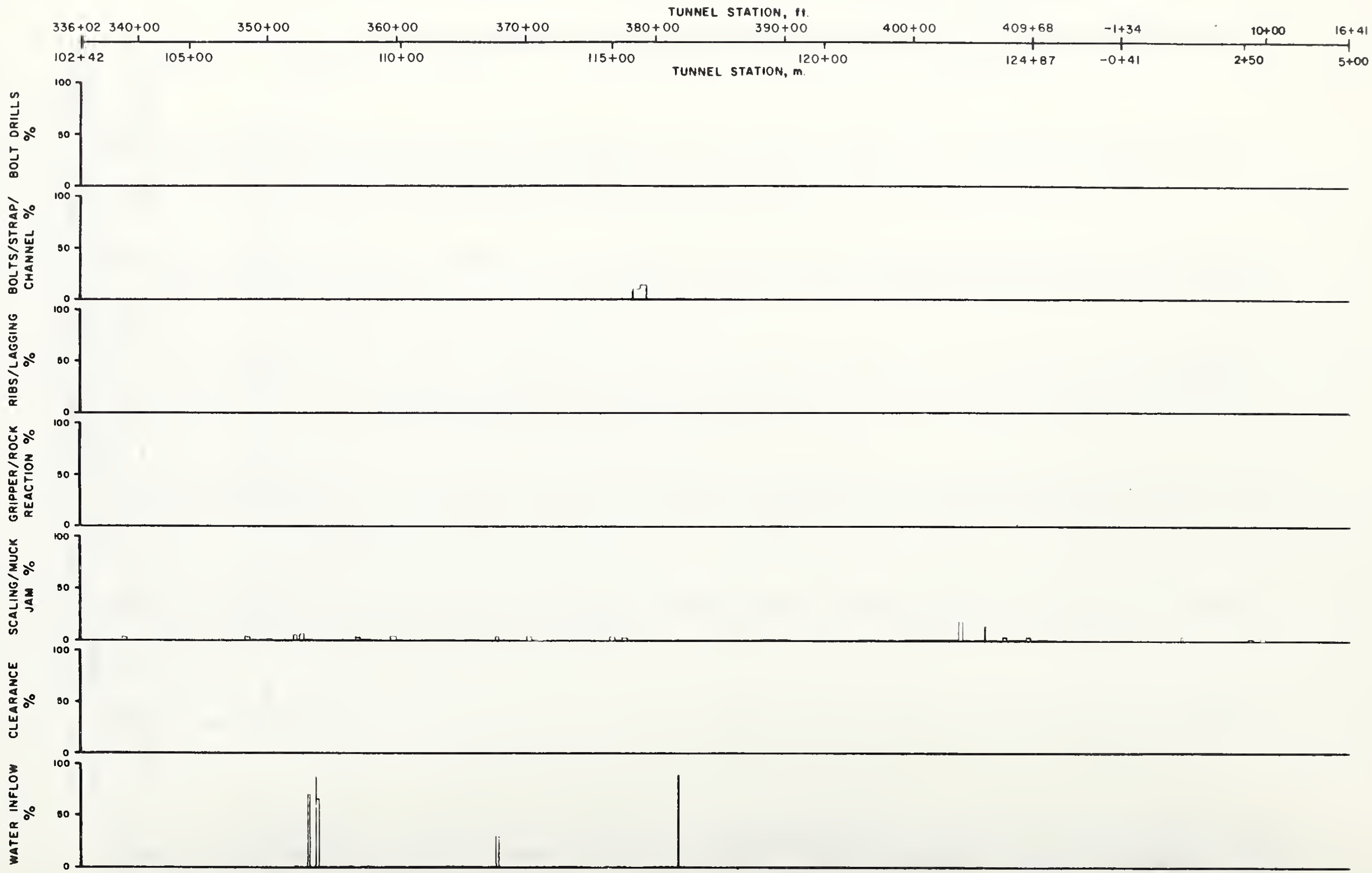


FIGURE B.28 SUMMARY OF GROUND CONDITION DOWNTIME FOR TARP CONTRACT 73-287-2H, STATION 336+02 TO 409+68 AND THE 125th STREET BRANCH TUNNEL described in Section 9. The factors affecting the downtime in each of the categories summarized in Figures B.20 through B.28 are discussed under the headings that follow.

