t No. FHWA-RD-75-97

LLING AND PREPARATION OF REUSABLE, LONG RANGE, HORIZONTAL BORE HOLES IN ROCK AND IN GOUGE

Vol. III. A Development Plan to Extend Penetration Capability, Increase Accuracy, and Reduce Costs

DEPARTMENT OF TRANSPORTATION
UNITED STATES OF AMERICA

May 1976

Final Report

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Prepared for

FEDERAL HIGHWAY ADMINISTRATION

Offices of Research & Development

Washington, D. C. 20590

FOREWORD

This report contains the results of a research effort conducted by the Federal Highway Administration, through Foster Miller Associates, Inc., to assess horizontal drilling as an alternative to pilot tunneling in geological investigations prior to the design and construction of highway tunnels.

This report evaluates the potential for improving horizontal drilling capability by: (a) more efficient use of existing equipment, modification of existing equipment, and adaption of equipment not previously employed for horizontal drilling, and (b) developing new horizontal drilling equipment and techniques. Means are identified to decrease the cost and/or increase the performance capability of horizontal drilling. Development plans to implement these improvements are outlined and estimates of development costs are indicated.

This is the third of three volumes. Volume I is published as FHWA-RD-75-95, subtitle: A State-of-the-Art Assessment. Volume II is published as FHWA-RD-75-96, subtitle: Estimating Manual for Time and Cost Requirements.

Copies of the report are being distributed by FHWA transmittal memorandum. Additional copies may be obtained from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

Charles F. Scheffey

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

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16. Abstract

The objective of this study is to assess horizontal drilling as an alternative to pilot tunneling in geological investigation prior to the design and construction of highway tunnels and to identify means to increase the penetration capability and accuracy and decrease the cost of horizontal drilling.

This volume evaluates the potential for improving horizontal drilling capability by: (a) more efficient use of existing equipment, modification of existing equipment, and adaption of equipment not previously employed for horizontal drilling and by (b) developing new horizontal drilling equipment and techniques. Within these guidelines, means are identified to decrease the cost and/or increase the performance capability of horizontal drilling. Development plans to implement these improvements are outlined and estimates of development costs are indicated.

This is the third of three volumes. Volume I is published as FHWA-RD 75-95, subtitle: A State-of-the-Art Assessment. Volume II is published as FHWA-RD-75-96, subtitle: Estimating Manual for Time and Cost Requirements.

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PREFACE

This report was prepared by Foster-Miller Associates, Inc., Waltham, Massachusetts under FHWA Contract No. DOT-FH-11-8486. ENSCO, Inc., of Springfield, Virginia and Jacobs Associates of San Francisco, California contributed to the program as subcontractors. Dr. Steven I. Majtenyi was the FHWA contract manager. The program manager at Foster-Miller was Dr. John C. Harding. Subcontractor efforts were under the direction of Mr. L. A. Rabin of ENSCO, Inc., and Mr. George E. Wickham of Jacobs Associates.

FMA greatfully acknowledges the help and cooperation of many individuals both in industry and government in the preparation of this three volume study. We regret that space does not permit acknowledging all who contributed.

METRIC CONVERSION FACTORS

Approximete Conversions to Metric Meesures

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	squere centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	squere yerds	0.8	square meters	m^2
mi^2	squere miles	2.6	square kilometers	km^2
	ecres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grems	g
lb	pounds	0.45	kilogrems	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teespoons	5	milliliters	ml
Tbsp	teblespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	querts	0.95	liters	l
gel	gellons	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	Fehrenheit temperature	5/9 (after subtrecting 32)	Celsius temperature	°C

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

Approximete Conversions from Metric Meesures

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	squere centimeters	0.16	squere inches	in^2
m^2	squere meters	1.2	squere yerds	yd^2
km^2	squere kilometers	0.4	squere miles	mi^2
ha	hecteres (10,000 m^2)	2.5	ecres	
		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	gellons	gel
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
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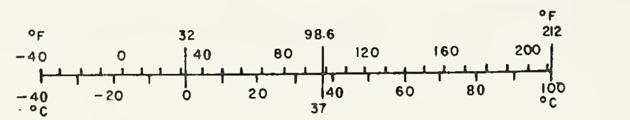

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont.)

LIST OF ILLUSTRATIONS (cont.)

LIST OF TABLES

LIST OF TABLES (cont.)

1. Executive Summary

1.1 Development Potential of Horizontal Drilling

Techniques for improving horizontal drilling potential can be divided into two categories:

(1) Improvements resulting from more efficient use of existing equipment, modifications of existing equipment, and the application of existing equipment, not now employed for horizontal drilling, to the horizontal drilling task.

(2) Improvements resulting from the development of new horizontal drilling equipment and techniques.

Clearly the first approach is the least cost, minimum development route to improving capability and will result in the quickest return for a given effort. Evaluation of this approach constitutes Task B of this study.

The second approach to improving horizontal drilling capability could be termed the "blue sky" or "clean sheet of paper" approach to the horizontal drilling problem. This approach involves the investment of more time and money and the assumption of higher risk, countered by increased potential improvement. Task C of this study is to conceptualize and evaluate new techniques for improving horizontal drilling capability.

1.1.1 Task B Results

In Volumes I and II the following drilling techniques were classed as state-of-the-art techniques for horizontal drilling in rock·

(1) Diamond wireline core drilling.

(2) Rotary drilling with rolling cutter bits.

(3) Down-hole motor drilling.

(4) Down-hole percussive drilling.

In the following sections the Task B potential of each of these drilling techniques is summarized. Task B guidance improvements are also summarized.

(a) Penetration Capability

Equipment manufacturers in the diamond wireline core drilling field are of the opinion that the in-hole components of a diamond wireline core drilling system are suitable for drilling horizontal holes up to 10,000 ft (3,048 m) in length. Analysis of the mechanics of horizontal drilling with this equipment leads to a similar conclusion. (See Chapter 3). However, presently available diamond drilling surface rigs do not have sufficient power to provide the thrust and torque necessary to drill to 10,000 ft (3,048 m). This is true simply because there has not been a requirement for such rigs. Chapter 3 develops performance specifications for surface rigs to attain the full penetration potential of available in-hole equipment. Suitable rigs can be obtained on a custom made basis from drilling rig manufacturers. (See Appendices A and B of Volume I). Estimated costs for rigs are developed in Chapter 7.

Rotary drilling with rolling cutter bits is the most developed method of vertical and directional drilling but the technique has recieved much less attention as a horizontal drilling method. The long horizontal-rotary drilling work carried out on the Seikan Tunnel Project in Japan, and by the Bureau of Mines and Kerr-McGee Corp. in the U. S., has all been performed with custom made surface drilling rigs (See Table 2.1, Volume I). More recent work, not cited in Volume I, has been conducted by the Bureau of Mines with a rig built by Lambert Drilling of Bridgeville, Pa. This program, concerned with drilling degasification holes in coal, has included drilling horizontal holes to 2,126 ft (648 m) in length.

With custom made surface drilling rigs of the appropriate specifications, rotary drilling with rolling cutter bits can be employed to drill horizontal holes to about 7,500 ft (2,286 m) in length. The technique is particularly well suited to the 6.75 to 9 inch (171 to 229 mm) hole size projected as necessary for advanced geophysical sensing techniques. Specifications for suitable surface rigs are developed in Chapter 3.

Horizontal penetration beyond 7,500 ft (2,286 m) is limited by potential drill string failure.

The down-hole motor drilling technique employing a surface unit to provide thrust is probably limited to horizontal penetrations of 5,000 ft (1,524 m) or less. Development of this technique to its full potential as a horizontal drilling technique will require the development of new hardware. The method has limited potential as a Task B drilling method, beyond its use as a steering tool.

Projections on the further development of down-hole percussive drilling as a technique for drilling long horizontal exploratory holes are very risky because of the limited data base from which to draw conclusions. The Jacobs Associates horizontal drilling program, discussed in detail in Volume I, has been the only long horizontal drilling program employing down-hole percussive techniques. The ground rules for that program, rapid penetration in medium and high strength rock, were much more limited then the requirements for this program. Problems of guidance and hole stability were not critical and consequently, were not treated in detail. A recent study of an "experimental guided tunneler" for the installation of underground power transmission lines recommends the down-hole percussive drilling technique for horizontal penetration.[7] However, the results of this study are of limited relevance to the problem of long horizontal drilling for tunnel site investigation because of the particular conditions for the guided tunneler study. These included:

1. A minimum hole size of 24 inches (610 m).
2. The hole is cased immediately behind the drilling unit.
3. The thrusting and steering system which is used for this system will require a substantial development effort.

In summary, while the experimental guided tunneler study is an interesting document, the results of the study are of limited importance to this program. This point is stressed because down-hole percussive drilling is not being recommended for further development as a long horizontal drilling technique for preexcavation tunnel site investigation. Some of the reasons for this decision are as follows:

1. There is no documented field experience with guided horizontal drilling by the down-hole percussive drilling technique.

2. The longest horizontal penetration by this technique is only 864 feet (262 m).

3. Down-hole percussive drilling employs pneumatic chip flushing and pneumatic chip flushing has little or no capability as a hole stability aid.

4. Down-hole percussive drilling is best suited to drilling in medium to high strength rock under dry conditions. It is not a particularly effective technique for drilling softer materials and is unsuitable for drilling in the presence of high water flows.

5. The down-hole percussive technique does not provide core samples.

In summary, the reasons for not recommending further development of down-hole percussive drilling to satisfy the requirements of this study fall into two general categories:

1. There is practically no documented data base from which to project the development potential of this technique.

2. The technique lacks the flexibility of other potential drilling techniques.

In summary, two drilling techniques show potential for increased penetration capability through modification of available equipment. These techniques are:

1. Diamond wireline core drilling.
2. Rotary drilling with rolling cutter cits.

(b) <u>Guidance</u>

Within the Task B ground rules there is substantial potential for improving guidance capabilities both in terms of the accuracy with which the hole can be surveyed and the accuracy and ease with which hole direction changes can be made. Before addressing the question of the potential of procedures and equipment beyond the present state-of-the-art it should be noted that available equipment is capable of much better performance than is normally achieved in practice. In theory, available equipment is capable of meeting the accuracy requirements of this study. (See Appendix D). However, practical considerations, related to time and cost, limit performance to the range indicated in Figure 2. Chapter 4 reviews procedures to assure that state-of-the-art equipment is employed in a manner which takes full advantage of its capabilities.

Task B developments have been identified to increase survey accuracy and reduce survey time. These developments are, respectively:

1. The application of gyroscopic survey tools with wireline telemetry to the survey of horizontal holes and 2., combining survey and coring equipment to provide a core barrel guidance system for diamond wireline core drilling.

The first of these techniques will give survey accuracy which exceeds the FHWA requirements of $\pm$ 30 ft (9 m) over 3 miles (4.8 km). The second technique is fundamentally a time and cost saving technique, however, improved survey accuracy will result through reduction of the nominal survey interval to 20 ft (6.1 m) (assuming that drilling is conducted with a 20 ft (6.1 m) core barrel).

Both of these techniques involve existing equipment which requires little or no modification. Gyroscopic survey tools with "real time" wireline telemetry are employed for surveying vertical and angled holes and can be made available on a custom order basis for surveying horizontal holes at cost estimates which range from $20,000 to $40,000. Survey and coring functions are now combined in a technique which is employed to obtain oriented core samples. (See Volume I, Section 6.6.1.2). Therefore, the combination of the survey and coring functions, with or without an oriented core feature, requires no new technology. Combining the survey and coring functions would reduce the time required to complete a nominal 5,000 ft (1,524 m) long hole by 4 percent and, with an oriented core feature, will substantially increase the value of the geological information obtained.

A significant advance in guided horizontal drilling will result from wider application of the down-hole motor to steering the drilling assembly. The down-hole motor has become the primary method of drilling directional changes for vertical and directional drilling in the petroleum industry. The use of the down-hole motor for drilling direction changes in horizontal drilling will result in substantial time savings. The most significant technical limitation to wider use of the down-hole motor is the lack of a real time survey tool to orient the down-hole motor. Both gyroscopic and magnetic devices can be made available on a custom order basis without significant development effort.

1.1.2 Task C Results

The only program specification which is not achievable within the Task B constraints is the requirement to penetrate to 3 mines (4.8 km). The key to achieving this objective is the development of a down-hole thrusting device which would free the drill string from the task of transmitting energy to the drill bit mechanically. The development of such a device is described in detail in Appendix C.

However, the most cost effective Task C development will be the development of techniques to reduce the time required for drill rod handling. Drill rod handling takes up approximately 50 percent of the total time required to drill a horizontal hole, regardless of technique. (See Chapter 7). Equipment to substantially reduce this time can be made available with only a moderate development effort. (See Section 7.5).

1.1.3 Horizontal Drilling Systems

Five potential horizontal systems are synthesized in Chapter 8. These systems are:

1. Diamond Wireline Core Drilling.
2. Rolling Cutter Rotary Drilling.

3. Rolling Cutter Core Drilling.
4. Down-Hole Motor Drilling with a Down-Hole Thruster.
5. Rolling Cutter Core Drilling with a Down-Hole Thruster.

The systems are synthesized from Task B and C developments presented in Chapters 3 - 7. The first two systems are primarily Task B systems while the last three are Task C systems. Table 25 summarizes the equipment which makes up each of the drilling systems and indicates the potential performance capabilities of each system.

1.2 Horizontal Drilling Development Guidelines

On the basis of this study, the following conclusions are evident:

1. Horizontal drilling has an order of magnitude cost advantage over pilot tunneling for horizontal penetrations out to 5,000 ft (1,524 m).

2. The economic advantage of horizontal drilling over pilot tunneling is likely to increase, even without substantial development, since horizontal drilling is essentially a mechanized activity while pilot tunneling is a more labor intensive technique.

3. There is a substantial potential to decrease the cost and/or increase the performance capability of horizontal drilling.

Having reached these conclusions, the next problem is to evaluate potential Task B/C developments. On the basis of the market for horizontal exploratory drilling the following evaluation guidelines can be drawn:

1. Horizontal drilling developments which are applicable to all guided drilling activities are preferable to developments which are applicable to horizontal drilling only.

2. A maximum horizontal penetration of 5,000 ft (1,524 m) should be sufficient to meet most requirements. Therefore, developments to increase penetration beyond the Task B limits should be given a low priority.