B.7.1 TBM Maintenance

Contributing downtimes in this category cover both general maintenance of the TBM and repair of the lubricating oil system, amounting to 14.3 percent of the total shift time. Table B.33 summarizes the downtime time causes, number of shifts affected by each cause, and the number of shift hours involved. Over 80 percent of the total downtime in this category was due to one of two causes: 1) cutterhead main bearing change, or 2) TBM cutterhead, saddle and bucket repair. At Station 351+32, the TBM was down for 91 shifts to replace the cutterhead main bearing. A total of 47 Saturday shifts were operated to repair damaged buckets and cutter saddles and to weld the four main pieces of the cutterhead together. Cutterhead checks were performed at the start of most shifts, and were often made concurrently with repairs to other parts of the excavation system. Most of the downtime on the lubricating oil system was caused by repairs of the lubrication oil pumps and motors, which were replaced eight times during the excavation of the eastern heading.

B.7.2 Electric Systems

Delays in this category occurred during 45 shifts and resulted in the loss of 177 hours, or 0.9 percent of the total shift time. Most ofthe downtime was used to repair the step-down and TBM transformers. At Station 231+45, a muck car derailed and damaged the main transformer. Fifteen shifts were required for repairs. At Station 12+85 in the branch tunnel, excavation was stopped for three shifts to repair the TBM transformer.

B.7.3 TBM Hydraulics

Delays in this category occurred during 68 shifts and amounted to 58 hours, or 0.6 percent of the total shift time. Most of the downtime was caused by repair of the hydraulic pumps and pump fittings. One of the cutterhead side support cylinders was replaced during branch tunnel excavation.

TABLE B.33 SUMMARY OF DOWNTIME CAUSES, NUMBER OF SHIFTS, AND SHIFT HOURS ASSOCIATED WITH CONTRACT 73-287-2H TBM MAINTENANCE

DOWNTIME CAUSE	NUMBER OF SHIFTS AFFECTED	NUMBER OF SHIFT HOURS INVOLVED
General Maintenance	207	1124
Cutterhead Check Only	326	152
Lube Oil System	63	63
Total	549[a]	1339

[a]During 47 shifts, repairs were performed in more than one maintenance category.

B.7.4 Cutter Change

The tunneling system was down expressly for cutter changes 139 times involving 159 shifts. Table B.34 summarizes the location of cutter changes, number of cutters changed, and hours of downtime for the changes. Some cutters were changed while tunneling was delayed for repairs to other system equipments. These changes include 48 replacements at the drop shafts, nine at other locations in the main tunnel, and 11 between the main and branch tunnels. Because it is not possible to determine the hours of delay when downtime was caused principally by other difficulties, the time required for these changes has not been included in the hours listed in Table B.34. The time loss at the drop shafts has been listed under the category of "shaft downtime" in Chapter 9. The time required for the 11 cutter changes during machine maintenance between the completion of the main tunnel and the start of the branch tunnel is included under the category of "other" in Chapter 9. A total of 5.5 percent of the shift time was used for cutter changes at other locations in the main and branch tunnels.

B.7.5 Stroke Recycle

Downtime due to recycling the thrust cylinders could not be estimated from available records. There were a total of 4,682 restroke cycles, at an average of 5.09 ft (1.55 m) per cycle.

B.7.6 Cutterhead Motors

Downtime in this category amounted to 248 hours, 2.7 percent of the total shift time, and occurred during 77 shifts. The TBM mined nearly 22 percent of the tunnel with fewer than eight motors on line. At Station 190+48, metal chips were found in the gear boxes, and all the motors were removed and repaired during seven shifts. At Station 351+32, eight shifts were required to repair the air clutches on all eight motors. The most common causes of downtime during other shifts were repair of airlines and air clutches.

B.7.7 TBM Conveyor

Downtime in this category was caused by repair and splicing of the conveyor belt. At Station 208+43, excavation was stopped for six shifts to remove and repair the belt and to clean out the main beam. At Station 11+80 in the branch tunnel, the TBM conveyor belt was replaced. A total of 76 hours, or 0.8 percent of the total shift time, was required for repairs during 31 shifts.

B.7.8 Train Delay

This category was used when a specific reason for absence of muck cars at the heading was not cited. Downtime due to lack of cars occurred during 378 shifts, and for 117 of these, delays were one hour or more. Sixty percent of the time loss in this category occurred during the first 20 percent of tunnel excavation. These delays were mostly caused by slow muck removal through Drop Shaft 6R. In total, 313 hours, or 3.3 percent of the total shift time, were spent waiting for an empty muck train.