3. Non-cored horizontal drilling is of little value as a site investigation technique.

4. Developments which decrease the cost of horizontal drilling and/or increase the amount of information obtained should be given a high priority.

5. Geophysical sensing equipment under development by FHWA (Reference contract FH-11-8602) will require a hole size of at least 6.75 in (171 mm).

On the basis of these guidelines, recommendations for future horizontal drilling effort have been generated. These recommendations are summarized in the next section.

1.3 Recommended Horizontal Drilling Development

On the basis of this study, the following recommendations are presented for the development of horizontal drilling as an alternative to pilot tunneling in preexcavation site investigation.

1.3.1 Diamond Wireline Core Drilling
Horizontal Drilling Demonstration Project

1. Recommended Task B/C Options

(a) Application of a Down-Hole Motor (Dyna-Drill) for steering. A magnetic wireline survey tool is required for motor orientation and survey of direction changes.

(b) Improved drill rod handling equipment.

2. Program Time and Cost Estimates

(a) $500,000., 1 to 1.5 year duration.

3. Options to Improve Capability

(a) Wireline gyroscopic survey tool - $20,000. - $40,000.

(b) Core barrel guidance system - $18,000. - $37,000.

1.3.2 Rotary Drilling Demonstration Project

1. Recommended Tast B/C Options

(a) A magnetic wireline survey tool (to be used in conjunction with the down-hole motor for steering).

(b) Improved drill rod handling equipment.

(c) A rolling cutter core bit test program. (Additional cost unknown, estimate $100,000.).

2. <u>Program Time and Cost Estimates</u>

(a) $750,000. - $1,000,000., 1.5 to 2 year duration.

3. <u>Options to Improve Capability</u>

(a) Wireline gyroscopic survey tool, $20,000. - $40,000.

1.3.3 Development of a Remote Steering Tool for Rotary Drilling

Development of a prototype remote steering tool for rotary drilling is estimated to require from $250,000. - to $500,000. and 1.5 to 2 years.

A successful device would return about $100,000. for a single 5,000 ft (1,524 m) diamond wireline drilling project.

2. Introduction and Scope of Work

2.1 Background and Objective

This is the third and final volume of a study on the Drilling and Preparation of Reusable, Long Range, Horizontal Bore Holes in Rock and in Gouge. Volume I is a "State-of-the-Art Assessment" of the horizontal penetration capabilities of available drilling equipment. Volume II is an "Estimating Manual for Time and Cost Requirements" and includes an assessment of the economics of state-of-the-art horizontal drilling techniques. However, the algorithm used in Volume II is suitable for evaluating any method of horizontal drilling and is in fact applied in this volume to evaluating the economics of future developments. The objective of Volume III is to identify and assess the potential for extending horizontal drilling penetration capability, increasing accuracy, and reducing costs.

The goal of this study is to identify techniques to drill holes to 3 miles (4.8 km). Hole diameters from 6.75 to 9 inches (171 to 229 mm) are of particular interest as this size range corresponds to the requirements of "A New Sensing System for Pre-Excavation Subsurface Investigation for Tunnels in Rock Masses," a study in progress for Federal Highway Administration, by ENSCO, Inc., of Springfield, Virginia (Contract FH-11-8602).[1] The hole should be within $\pm$ 30 ft (9 m) of the intended trajectory. In summary, then, the ultimate goal of this study is to identify horizontal drilling procedures which will achieve the following specifications:

1.	Hole Length	3 miles (4.8 km)
2.	Hole Diameter	2 to 24 inches (40.8 to 610 m) with emphasis on 6.75 to 9 inches (171 to 229 mm).

3.	Deviation	$\pm$ 30 ft (9 m)
4.	Material Drilled	Soft, medium, and hard rock and gouge.
5.	Hole Life	Up to one year.

These specifications represent a level of performance far in excess of state-of-the-art capabilities. Therefore, improving horizontal drilling capability involves improving penetration capability and improving hole guidance accuracy. It is quite reasonable to expect that improved capability in these areas will, all other things being equal, increase drilling costs. However, the cost of horizontal drilling, or any other service for that matter, is probably the major variable influencing its utilization. Consequently a third consideration in increasing the viability of horizontal drilling is to reduce costs.

In summary, the factors which must be overcome to achieve the specifications called for in the contract and increase the utilization of horizontal drilling fall into the following categories:

1. Penetration Capability
2. Hole Guidance Accuracy
3. Economics

2.2 Scope of Work

The scope of work of the contract is defined in the "Prospectus" which is included as an enclosure to the contract. This definition is as follows:

"This study involves:

1. Establishment of the state-of-the-art.

(a) Assessment of existing horizontal penetration capabilities and past experiences.

(b) Development of cost and performance data on domestic and foreign equipment on the market.

2. Recommendation for more efficient use of existing equipment and machines including design drawings and specifications for modifications of conventional equipment that can achieve the objectives of this study.

3. Development of conceptual designs of new penetration techniques.

4. Feasibility studies on novel ideas.

Each system developed shall include optional core sampling and optional measurement of water pressure and water permeability before stabilizing the hole."

Item 1 above constitutes Task A of the contract - Assess Available Techniques. This task has been completed in Volumes I and II.

Item 2 above constitutes Task B of the contract - Modifying Conventional Equipment. This task is covered in this volume.

Items 3 and 4 above constitute Task C of the contract - New Conceptual Design Alternatives. Task C results are also presented in this volume.

2.3 Summary of Task A Results

The results of the Volume I "State-of-the-Art Assessment" are summarized in Tables 1 and 2 and Figures 1 and 2. Table 1. presents an assessment of the penetration capability of the four candidate long horizontal drilling techniques. Figure 1 presents a graphic representation of the assessment. Figure 2 is a graphic representation of the accuracy to which a horizontal hole can be drilled with state-of-the-art equipment and procedures. A time and cost estimate summary for the four techniques is presented in Table 2. These estimates are for a nominal set of parameters and results can vary substantially as hole parameters are varied. The data presented in this section will serve as a basis for evaluating of the relative merits of potential future developments.

2.4 Organization of Report

This report is organized as follows. Section 1 summarizes the results of Task B and C efforts and lists recommendations for further horizontal drilling development effort.

Section 2 reviews the background and objectives of the program, defines the scope of effort of the program, summarizes the results of previous program effort (Task A), and then summarizes the organization of this document.

Section 3 evaluates the possibility of extending the horizontal penetration capability of available horizontal drilling equipment and assesses the potential of new, innovative techniques. Specifications are presented for equipment capable of achieving the penetration goals of this study.

Section 4 reviews present guidance techniques and assesses the requirements for bringing the state-of-the-art of horizontal drilling guidance procedures to the level of development of guidance procedures

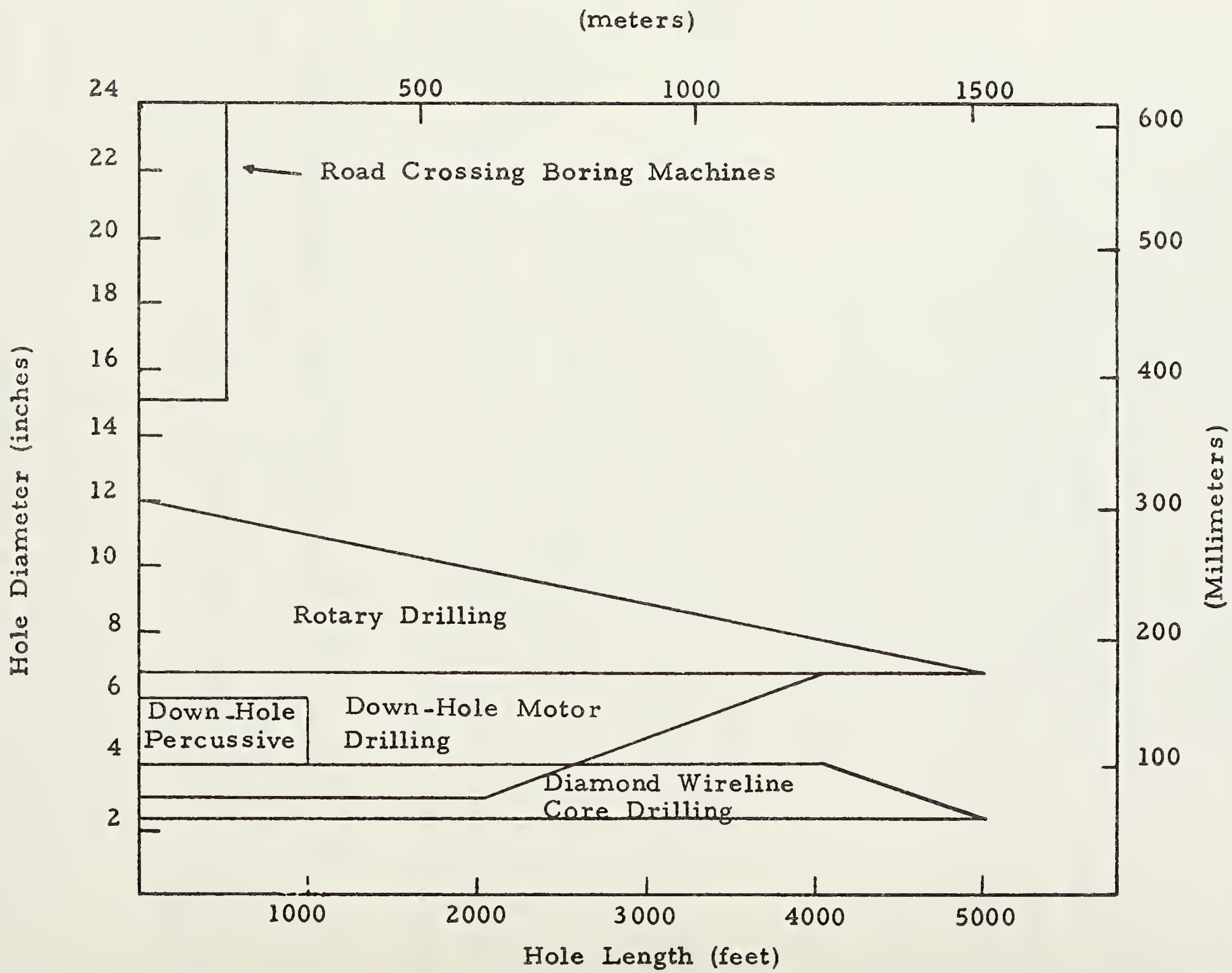

Figure 1 - State-of-the-Art Horizontal Penetration Capability

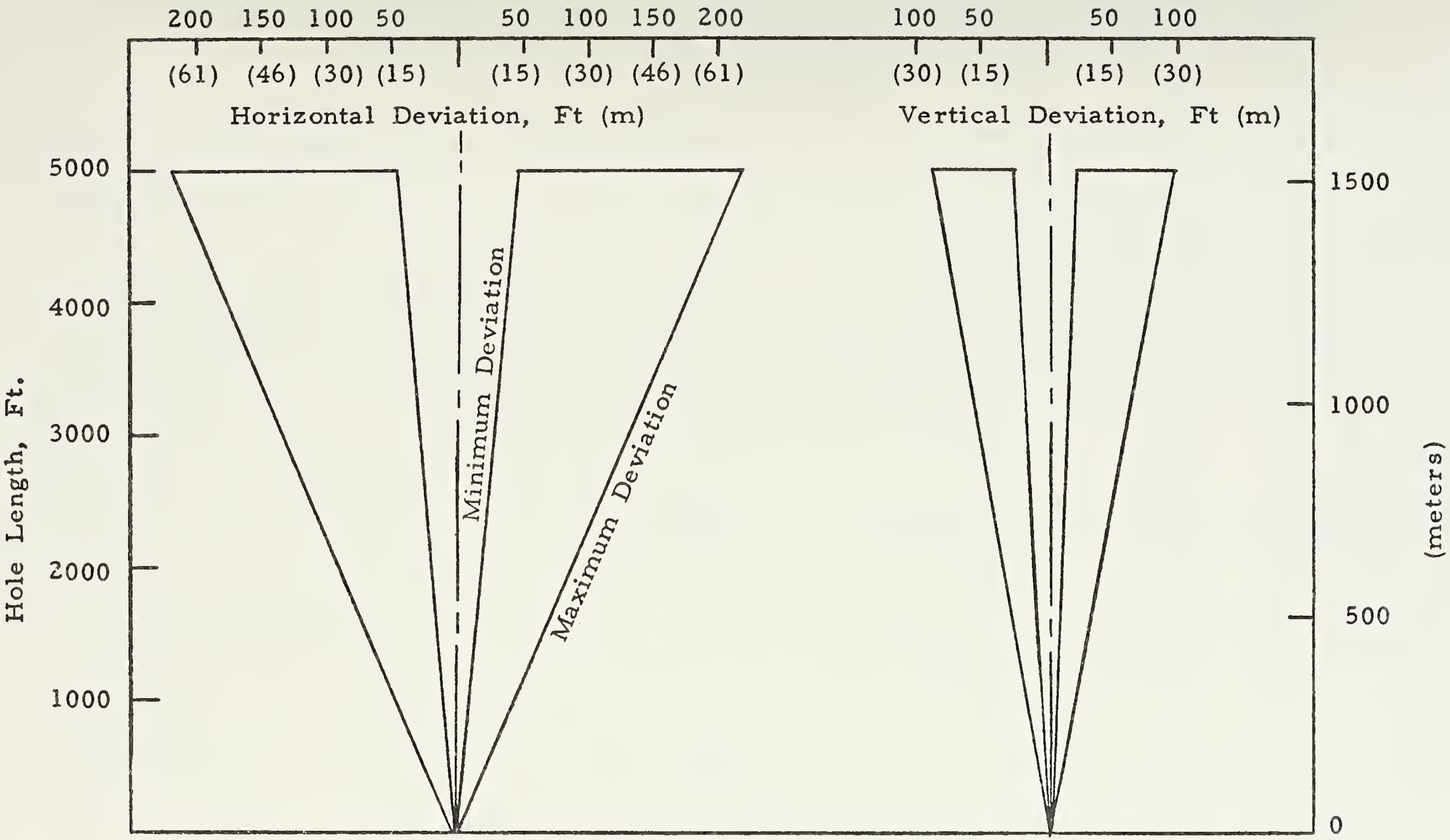

Figure 2 - State-of-the-Art Guidance Capabilities

TABLE I

LONG HORIZONTAL DRILLING PENETRATION CAPABILITY

Technique	Hole Length, feet (m)	Hole Diameter inches (mm)
Diamond Wireline Core Drilling	4000 (1220) to 5000 (1524)	2.98 (76) 2.36 (60)
Rotary Drilling	0 to 5000 (1524)	12 (305) 6.75 (171)
Down-Hole Percussive Drilling	1000 (305)	4-6 (102-152)
Down-Hole Motor Drilling	2000 (610) to 4000 (1220)	3 (76) 6.75 (171)

TABLE 2

LONG HORIZONTAL DRILLING TIME AND COST ESTIMATES FOR AVERAGE GEOLOGY*

Drilling Technique	Hole Diam. in. (mm)	Coring Interval ft (m)	1000 (305)	2000 (710)	3000 (915)	4000 (1220)	5000 (1525)
			Distance, feet (meters) / Time, hours / Cost, $/ft ($/meter)				
Diamond Wireline	3 (76)	100%	275	712	1,346	2,161	3,144
			32 (105)	38 (125)	45 (148)	53 (174)	61 (200)
Rotary	6.75 (172)	60 (18)	224	554	1,038	1,708	2,502
			55 (180)	60 (197)	68 (223)	77 (253)	86 (282)
Down-Hole Motor	6.75 (172)	60 (18)	252	599	1,106	1,800	---
			70 (230)	74 (243)	80 (263)	89 (292)	---
Down-Hole Percussive	6 (152)	60 (18)	217	---	---	---	---
			48 (157)				

*Assumes 11 percent soft rock, 59 percent medium rock, 30 percent hard rock and equipment employed in directional drilling for the petroleum industry. Further procedural changes and equipment development necessary to attain the guidance goals of the contract are presented and assessed.

Section 5 reviews the hole stabilization methods available for maintaining the hole while drilling and for the contract specified term of one year after hole completion. An attractive technique for placing plastic casing for long term hole stability is presented in this section.

Section 6 evaluates potential improvements in information gathering techniques and assesses several new developments in this area.

In Section 7, the economics of state-of-the-art horizontal drilling procedures are broken down in detail to determine potential areas for cost savings. The economic impact of improved procedures and new developments is also evaluated in this section.

Section 8 defines a series of horizontal drilling systems and assesses their capabilities. The systems presented range from assemblies of available equipment with modifications to improve performance capability to wholly new systems for which all components would require extensive development efforts.

Section 9 outlines development plans for the improved drilling systems.

In Section 10, conclusions are drawn as to which candidate development efforts are potentially cost effective for FHWA to pursue. Recommendations for development are presented in accordance with these conclusions.

3. Extending Penetration Capability

The drilling of a horizontal hole requires the expenditure of energy at the rock face. In conventional drilling techniques, this energy is provided by thrust and torque applied to the drill bit. As the hole gets longer, it becomes more difficult and inefficient to provide the required energy. As a practical matter, in horizontal drilling beyond a certain length, it becomes physically impossible to provide this energy using conventional techniques.

Methods of providing the necessary energy to the drill bit in horizontal drilling include:

1. Surface Drilling
2. Down-Hole Motor Drilling
3. Down-Hole Thruster Drilling

In surface drilling, both the torque and the thrust are provided directly by the surface equipment. The second technique provides torque by means of a down-hole motor and thrust from a surface rig. The third technique provides thrust by means of a down-hole thruster and torque by means of either a down-hole motor or a surface rig.

The following sections discuss the pros and cons of each of these drilling techniques, their potential penetration capabilities, and the equipment requirements necessary to achieve these capabilities. The analysis on which these evaluations are based is presented in Appendix A. An alternative evaluation of horizontal drilling penetration capability, performed by ENSCO, Inc., of Springfield, Va. (Program subcontractor) is presented in Appendix B. Both evaluations reach essentially the same conclusions.

3.1 Surface Drilling

Surface drilling is the most developed of the three penetration techniques and falls primarily into two categories depending on the type of drill bit used - rotary drilling using rolling cutter bits and diamond drilling using diamond coring bits.

To date, most long horizontal drilling has been performed with diamond core drilling equipment. The only significant rotary horizontal drilling has been that performed for the USBM in coal and for the Seikan tunnel in Japan. Diamond coring bits have a highly developed technology and are currently the only bits which have been extensively used for coring. The rolling cutter bit is the preferred rock drilling bit for petroleum drilling and development of the bit is proceeding at an impressive rate. Rolling cutter core bits have been employed with good results for recent ocean floor coring work.[2,3] This work is discussed further in Chapter 6. Rotary drilling in deep vertical holes is a highly developed technique which differs from horizontal drilling in that the drill string is always in tension. The fact that horizontal drilling, by either rolling cutter or diamond drilling tehcniques, is performed with the drill string in compression is a significant factor in limiting ultimate penetration capability because of drill string buckling problems.

Table 3 presents the maximum lengths to which the various drilling operations required for surface drilling can be performed for a variety of hole diameters. For the range of hole diameters presented, the ability of the drill string to transmit the torque required to start the drill bit and string rotating is the limiting factor on penetration capability. This analysis indicates that diamond drilling in the diameter range, 2.360 in (60 mm) to 4.827 in (123 mm) can be developed to around 10,000 ft. (3048 m) and that rotary drilling in the 6.75 in (172 mm) to 9.875 in (251 mm) diameter range can be developed to around 7,500 ft (2286 m).

These penetration capabilities should be possible to achieve with modifications to existing equipment and current drilling procedures.

TABLE 3

MAXIMUM PERFORMANCE LENGTHS FOR DRILL STRING OPERATIONS IN SURFACE DRILLING

		Hole Diameter, in (mm)				
		BQ, 2.360 (59.9)	PQ, 4.827 (122.6)	6-3/4 (171.5)	8-3/4 (222.3)	9-7/8 (250.8)
Operation	Friction Coefficient	Maximum Length, ft (m)				
Drill String Removal Thrust	0.38	24,800 (7,560)	24,000 (7,320)	20,700 (6,310)	21,000 (6,400)	20,400 (6,220)
Drill String Insertion Thrust	0.38	16,500 (5,030)	19,400 (5,910)	10,700 (3,260)	10,900 (3,320)	12,200 (3,720)
Drilling Thrust	0.1	50,100 (15,270)	62,000 (18,900)	18,700 (5,700)	20,900 (6,370)	25,100 (7,650)
Drilling Torque	0.1	28,400 (8,660)	34,200 (10,400)	10,700 (3,260)	13,000 (3,960)	16,000 (4,880)
Spin-Up Torque	0.38	9,400* (2,870)	10,300* (3,140)	7,200* (2,190)	7,300* (2,230)	7,800* (2,380)

* Limiting Length

The thrust and torque requirements for drilling rigs for surface drilling are presented as functions of hole length and diameter in Figures 3 and 4.

3.2 Down-Hole Motor Drilling

Down-hole motor drilling is the next most developed technique, but has also been primarily developed for drilling in vertical holes. Whereas in surface drilling, the energy was applied to the rock force by torque and thrust applied to the drill string, down-hole motors are located right at the rock face and apply the torque directly to the drill bit. The thrust, however, is still applied from the surface through the drill string. Down-hole motors are supplied by energy which may be transported pneumatically, electrically, or hydraulically. The advantages of down-hole motor drilling are that it incorporates an inherently efficient energy transport system and is readily adaptable for remote steering. Disadvantages to the down-hole motor itself are that it is severely limited by the geometry of the space available and it is required to operate in a hostile environment. Disadvantages to down-hole motor drilling as a technique are that the drill string is still in compression, it is not possible to obtain core samples, and, because the drill string is not rotating, there is higher friction and potential problems of chip removal.

Table 4 presents the maximum lengths to which the various drilling operations required for down-hole motor drilling can be performed for a variety of hole diameters. For the range of hole diameters presented, the ability of the drill string to transmit the thrust required for drilling is the limiting factor on penetration capability. This analysis indicates that down-hole motor drilling in the BQ to PQ size range can be developed to around 2,700 ft (823 m) and that down-hole motor drilling with rolling cutter bits in the 6.75 in (171 mm) to 9.875 in (251 mm) diameter range can be developed to around 5,000 ft (1,524 m).

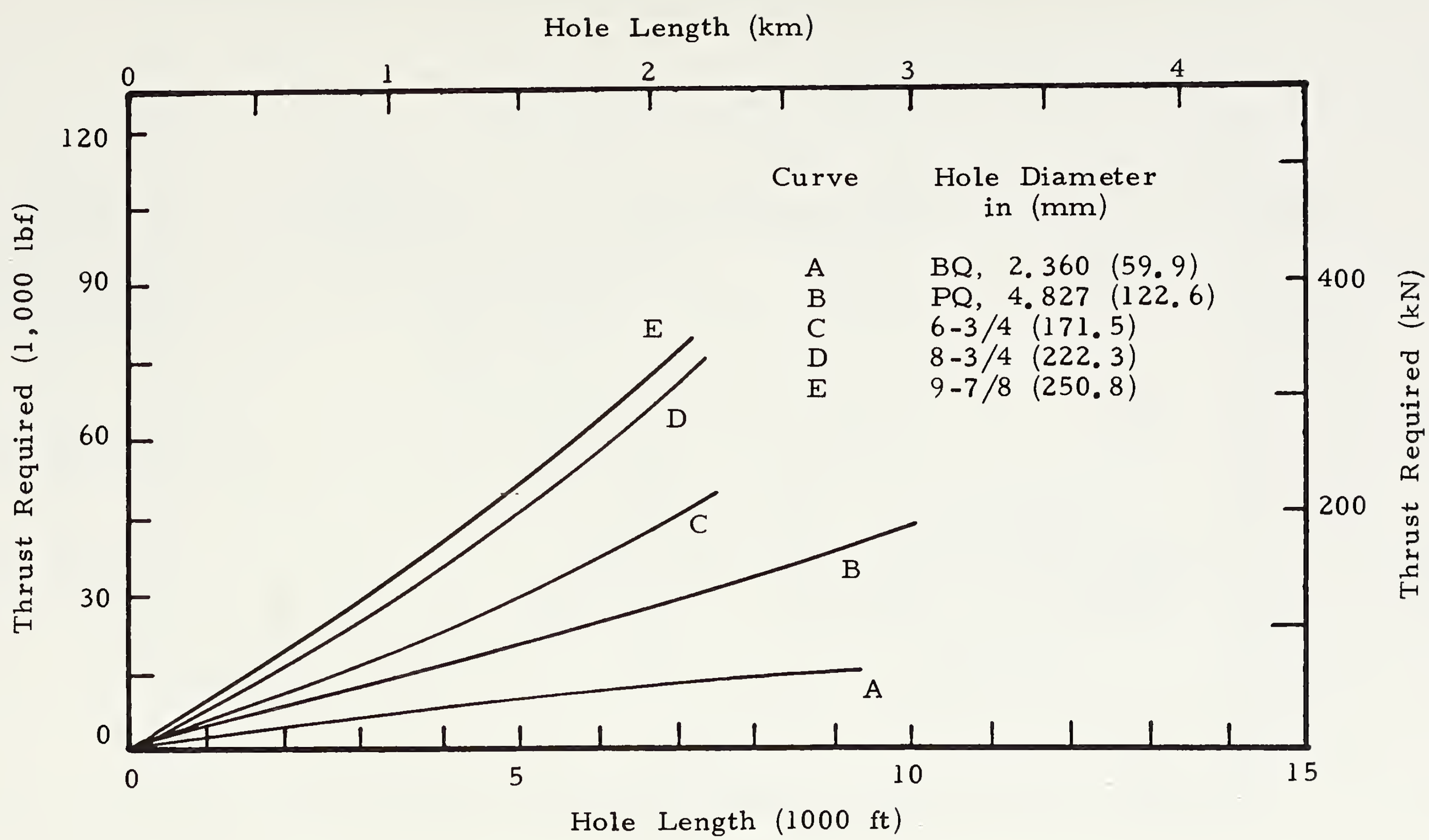

Figure 3 - Thrust Requirements for Surface Rig in Surface Drilling

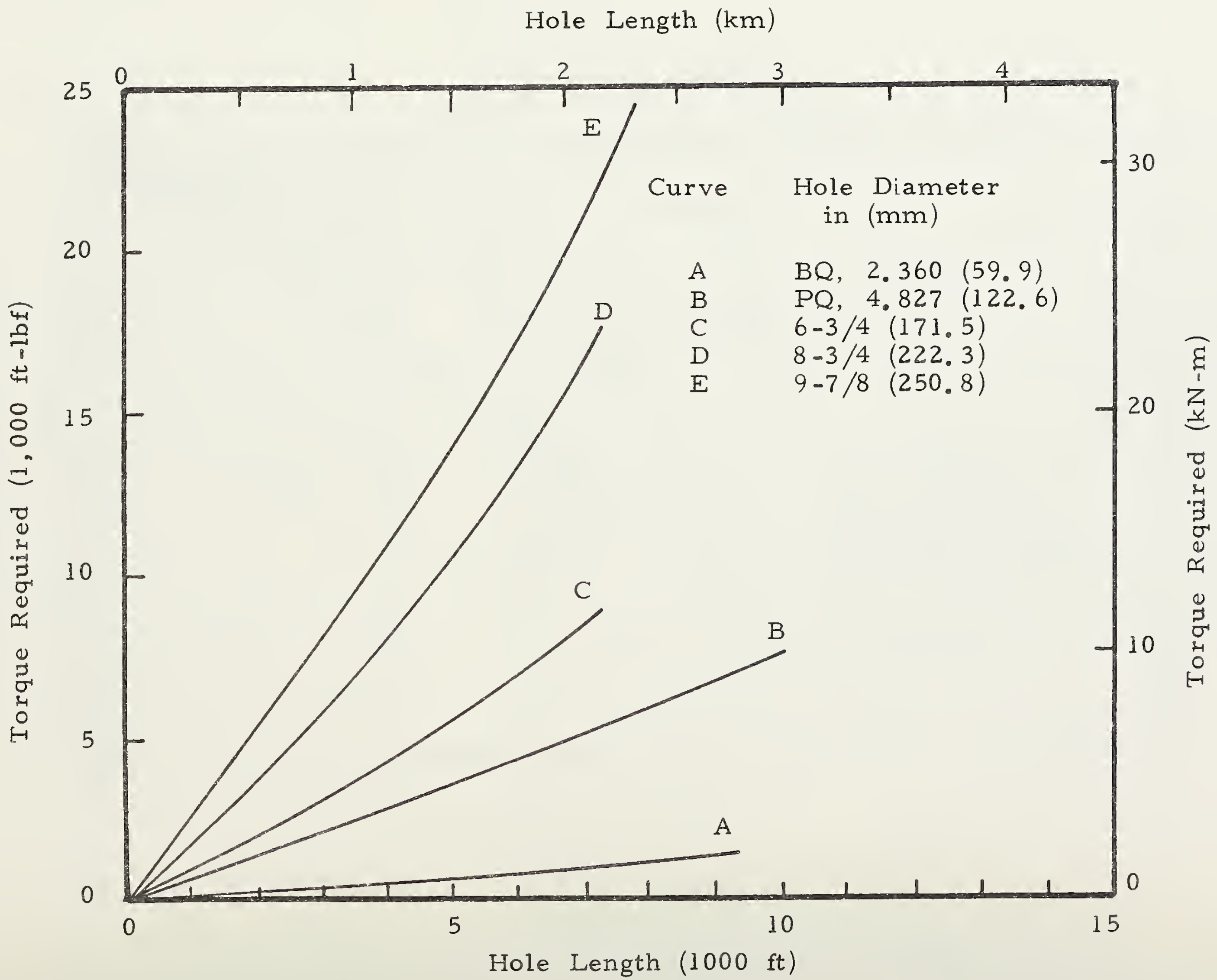

Figure 4 - Torque Requirements for Surface Rig in Surface Drilling

TABLE 4

MAXIMUM PERFORMANCE LENGTHS FOR DRILL STRING OPERATIONS IN DOWN-HOLE MOTOR DRILLING

		Hole Diameter, in (mm)			
		3 (76.2)	6-3/4 (171.5)	8-3/4 (222.3)	9-7/8 (250.8)
Operation	Friction Coefficient	Maximum Length, feet (m)			
Drill String Removal Thrust	0.38	14,500 (4,420)	21,500 (6,550)	20,700 (6,310)	20,700 (6,310)
Drill String Insertion Thrust	0.38	5,800 (1,770)	7,900 (2,410)	8,500 (2,590)	7,800 (2,380)
Drilling Thrust	0.38	2,700* (825)	4,400* (1,340)	5,300* (1,620)	4,400* (1,340)