B.7.9 Derailment

There were 445 derailments during the tunnel excavation. Table B.35 summarizes the derailment locations, number of incidents, and

TABLE B.34 SUMMARY OF CUTTER CHANGES, TUNNEL LOCATIONS, NUMBER OF SHIFTS, AND HOURS OF DOWNTIME FOR THE TARP CONTRACT 73-287-2H TUNNEL

LOCATION	NUMBER OF CUTTERS CHANGED	NUMBER OF SHIFTS WITH CUTTER CHANGE DOWNTIME	DOWNTIME HOURS
MAIN TUNNEL	287	132	467
DROP SHAFT ADITS	48	---	---
BETWEEN TUNNELS	11	---	---
BRANCH TUNNEL	54	27	50
TOTAL	400	159	517

downtime hours required to reset the train. The most time consuming individual derailments were those that occurred in the tunnel and at the drop shafts, but the majority of the incidents occurred on the trailing floor. Most of the trailing floor sled derailments occurred as the TBM mined around the horizontal curve near Station 245+00. Cleaning up after the derailments and putting the train back on line required 3.7 percent of the total shift time.

B.7.10 Utilities

This category includes downtime for ventilation, air, water, andtrack line installation, and electric cable extension and loss of electricity. Table B.36 summarizes the number of shifts and downtime hours affected by utility supply. The fanline exit was moved to Shaft 6U at Station 226+40 and to Shaft 6B at Station 346+80. The microdyne fan, mounted on the trailing floor, was changed three times. At Station 197+60, 18 shifts were spent installing a rail switch near the main mucking shaft, 6R. At Station 325+10, 11 shifts were required to install another switch in the tunnel. The rail line in the tunnel was supported by rock bolts, installed in the tunnel invert with drills

TABLE B.35 SUMMARY OF DERAILMENTS, LOCATIONS, AND HOURS OF DOWNTIME FOR TARP CONTRACT 73-287-2H TUNNEL

DERAILMEMT LOCATION	NUMBER OF DERAILMENTS	DOWNTIME HOURS
Trailing Floor	204	113
Trailing Floor Ramp and Switch	64	56
Trailing Floor Sled	10	10
Tunnel	14	32
Shafts and Switches	20	31
Unspecified Location	133	102
Total	445	344

mounted on the trailing floor. Drill repairs, trailing floor track repair, and switch installation were the primary causes of downtime associated with the railroad track. Downtime due to fan, air, water, rail, and electric lines amounted to 5.5 percent of the total shift time.

B.7.11 Car Pass

This category includes downtime primarily caused by repairs to the car pass assembly. Many of these delays were required to repair the sliding floor, and drive chains were replaced 15 times. Several delays occurred when empty muck trains returned to the trailing floor with cars still partly full of muck. These cars were difficult to uncouple from the train because of their weight. In some places, the track was not level, and delays occurred where the sliding floor transfer was uphill. Delays and repairs to the car pass system directly affected 153 shifts, but other shifts were indirectly affected by slow mucking when the car pass system was down. A total of 149 hours, or 1.6 percent of the total shift time, was directly associated with car pass assembly repairs.

TABLE B.36 SUMMARY OF UTILITY SERVICES, NUMBER OF SHIFTS AND HOURS OF DOWNTIME FOR THE TARP CONTRACT 73-287-2H TUNNEL

SERVICE	NUMBER OF SHIFTS AFFECTED	DOWNTIME HOURS
Fan line	90	115
Air, Water, and Electric Lines	67	64
Surface Power	21	41
Rail	72	297
Total	238[a]	517

[a]During 12 shifts, work was performed on more than one utility service.

B.7.12 Shaft Operations

Downtime in this category was caused by repairs to the mucking system at Shaft 6R. Table B.37 summarizes the mucking system components, number of shifts affected, and hours of downtime due to component repair. A total of 97 shifts was involved in mucking system repair. The crane cable was changed nine times. When the TBM was at Station 354+04, the crane at Shaft 6R dropped a muck car and the muck car guides in the shaft were damaged. Two shifts were required for repairs. In total, shaft mucking system repairs accounted for 2.4 percent of the shift time.

B.7.13 Trailing Conveyor

Downtime for repair of the trailing floor conveyors occurred during 124 shifts. Repair of belt tears, rollers, and bearings accounted for a majority of the downtime in this category. The conveyor motor was replaced during two shifts at Station 254+26, and three shifts were required to replace the pump for the hydraulic system at Station 288+83. A bearing on the front roller was replaced over two shifts at Station

TABLE B.37 SUMMARY OF SYSTEM COMPONENTS, NUMBER OF SHIFTS, AND SHIFT HOURS ASSOCIATED WITH SURFACE MUCKING EQUIPMENT REPAIR FOR THE TARP CONTRACT 73-287-2H TUNNEL

COMPONENT	NUMBER OF SHIFTS AFFECTED	DOWNTIME HOURS
Crane	57	111
Cable Changes	14	55
Bridle	22	39
Muck Guide	4	21
Total	97	226

320+25. In total, 157 hours, or 1.7 percent of the total shift time,were involved with conveyor repairs.