* Limiting Lengths

These penetration capabilities should be possible to achieve with modifications to existing equipment and current drilling procedures. The thrust requirements for the surface rig for down-hole motor drilling are presented as a function of hole length and diameter in Figure 5.

3.3 Down-Hole Thruster Drilling

The third drilling technique, down-hole thruster drilling, is the least developed currently, however, it shows the greatest development potential. This is primarily because the down-hole thruster allows the drilling to take place with the drill string in tension instead of compression.

Down-hole thruster drilling with a surface rig providing the torque probably represents the cored hole long range drilling system of the future. The major advantages of this drilling system are that the drill string is in tension, it is capable of providing core samples, and is capable of remote steering. Disadvantages are that the down-hole thruster is severely limited by geometry and must operate in a hostile environment, and that the rotating drill string makes telemetry of data difficult.

Table 5 presents the maximum lengths to which the various drilling operations required for down-hole thruster drilling with a surface rig can be performed for a variety of hole diameters. For the range of hole diameters presented, the ability of the drill string to transmit the torque required to start the drill bit and string rotating is the limiting factor on penetration capability. This analysis indicates that down-hole thruster drilling with a surface rig and diamond bits in the 2.360 in (60 mm) to 4.827 in (123 mm) diameter range can be developed to just over 10,000 ft (3048 m) and with rolling cutter bits in the 6.75 in (171 mm) to 9.875 in (251 mm) diameter range, it can be developed to just over 9,000 ft (2743 m).

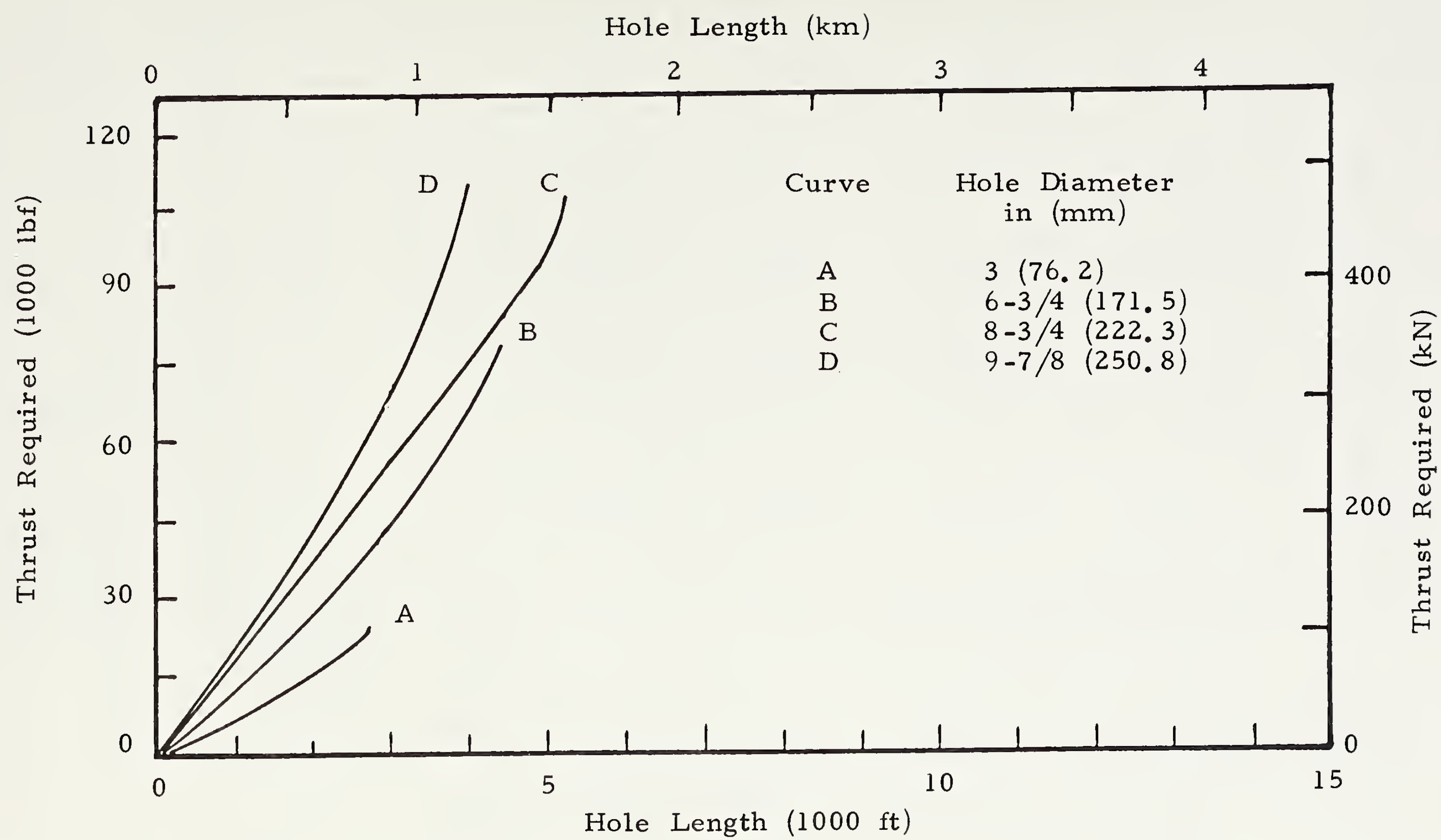

Figure 5 - Thrust Requirements for Surface Rig in Down-Hole Motor Drilling

TABLE 5

MAXIMUM PERFORMANCE LENGTHS FOR DRILL STRING OPERATIONS IN SURFACE DRILLING WITH A DOWN-HOLE THRUSTER

		Hole Diameter, in (mm)				
		BQ, 2.360 (59.9)	PQ, 4.827 (122.6)	6 3/4 (171.5)	8 3/4 (222.3)	9 7/8 (250.8)
Operation	Friction Coefficient	Maximum Length, feet (m)				
Drill String Removal Thrust	0.38	24,800 (7,560)	24,000 (7,320)	20,700 (6,310)	21,000 (6,400)	20,400 (6,220)
Drill String Insertion Thrust	0.38	24,800 (7,560)	24,000 (7,320)	20,700 (6,310)	21,000 (6,400)	20,400 (6,220)
Drilling Thrust	0.1	94,300 (28,750)	91,300 (27,800)	78,500 (23,900)	79,700 (24,300)	77,700 (23,700)
Drilling Torque	0.1	34,800 (10,600)	37,800 (11,500)	21,300 (6,490)	25,100 (7,650)	26,800 (8,170)
Spin-Up Torque	0.38	10,500* (3,200)	19,900* (3,320)	9,200* (2,800)	9,200* (2,800)	9,300* (2,830)

* Limiting Lengths

The achievement of these penetration capabilities requires the development of the down-hole thruster as well as the modification of existing equipment. The thrust requirements for the down-hole thruster and the torque requirements for the surface rig are presented in Figures 6 and 7 respectively as functions of hole length and diameter.

Down-hole thruster drilling with a down-hole motor most probably represents the non-cored long range drilling system of the future. Major advantages of this drilling system are that the drill string is in tension, there exists the possibility of utilizing a flex hose or something similar instead of drill rod, it has remote steering capability, and the fact that the drill string is not rotating greatly simplifies the telemetry problems. Disadvantages are that the down-hole motor and thruster are severely limited by geometry, must operate in a hostile environment, have no coring capabilities, and there are potential problems of chip removal.

Table 6 presents the maximum lengths to which the various drilling operations required for down-hole thruster drilling with a down-hole motor can be performed for a variety of hole diameters. All the drilling operations can be performed to the same limit and collectively limit the penetration capabilities. This analysis indicates that down-hole thruster drilling with a down-hole motor and B to P size diamond bits can be developed to almost 15, 000 ft (4, 572 m) and with rolling cutter bits in the 6. 75 in (171 mm) to 9. 875 in (251 mm) diameter range, it can be developed to beyond 15, 000 ft (4, 572 m).

The achievement of these penetration capabilities requires the development of the down-hole thruster. The thrust requirements for the down-hole thruster are presented in Figure 8 as a function of hole length and diameter.

A detailed design concept for a down-hole thruster system is presented in Appendix C.

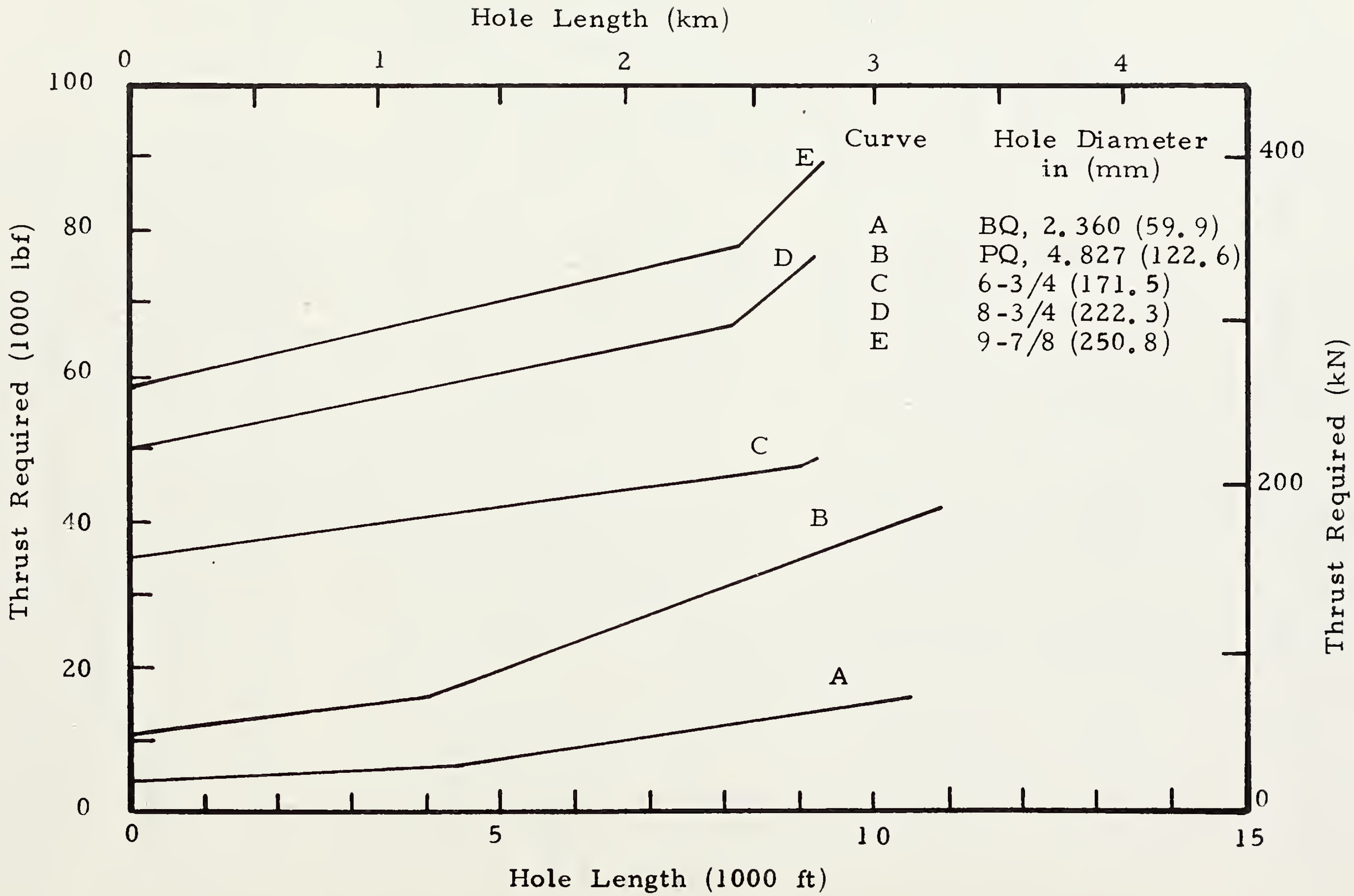

Figure 6 - Thrust Requirements for Thruster in Surface Drilling with a Down-Hole Thruster

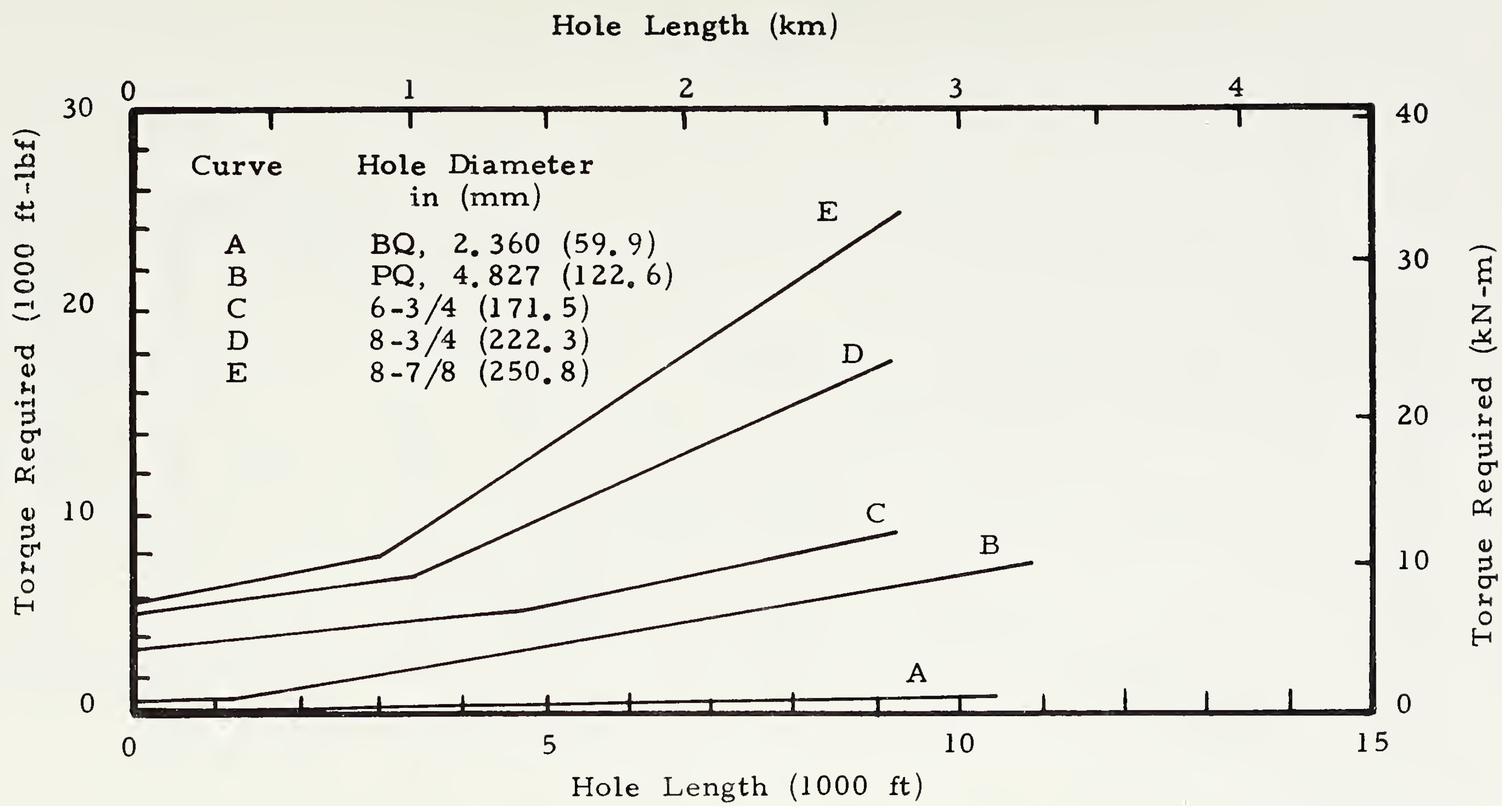

Figure 7 - Torque Requirements for Surface Rig in Surface Drilling with a Down-Hole Thruster

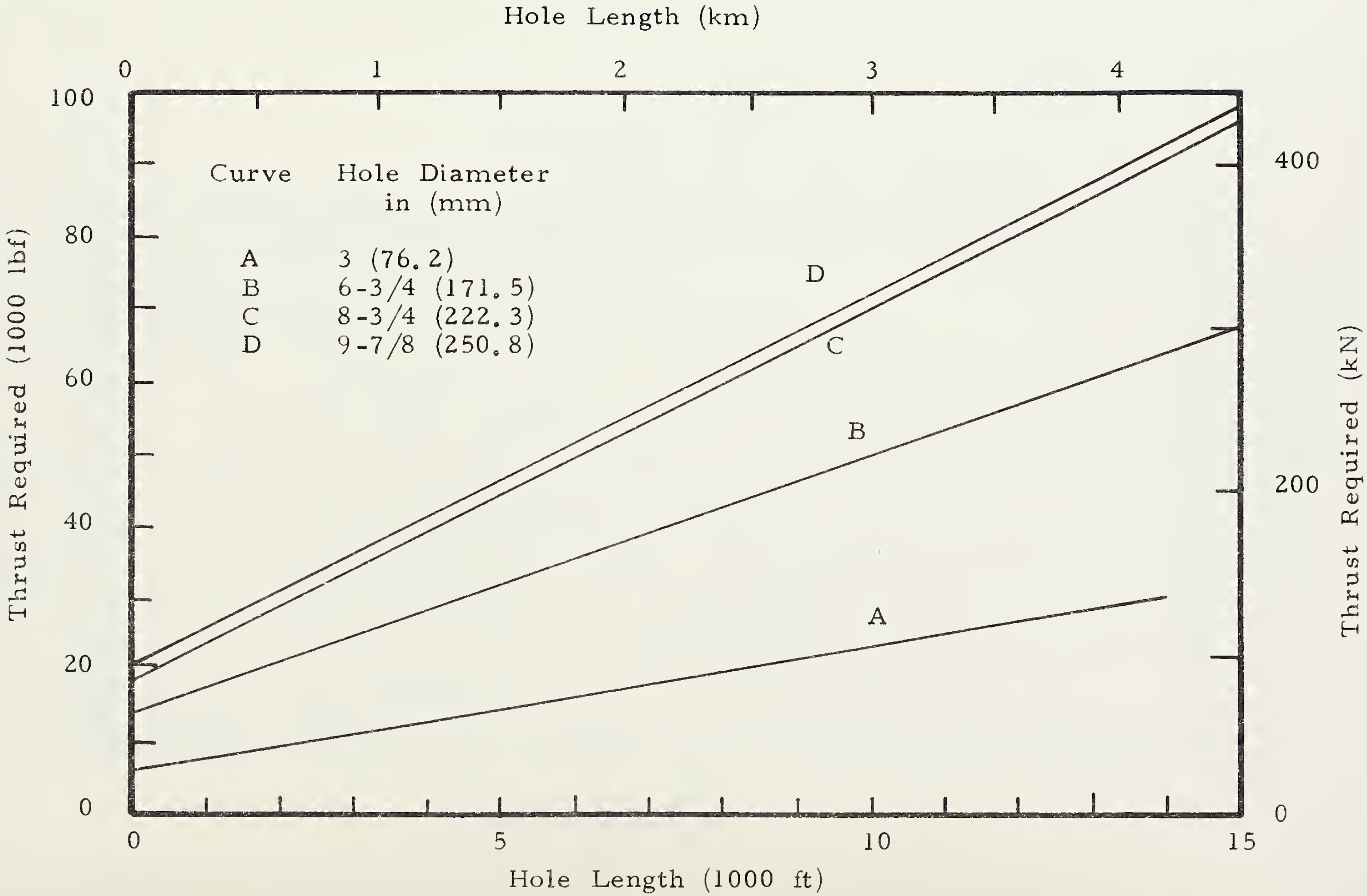

Figure 8 - Thrust Requirements for Thruster in Down-Hole Motor Drilling with a Down-Hole Thruster

TABLE 6

MAXIMUM PERFORMANCE LENGTHS FOR DRILL STRING OPERATIONS IN DOWN-HOLE MOTOR DRILLING WITH A DOWN-HOLE THRUSTER

Operation	Friction Coefficient	Hole Diameter, in (mm)			
		3 (76.2)	6 3/4 (171.5)	8 3/4 (222.3)	9 7/8 (250.8)
		Maximum Length, feet (m)			
Drill String Removal Thrust	0.38	14,500 (4,520)	21,500 (6,550)	20,700 (6,310)	20,700 (6,310)
Drill String Insertion Thrust	0.38	14,500 (4,520)	21,500 (6,550)	20,700 (6,310)	20,700 (6,310)
Drilling Thrust	0.38	14,500 (4,520)	21,500 (6,550)	20,700 (6,310)	20,700 (6,310)

4. Improving Guidance Capability

Guided horizontal drilling involves surveying the hole as it is drilled and steering the drilling assembly along the desired trajectory. A detailed description of the state-of-the-art of guidance techniques is presented in Volume I. The equipment involved includes:

1. Survey tools, to survey the hole.
2. Steering tools, to deviate the drilling assembly.

Steering tools are oriented with a survey tool, or in the case of a down-hole motor, with a "real time" survey instrument.

4.1 Present Guidance Techniques for Horizontal Drilling

If any drilling technique can be characterized as a "standard" procedure for horizontal drilling it is diamond wireline core drilling. The guidance procedure used with wireline core drilling involves surveying the hole with magnetic single shot or multi-shot devices and deflecting the drilling assembly, as required, by wedging.* Variation in drilling thrust and rotational speed in conjunction with drilling assembly changes (the use of stabilizers, collars, etc.) can be used to make the assembly climb or drop. The latter technique is very much an art in horizontal drilling. The procedures developed for horizontal drilling with diamond wireline equipment have been developed, for the most part, in the AEC drilling program at Mercury, Nevada and various projects associated with the mining industry. A recent Bureau of Mines Report of Investigation gives detailed procedures for drilling guided horizontal holes in coal seams with rotary drilling equipment.[4] The procedures are essentaily equivalent to those used in the AEC horizontal drilling program.

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* The procedure of deflecting the drilling assembly with a metal wedge is termed wedging in the mining industry and whip stocking in the petroleum drilling industry.

4.2 Guidance Procedures Employed in the Petroleum Drilling Industry

In directional drilling in the petroleum industry the survey function is also normally handled by magnetic single shot or multi-shot devices. Gyroscopic survey tools may be used to survey a completed hole but, typically, they are not used in the directional drilling operation. In this type of drilling the down-hole motor, and in particular the Dyna-Drill, has supplanted whip stocking as the preferred method of deflecting the drilling assembly. Variations in drilling thrust and rotational speed and drill string assembly, analogous to the procedures utilized in horizontal core drilling, are used to increase or decrease the inclination of the hole. However, these procedures are much more highly developed and standardized in the directional drilling industry than are any similar procedures employed in horizontal drilling. A final piece of hardware which is, at the present time, unique to the directional drilling industry, is the "real time" survey tool. Fundamentally this tool is no more than a magnetic survey device with a conducting wire attached to provide real time readout to the surface. The purpose of this tool is to indicate the orientation of the down-hole motor when making hole deviations and to survey the hole deviation as it is drilled.

4.3 Applying Petroleum Drilling Guidance Procedures to the Horizontal Drilling Task

In postulating the use of a rotary drilling/down-hole motor system or pure down-hole motor system for horizontal drilling, one should recognize the problems caused by the fact that available wireline survey tools are not designed for use in horizontal drilling. Without a wireline survey tool the driller must orient the down-hole motor on the basis of rules of thumb for drill string rotation due to torque reaction as a function of drill string length. The driller must drill and survey the hole deflection leg to determine if his orientation estimate was correct. Such procedures are not totally satisfactory in the petroleum drilling industry, and, given the problems of predicting drill string friction characteristics, they are likely to be much less satisfactory in horizontal drilling. In short, the availability of wireline survey tools configured for use in horizontal holes must be considered a prerequisite to the wide spread use of the down-hole motor for performing the steering function in horizontal drilling. The technical problems in adapting the wireline survey tool to horizontal drilling are not significant. Devices could be made available at the present time, on a custom order basis. However, as was until recently the case with the Dyna-Drill, the pricing policy for wireline survey services is derived from petroleum drilling practice and is not compatible with the use requirements of horizontal drilling. The economics of this tool are discussed further in Chapter 7.

A first step then, in improving the guidance procedures utilized in horizontal drilling, is to make a high angle wireline steering tool available at a cost effective price. It is our judgement that this will happen when equipment manufacturers are convinced that there is a market for horizontal drilling. One method of encouraging the development of such a market is to support a horizontal drilling demonstration program.

4.4 Task B Guidance Developments

4.4.1 Procedural Changes to Improve the Accuracy of Available Magnetic Survey Devices

(a) Survey

The accuracy of available magnetic single shot and multi-shot survey instruments can be optimized by the use of appropriate calibration procedures. For example, a short horizontal hole can be drilled to the maximum distance which can be surveyed by optical, line-of-sight techniques. This length of hole then becomes a calibration stand. The standard drilling string assembly can then be run into the calibration hole and a survey point taken. This survey reading can be compared with the absolute reference provided by the optical survey so that subsequent survey readings can be corrected for calibration errors. This procedure and other procedures to optimize survey instrument performance could best be evaluated and standardized through a demonstration drilling program.

Appendix D presents an analysis of the time penalties associated with achieving various levels of survey accuracy. This analysis indicates that the specified hole accuracy requirements could be met with available equipment but that the time and cost penalties associated with achieving this level of performance are prohibitive.

(b) Gyroscopic Survey Devices

The next step in accuracy beyond available magnetic survey devices is to employ gyroscopic subsurface survey devices. Gyroscopic devices are available with camera systems to record survey readings or with wireline systems to provide a "real time" readout of survey results. Single shot and multi-shot (photographic recording) devices are available for use in horizontal holes. The real time wireline readout instruments can be made available on a custom order basis. A complete system is estimated to cost from $20,000 to $40,000.[5]

The single shot and multi-shot gryoscopic devices may or may not offer an accuracy advantage over comparable magnetic reference devices. If cost were not a factor, the gyroscopic devices could be made to give better accuracy than the magnetic devices. Given the compromises involved in building the gyro systems to a price at which they can be marketed, they may not necessarily be superior to magnetic instruments in a field situation. Field tests would have to be conducted to compare performance of gyroscopic and magnetic single and multi-shot devices in the "real world" environment.

There is a limited amount of field data available which indicates that real time readout gyroscopic survey tools give an order of magnitude improvement over magnetic methods in surveying borehole trajectory. However, at today's prices, the cost of the gyroscopic device will be about 3 to 6 times that of available magnetic survey instruments.