B.7.14 Survey/Methane Probe

The contractor was not required to drill a methane probe hole on this project. Delays caused by resetting the laser and repair of the laser targets occurred during 26 shifts, with most of the time loss occuring while the TBM was negotiating curves in the tunnel alignment. In total, 28 hours, or 0.3 percent of the total shift time, were required for laser resets and target repairs.

B.7.15 Bolt Drills

There were no delays associated with repair of the bolt drills used for rock support in the tunnel.

B.7.16 Bolt/Strap/Channel Installation

Steel mesh, straps and rock bolts were used in the tunnel. Most of the rock support was installed while the TBM was in operation, but near Station 378+50, eight shifts were required to install bolts for support in an area with bedding plane overbreak in the crown. In total, excavation was delayed during 13 shifts for bolt, strap, and mesh installation, and these delays amounted to 69 hours, or 0.7 percent of the total shift time.

B.7.17 Ribs/Lagging

No steel sets were installed in this tunnel.

B.7.18 Gripper/Rock Reaction

The only instances when special provisions had to be made to allow the gripper pads to sustain a forward reaction occurred while mining past the adits to the drop shafts. In these cases, the gripper pad on the side away from the adit was rock bolted to the tunnel wall after each thrust cylinder recycle. The time required for gripper support is included in the category of shaft downtime in Chapter 9 and these delays are not plotted in Figures B.26 through B.28.

B.7.19 Scaling/Muck Jam

In several areas, muck accumulations in the TBM main beam jammed the TBM conveyor and the main beam had to be cleaned. Similar problems developed on the trailing conveyors and in the muck hoppers. Muck also tended to accumulate under the hopper at the end of the trailing conveyor and on the car pass. Four times, rock falls occurred behind the heading, and loose rock had to be scaled from the crown and large rock pieces broken up. In total, excavation was delayed during 51 shifts for 36 hours, or 0.4 percent of the total shift time.

B.7.20 Clearance

Advance of the trailing sleds through steel supported sections resulted in some components jamming against or snagging on the supports. This problem was most noticeable for the ventilation equipment while negotiating horizontal curves in the alignment. A total of 1 hour was required for clearance.

B.7.21 Water Inflow

Mining in this tunnel was on a downhill grade so that water inflows from anywhere in the tunnel accumulated at the heading. There was only one significant instance of water inflow from the tunnel walls, near the heading at Station 354+04. The contractor established sumps at several of the drop shaft adits and these controlled the inflow with the exception of four cases when the pumps stopped. When the heading was at Station 402+86, a containment structure at Drop Shaft 6K failed, and the tunnel was flooded. Fifty shifts were spent removing the water and repairing damaged equipment. In total, 480 hours, or 5.2 percent of the shift time were required during 69 shifts to remove water from the heading and to clean up and repair equipment.

IMPROVEMENTS TO TUNNEL BORING MACHINE DESIGN

Tunnel boring machine downtimes have been analyzed in 21 classes. The analysis indicates that decreased downtime could be expected if modifications in the excavation system design are done. The areas include muck handling, utility and support installation.

Information on these recommendations for design improvements are presented on pages 14-6 to 14-7.

CORRELATIONS BETWEEN ROCK INDEX PROPERTIES AND PENETRATION RATE

Correlations between rock index properties and penetration rates achieved with maximum tunnel boring machine thrust and torque are developed and it is shown that the predicting capabilities of index tests are significantly improved when the penetration rate is normalized with respect to thrust.

Information on this finding is presented in pages 11-2 to 11-13, pages 11-20 to 11-30, and pages 14-9 to 14-11.

RELATIONSHIP BETWEEN PENETRATION, THRUST AND CUTTER ROLLING FORCE

The interrelationship among penetration, thrust and rolling forces is analyzed with a 3-dimensional model which provides a rational basis for exploring variations in cutter forces and penetration rock as a function of rock type.

Information on this finding is presented in pages 11-32 through 11-39.

CRITICAL ENERGY RELEASE RATE, G_{IC}

This parameter, a rock property, reflects the energy required to propagate fractures. It deserves further attention for use in prediction of cutting tool performance in massive brittle rock.

Information on this finding is presented in pages 12-28 to 12-34.

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