(c) Core Barrel Guidance Systems

On drilling projects where wireline coring procedures are being used to obtain either intermittent or continuous core samples from the hole, substantial time and cost savings can be realized by combining the coring and survey functions. This is already done in a procedure known as oriented core sampling, discussed in Volume I. Section 7 examines the potential time and cost savings of such procedures. The procedures now used to obtain oriented core samples employ magnetic survey instruments but gyroscopic instruments could also be employed. The use of a gyroscopic instrument would eliminate the need to construct the system from non-magnetic materials. Appendix E presents a possible design for a core barrel guidance system employing a gyroscopic survey tool.

4.4.2 Steering

(a) Down-Hole Motors

As noted previously in this chapter, use of the down-hole motor to perform the steering function in horizontal drilling will offer a substantial time savings over the widely used wedging or whip stocking technique. Therefore, a logical Task B development is to employ the down-hole motor as the preferred hole deviation method for all horizontal drilling. Unfortunately, as noted in Chapter 3, the down-hole motor probably can not be used to drill effectively beyond 3,000 ft (914 m) in smaller horizontal holes (corresponding to diamond wireline core drilling), or 5,000 ft (1,524 m) in larger horizontal holes (corresponding to rotary drilling with rolling cutter bits). Consequently, the horizontal driller must resort to the more time consuming wedging or whip stocking technique when drilling beyond these distances. The limitations of the down-hole motor can be overcome by developing a suitable down-hole thruster device, as noted in Chapter 3.

(b) Wireline Survey Tools

A wireline survey tool is nothing more or less than a magnetic or gyroscopic survey tool with wireline telemetry to give real time information on steering tool (down-hole motor for example) orientation. The drill rod torque reaction caused by a down-hole motor makes the true orientation of the motor very difficult to determine without some form of real time survey information. These tools are now widely used for directional drilling and could be made available for horizontal drilling on a custom order basis.

(c) Remotely Actuated Kick Subs

With the exception of the Dyna-Drill with the bent housing, none of the down-hole motors can, by themselves, deviate the hole. Indeed they are applicable, and are often used, for drilling straight holes. The most common method for deviating a hole with a down-hole motor is by use of the bent sub. A bent sub is a short sub (section of drill rod) that has its upper thread cut concentric with the axis of the sub body, and its lower thread cut concentric with an axis at an angle (from $1/2^{\circ}$ to 3°) in relation to the axis of the upper thread. Thus, the down-hole motor is deviated from the axis of the drill string by the number of degrees incorporated into the bent sub. Usually a non-magnetic drill collar is run above the bent sub to facilitate accurate orientation.

One danger when working with either a motor with a bent housing, or on a bent sub, is that the bit will tend to dig into the wall when tripping in or out of the hole. This is due to the bend in the bottom hole assembly. To overcome this danger, a kick sub with a flexible joint has been developed. This tool allows the motor to be run in and out of the hole in the straight position. It also allows both straight and deviated drilling without removing the motor from the hole. The kick sub is made up with the motor below it. It is tripped into the bottom in the straight condition and oriented by standard techniques. It can then be activated from the surface to any deflection angle from $1/2^{o}$ to 2^{o} by dropping a locking probe down the drill string. With the locking probe in position in the tool, circulation is started. A portion of the circulation pressure causes four internal pistons to move downward. The pistons activate a cam-like control lever which forces the pivot shown in Figure 9 to move in one direction and the bottom of the sub to move in the opposite direction. The size of the locking probe determines the deflection angle. The probe can be retrieved at any time with a wireline overshot and a probe of a different size run in its place.

Presently available kick sub devices are not suitable for application to horizontal drilling. However, with suitable modification or redesign a kick sub could be made which would be applicable to horizontal drilling. Used in conjunction with the down-hole motor, a kick sub would provide a remotely steerable horizontal drilling system. The economics of such a system are evaluated in Chapter 7. This approach could prove to be a cost and time effective technique for drilling non-cored horizontal holes.

4.5 Task C Guidance Developments

4.5.1 Improved Survey Capability

4.5.1.1 Wireless Telemetry Systems

The next significant development in hole survey devices will be survey instrumentation employing a wireless telemetry system to communicate data to the surface. A typical system would utilize sensing packages which stay down-hole with the drilling

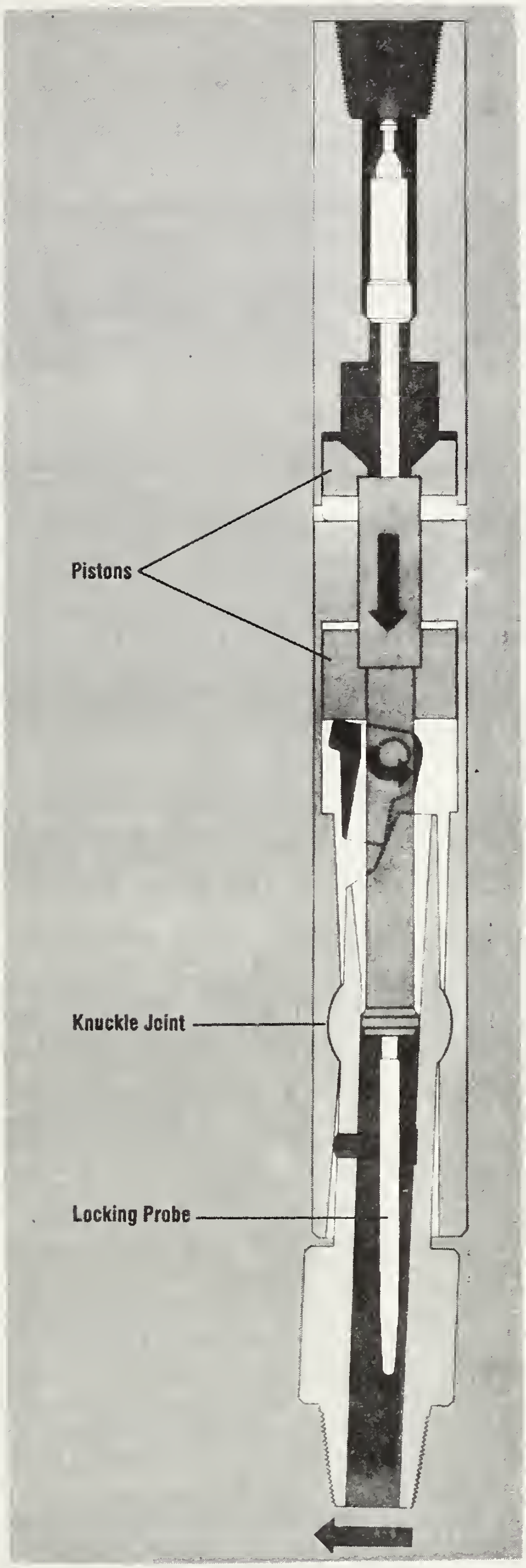


Figure 9 - The DYNA-FLEX[R] Hydraulically Actuated Bent Sub
(Courtesy, Dyna Drill Co.)

assembly and provide continuous real time data on a variety of parameters.

Three methods of telemetry which appear to be feasible are:

(a) Mud modulators
(b) Acoustic telemetry
(c) Electromagnetic telemetry

(a) <u>Mud Modulators</u>

Mud modulator systems use the drilling mud column as a signal carrier. The instrument package puts out pressure pulses by intermittently restricting the flow of drilling fluid. A sensor at the surface monitors these pulses so that they may be decoded and displayed. The only available mud modulator instrumentation systems are the BJT Teledrift (R) and BJ Teleorienter T.M. offered by Dyna-Drill Co. These are very simple systems which provide approximate data on hole drift and tool orientation respectively. The Teleorienter should be suitable for orienting down-hole motors in drilling hole deviations. However, the device has not been applied to horizontal drilling and field testing would be required to evaluate the suitability of the Teleorienter for horizontal drilling operations.

Both Raymond Precision Industries, Inc. and Gearhart-Owen Industries, Inc. are developing advanced mud modulator telemetry systems for petroleum drilling applications.

(b) <u>Acoustic Telemetry</u>

It is possible to introduce an acoustic signal into the drill string. The string itself then becomes the signal path. Although indications have been found of development effort in this area, there is no evidence of a system having been built and tested, nor any indication of the availability of such a system in the foreseeable future.

(c) Electromagnetic Telemetry

Figure 10 illustrates an in-hole survey and steering tool developed for the Bureau of Mines. The system is installed in a plenum chamber in the non-magnetic drill collars behind the bent sub. Data are telemetered to the surface using the drill string as the electrical circuit and the earth as the current return.

The tool worked well in horizontal holes in excess of 1,000 ft (305 m) deep. It provided both survey and steering information in real time. As is typical of first generation developmental tools, it was overly complex for an operational environment. However, as is also typical of this type of tool, it has the potential of major simplifications to provide the same capability at a degree of complexity equivalent to that of wire line steering tools. It has the same advantages as the Teleorienter, with the additional advantage of providing continuous real time survey data.

Because of the nature of electromagnetic propagation in the earth, this tool has little application to current slant drilling practice. However, it seems to be quite applicable to horizontal and hard rock drilling, where depths from the surface are relatively shallow and the electromagnetic losses in rock are modest.

4.5.2 Improved Steering Capability

Available steering tools have been discussed in detail in Volume I. There are several developments in this area which are of interest in terms of developing improved steering capability.

(a) Remote Steering Tool for Rotary Drilling

The down-hole motor does not by any means represent the ideal hole deviation tool. Although the down-hole motor/bent

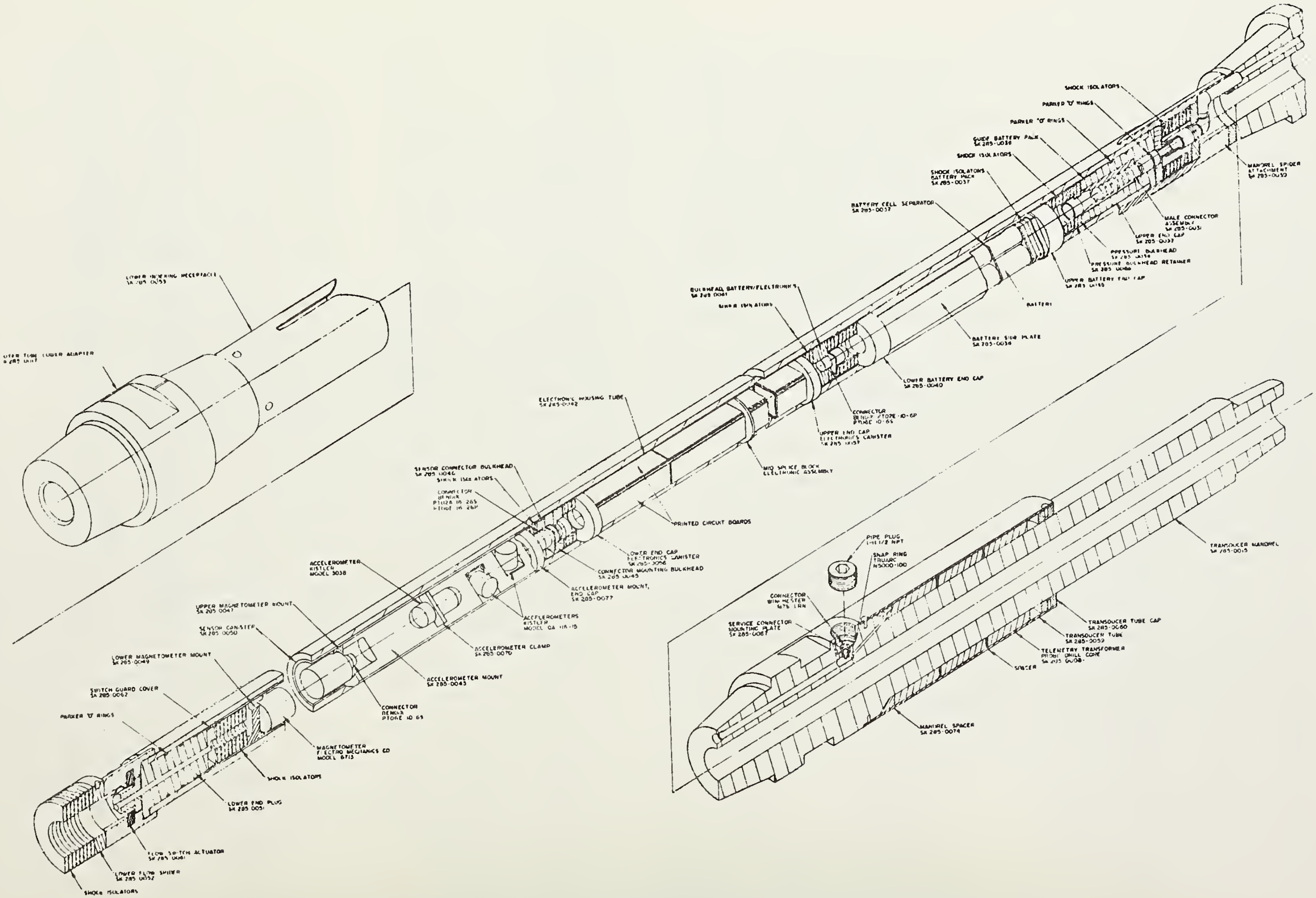


Figure 10 - Bureau of Mines Wireless Telemetry Survey Device

housing or bent sub technique does offer a substantial time savings over the older wedging and whip stocking techniques, it still requires two round trips of the drill string whenever a hole deviation is required. The development of a remotely actuated steering device to be employed with rotary drilling techniques would have several significant advantages over existing techniques for drilling hole deviations including:

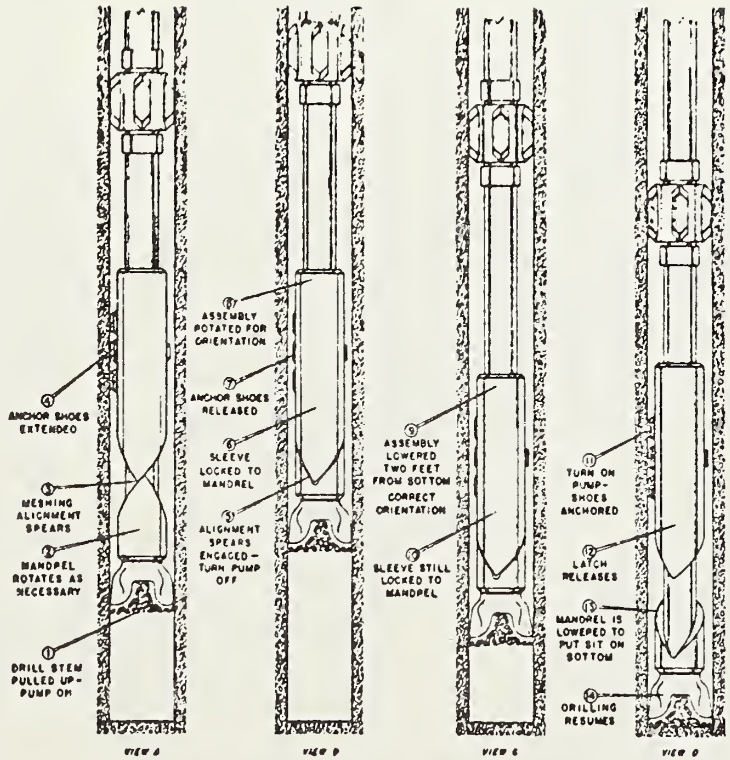
1. Elimination of drill string tripping when hole deviations are required.

2. "Steered" drilling capability out to the full penetration range of the drilling equipment.

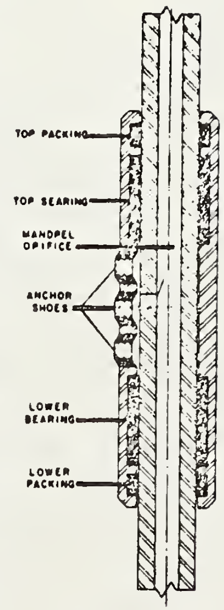
3. Elimination of standby charges for special steering equipment, such as down-hole motors.

In Figure 11 a remotely actuated steering tool called "Bit Boss" is illustrated.[6] The Bit Boss is a special down-hole tool which uses hydraulically activated shoes to push against the sides of the hole and thus provide control of hole angle. Drilling fluid pressure activates the hydraulic shoes to lock the anchor sleeve in the desired orientation. The mandrel and bit slide through the anchor sleeve to drill at a preset angle.

The Bit Boss cannot be left in the hole to serve as a remote steering tool because it can not be deactivated for straight ahead drilling. Therefore, the device offers no real advantage over a down-hole motor and is not typically employed as a steering tool. However, the Bit Boss concept, with appropriate modifications to allow the device to be deactivated for straight drilling, would meet the requirements for a remote steering tool for rotary drilling.



Operation of the tool (follow numbers in sequence)



Section of assembly showing means of expanding anchor shoes

Figure 11 - "Bit Boss" Hydraulic Directional Control Device[6]

One concept for a remotely operated steering tool is illustrated in Figure 12. This device is similar in principle to the Bit Boss, but the device is activated by pumping a survey tool to the steering tool. The survey tool opens a valve which allows the drilling fluid to be pumped to the anchor shoes. After the hole is deviated to the desired trajectory, the survey tool is withdrawn and the steering tool functions as a non-rotating stabilizer for straight drilling.

An important consideration in the development of a remotely actuated steering tool is that the device would be suitable for any guided drilling activity and not just horizontal drilling. This substantially increases the market for such a device with a corresponding increase in the incentive to undertake the development.

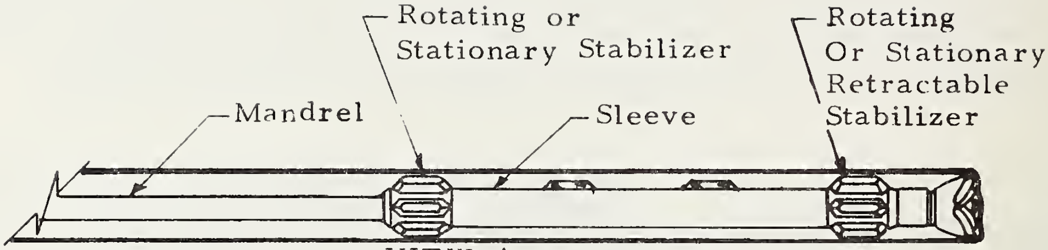
(b) <u>The Down-Hole Thruster with Steering Shoe</u>

The proprietary horizontal drilling program being pursued by Continental Oil Co. (CONOCO) shows promise of developing a horizontal drilling procedure with several unique advantages. The system employed by CONOCO uses a down-hole motor, a down-hole thruster, and a remotely actuated steering shoe. The experimental guided tunneler proposed in a recent Electrical Power Research Institute study also employs a down-hole thruster and steering shoe system.[7] In addition to the potential for improved penetration which this system affords (see Chapter 3) it also has several unique advantages with regard to its steering capability:

1. The drilling system can be steered remotely from the surface.

2. The thruster provides an anchored support close to the drill bit for drilling hole deviations.

This second feature can be critical in terms

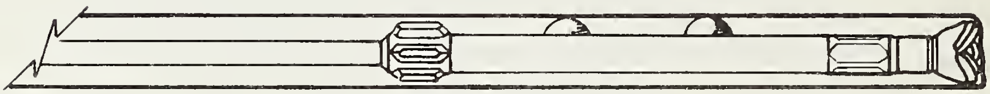


VIEW A

(1) Straight drilling, sleeve latched to mandrel.

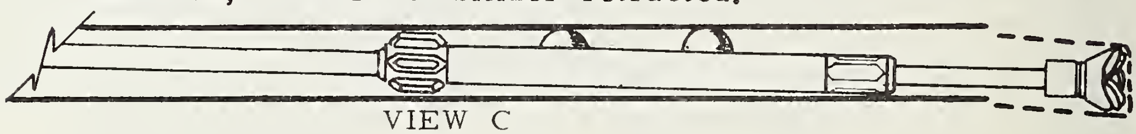
(2) Drilling stopped, survey tool pumped to steering tool.

(3) Pumped stopped, steering tool oriented to give desired deviation.



VIEW B

(4) Pump on, sleeve unlatched from mandrel, anchor shoes extended, forward stabilizer retracted.



VIEW C

(5) Drill hole deviation.

(6) Pull drill bit back (VIEW B)

(7) Pump stopped, sleeve latched, anchor shoes retracted, forward stabilizer extended, retrieve survey tool. (VIEW A)

(8) Resume drilling. (VIEW A)

Figure 12 - Remotely Activated Steering Tool For Rotary Drilling

of employing the down-hole motor as a steering tool for horizontal holes beyond a few thousand feet in length. Chapter 3 establishes the need for a down-hole thruster to transmit thrust to the down-hole motor. Another potential problem area, addressed in Appendix F, is torsional instability when attempting to deviate long horizontal holes. If field experience indicates that this problem does in fact exist, it could be prevented by employing a down-hole anchor, such as a thruster, to prevent torsional oscillations of the drill string.

4.6 Summary of Guidance Development

In general, guidance equipment which fits the Task B development category can be made available without significant development effort. Although the equipment is not available "off-the-shelf" (and thus does not fit the Task A state-of-the-art classification) it can be purchased on a custom order basis. This, quite naturally, will make the equipment much more expensive than similar standard equipment. If this equipment is to become part of a vendor's standard line, and thus cheaper, a market must exist for the equipment. To date, the market for horizontal drilling adaptations of standard equipment has not warrented making such equipment available. One technique to stimulate such a market is to sponser programs which will demonstrate the potential of horizontal drilling as a geological exploration technique. Programs which are not primarily demonstration programs are not appropriate for Task B equipment.

As in any aspect of horizontal drilling, Task C guidance development programs are most logical in cases where the potential equipment has application to all types of guided drilling.

5. Hole Stability

The FHWA Prospectus for this study states specifically that "metal casing is unacceptable" as a hole stabilization technique. Therefore, the study requirement for a hole life of up to one year must be met by other means.

Hole stabilization is discussed in detail in Section 6 of Volume I of this study. This discussion is reviewed briefly below. Hole stabilization involves (1) keeping the hole open during the drilling operation, and (2) maintaining hole integrity after the hole is completed.

Hole stability during the drilling operation will be provided by the drilling fluid. Among the drilling fluids, drilling mud is most effective in stabilizing the hole. If stability problems cannot be handled by drilling muds, grouting procedures will have to be employed. Casing of the hole in stages, with a corresponding decrease in size as the hole progresses, would normally be employed where stability problems cannot be overcome by either the drilling mud program or grouting procedures, or where a "permanent" hole is required after completion of the drilling operation. However, non-metallic casing for horizontal drilling is not an available procedure. Later in this section a procedure to install non-metallic casing is presented.

Long term stability is provided by either grouting or casing. Drilling fluids are effective in stabilizing the hole during the drilling operation only and do not contribute to long term hole stability.

5.1 Drilling Muds

Drilling mud technology is highly developed. Mud supplies and services are available from several companies to meet the needs of the drilling client or contractor. The state-of-the-art of drilling mud technology represents neither a current limitation to horizontal drilling capabilities nor does it appear to be a constraint where FHWA sponsored development would be effective. For readers desiring more information on drilling muds than was provided in Volume I of this study, a recent paper titled, "Drilling Fluids and Environments" by Jay Simpson of Baroid Division of N. L. Industries, Inc. is recommended.[8] This paper recommends two areas for future research in the area of drilling fluids. The first is the study of drilling fluid performance at very high temperature and pressure and the second is a comprehensive study of both initial and long-term effects of drilling fluids on the environment.

5.2 Grouting

Appendix C of Volume I is a discussion of grouting procedures and grouting economics which was prepared for this study by Jacobs Associates of San Francisco, California. Jacobs was assisted in this effort by Edward D. Graf, a noted grouting consultant from Daly City, California. This is perhaps the most informative and up to date survey of grouting available in the open literature. The economic analysis in the survey points up the importance of careful management of the grouting program and the conclusions of the survey are worth repeating.

The first conclusion is that hole stabilization can be the most important economic factor in drilling long horizontal holes. The cost of a grouted hole can be more than twice the total cost of a hole where no grouting is required. The second conclusion is that the cost of a hole can be nearly doubled if an incorrect assessment of conditions or a poor selection of grouting methods and materials is made.

As in the case of the drilling mud industry, the grouting industry is a highly developed industry with a substantial market. Materials and services are available from several companies, as indicated in Appendices I and II of Volume I. The prospective horizontal drilling customer would be well advised to avail himself of such services. With the information provided in Volume I it is possible to make an intelligent evaluation of grouting materials and services. The level of development in the field of grouting is not a significant limitation to horizontal drilling capability.

5.3 Casing

Standard metallic casing procedures are not acceptable for this study and efforts to develop non-metallic casing methods have not yet proved successful. However, the drain emplacement procedure developed by Soil Sampling Services of Puyallup, Washington, which is described in Section 6.3 of Volume I, forms the basis for a promising technique to install non-metallic casing.

To review, the Soil Sampling Services procedure is depicted in Figure 13. The steps employed are as follows:

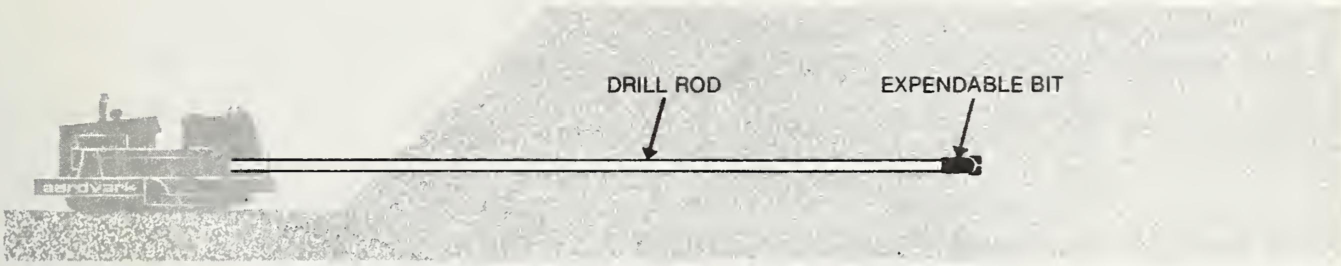
(1) A horizontal hole is drilled to the desired depth.

(2) The drill string remains in the hole as P.V.C. well screens are inserted inside the drill rods for the full length of the hole.

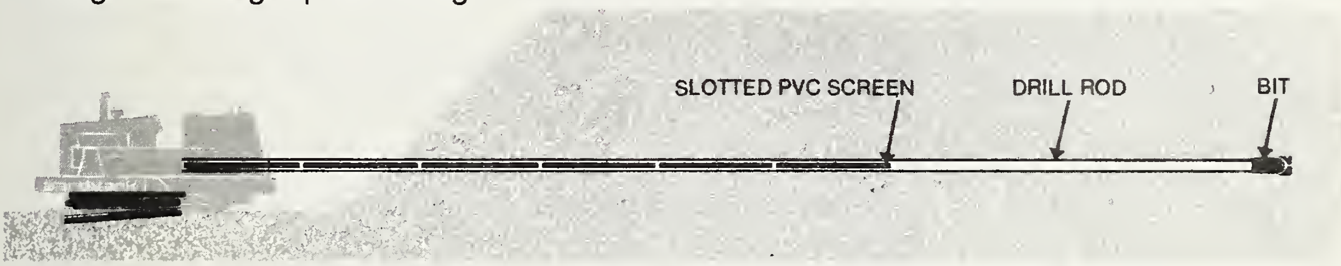
(3) A floating piston is inserted into the drill rod behind the well screen and is held against the well screens by hydraulic pressure. The drill rod is disengaged from the drill bit and withdrawn from the hole as the floating piston holds the P.V.C. well screens in place.

(4) After the drill is completely withdrawn, with the floating piston, the drain installation is complete.

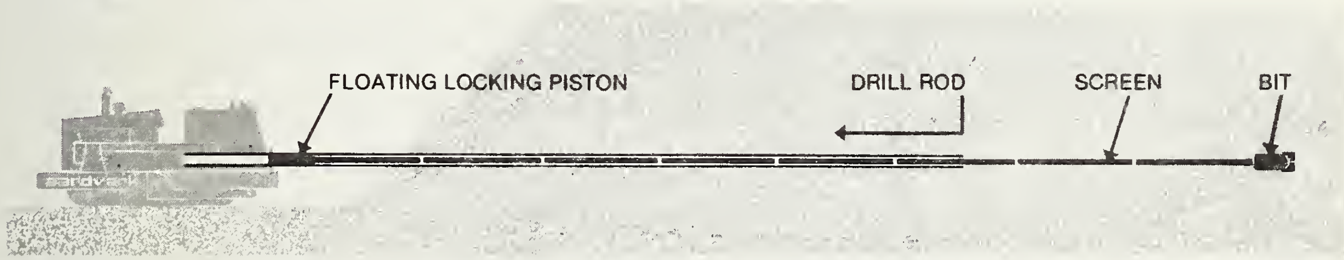
This general technique is clearly adaptable to the installation



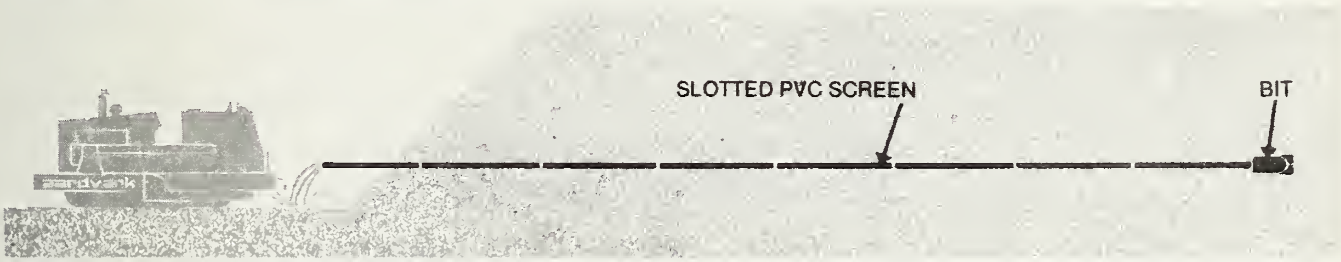
Horizontal hole is drilled by conventional rotary method. The Aardvark offers a wide range of height and angle positioning.



Upon completion of the boring, P.V.C. well screens are inserted inside the drill rod to the full length of the hole.



Floating locking piston is inserted, holding the screens in place by hydraulic pressure while the drill rod is withdrawn.



Completed drain installation. Screens of fine slot size prevent clogging and formational mining. Collector lines or ditches can be installed.

Figure 13 - Installation Procedure for Horizontal Drainage Screens
(Courtesy, Tigre Tierra, Inc.)

of non-metallic casing materials such as plastic, fiberglass, treated paper, etc. Loss of hole gauge need not be excessive. An N size diamond core drilled hole of 2.98 inches (76 mm) in diameter could be cased with a 2.313 inch (59 mm) O.D. casing, which would allow 1/16 inch (1.6 mm) of clearance to install the casing within the drill rod.

For larger holes, where minimum loss of hole diameter is desired, the procedure depicted in Figure 14 could be employed. The steps to be followed in this procedure are as follows:

(1) A horizontal hole is completed to the required length and the drill string is withdrawn.

(2) Conventional casing or full hole gauge flush joint drill rod is installed in the hole to full depth.

(3) The desired non-metallic casing material is installed inside the pipe to full hole length.

(4) A floating piston is inserted in the pipe and the pipe is withdrawn leaving the casing material intact.

This non-metallic casing technique should require very little development effort beyond that already done by Soil Sampling Services. In all probability some form of licensing agreement would have to be arranged with Soil Sampling Services to apply this procedure commercially. The suitability of such a casing procedure will depend on the results of the sensing system study being performed for FHWA under Contract FH-11-8602. In particular, a determination would have to be made as to which, if any, casing materials would be compatible with the sensing systems developed under Contract FH-11-8602.[1]

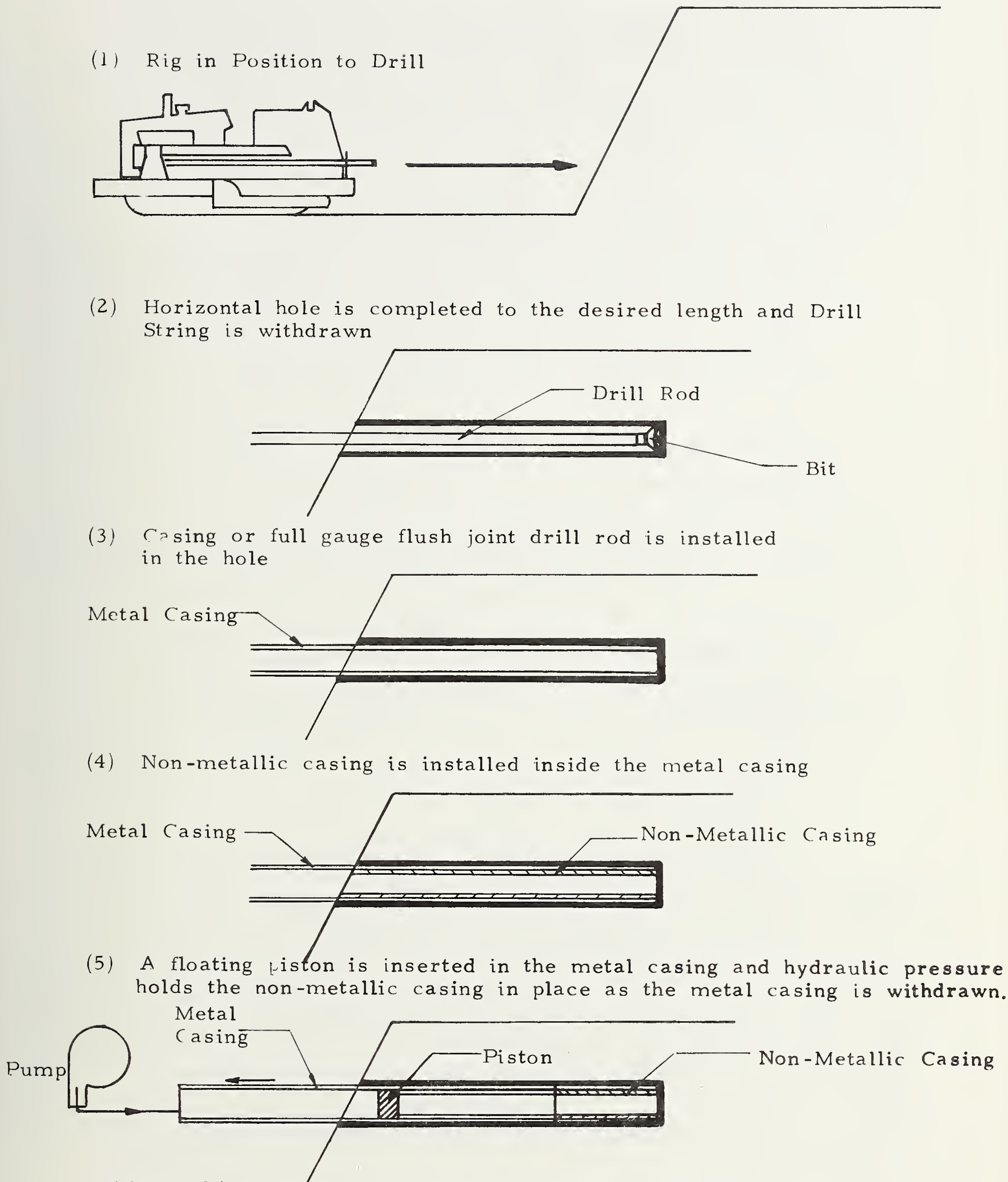


Figure 14 - Installation Procedure For Non-Metallic Casing

6. Information Gathering Techniques

Extensive geophysical investigation from boreholes is beyond the scope of this study. However, there are several specific information gathering procedures which are best performed during or immediately after the drilling operation and these procedures are considered in this study. In particular, Volume I of the study evaluated the state-of-the-art of the following information gathering techniques:

- Core drilling and retrieval, including procedures for drilling and retrieving oriented core samples.

- Undisturbed sampling and retraction from gouge.

- In situ measurement of water permeability and pressure.

In this volume possible further development of these techniques is considered as well as an evaluation of:

- Photographic and other optical techniques for examining exposed rock walls to identify materials and geological structure.

6.1 Core Sampling Development

One of the more promising developments in core drilling has been the application of a tungsten carbide insert roller coring bit to core drilling in the Deep Sea Drilling Project.[2,3] Rolling cutter core bits developed during this program have reached a level of performance superior to all other core bits and are now used exclusively.[3] The "standard" bit size for this work is a 10.125 inch (257 mm) bit which cuts a 2.5 inch (64 mm) core.

Development of rolling cutter coring bits for horizontal drilling would provide an ideal system to meet the objectives of this study. A horizontal drilling system using rolling cutter coring bits would provide a continuously cored hole with a diameter appropriate for proposed geophysical sensing systems. It would also provide the horizontal driller with the most cost effective state-of-the-art drilling technology.

A recent paper on Vertical and Horizontal Coring and Sampling, addressed research needs and development opportunities in the field.[9] Among the developments recommended in this paper is a "Wireline Retrievable Combination Core Bit and Barrel." This development is seen as "making coring more cost effective."[9]

6.2 Undisturbed Gouge Sampling

The material presented in Volume I essentially satisfies the study requirements for undisturbed gouge sampling. Further development in this area is not recommended as an FHWA goal.

6.3 In Situ Water Permeability and Pressure Measurement

Possible development in this area is discussed in Volume I. One supplier, not referenced in Volume I, who provides equipment related to this function is Terrametric, Inc. of Golden, Colorado.

6.4 Optical Techniques to Examine Exposed Hole Surfaces

Tasks B and C of the study contract call for an evaluation of (1) "costs of camera pictures of exposed rock walls" (Task B) and (2) an evaluation of the "potential of applying optical techniques inside the bore hole for identifying materials and geological structure" (Task C). State-of-the-art photographic and video equipment is available to investigate features of horizontal bore holes. Optical equipment could also prove to be useful as a trouble shooting tool in horizontal drilling projects.

Information provided by optical investigation of lost circulation zones or unstable hole walls could mean the difference between continuing or abandoning a multi-million dollar drilling project.

Two types of cameras have proved useful in optical evaluation of boreholes; (1) film and (2) television. Television systems have the advantage of providing "real time" continuous pictures which can be viewed at a surface monitor. Film cameras have the advantages of superior resolution, color reproduction, and lower costs.

An operational advantage of television systems is that they allow the operator to see hole conditions at the camera location and thus avoid conditions which might cause the camera to be lost. (Collapsed holes, internal cavernous zones, fallen rock, etc.)

The German made IBAK television system has provided very satisfactory results in work performed by the Norfolk District of the Army Corps of Engineers.[10] A new 62 mm borehole TV inspection system available from Sperry Support Services, Huntsville, Alabama, appears to be at least equivalent to the IBAK system.

A state-of-the-art survey of borehole cameras is provided in "Borehole Cameras" by Raymond Lundgren, F.C. Sturges, and L.S. Cluff.[11]

As a general rule, borehole inspection becomes easier as hole size increases. The likelihood of losing the camera in the borehole also decreases as hole size increases. The hole walls must be relatively clean and the hole must be free of muddy water to get pictures which would be useful to a geologist. Drilling mud must be removed from the hole walls if satisfactory pictures are to be obtained.

Generally, optical systems are designed for vertical holes or horizontal holes which are accessible from both ends. Therefore, the camera will have to be mounted on the end of the drill string for exploring blind horizontal holes. The drill string provides a reference for axial location of the camera and can also serve as a radial reference for side viewing of the hole. (Viewing perpendicular to the axis of the hole).

In the next two sections listings of film and television borehole inspection systems are provided. Special thanks are due to John Bowman of the Norfolk District of the Corps. of Engineers for help in compiling this information.

6.4.1 Film Type Borehole Cameras

A listing of various film cameras for borehole inspection is provided below. Economic data is provided where available. The Republic "NX" camera has been used successfully by the Army Corps. of Engineers.[10]

(a) Birdwell Down-Hole Camera

Manufacturer:	Seiscor, Tulsa, Oklahoma
Diameter (o.d.):	4.5 inches (114 mm)
Minimum Size Hole:	6 inches (152 mm)
Length of Probe:	48 inches (1,219 mm)
Weight of Probe:	50 pounds (222 N)
Power Supply:	115 volts, 60 cycle
Depth Limit:	8,000 ft (914 m)
Light Source:	Strobe Light
Film Type:	16-mm color or black and white
Interpretation of Geologic features:	Limited, as this unit was primarily designed for axial view photography for non-geologic uses.
Requires dry hole	

(b) Laval Down-Hole Camera

Manufacturer:	Lavel Corp., Fresno, California
Available:	Underground Surveys Corp. 1899 N. Helm, P.O. Box 6119 Fresno, California 93727 Phone: 209-255-1608

Diameter (o. d.):	4.75 inches (121 mm)
Minimum Size Hole:	6 inches (152 mm)
Length of Probe:	50 inches (1,270 mm)
Weight of Probe:	35 pounds (156 N)
Power Supply:	110 volts a.c., 60 cycle
Depth Limit:	10,000 ft (3,048 m)
Light Source:	Strobe cell.
Film Type:	35-mm color or black and white
Interpretation of geologic features:	Excellent, as this unit takes stereo pairs
Comments:	The main disadvantage of this unit is that it is limited to 6 inch (152 mm) or larger diameter holes. A model for 3 inch (76 mm) holes is under development.

(c) <u>Republic 'NX' Borehole Camera</u>

Manufacturer:	Republic Research, St. Paul, Minnesota
Diameter (o. d.):	2.75 inches (70 mm)
Minimum Size Hole:	NX 3 inches (76 mm)
Length of Probe:	30 inches (762 mm)
Weight of Probe:	30 pounds (133 N)
Power Supply:	110 volts, a.c., 60 cycle
Depth Limit:	7,000 ft (2,134 m)
Light Source:	Strobe cell.
Film Type:	16-mm color or black and white
Interpretation of geologic features:	Excellent
Cost:	$500/week - $225/week/month.

6.4.2 Television Borehole Inspection Systems

(a) Eastman TV Camera F. B. 400

Manufacturer:	Eastman International Company, G. M. B. H., Hanover, Germany
Diameter (o. d.):	2. 5 inches (64 mm)
Minimum Size Hole:	NX 3 inches (76 mm)
Length of Probe:	54 inches (1,372 mm)
Weight of Probe:	60 pounds (267 N)
Power Supply:	220 volts a. c., 60 cycle
Depth Limit:	1,500 ft (457 m)
Light Source:	Incandescent lamps
Film Type:	Monitoring television screen - no film except video.
Interpretation of geologic features:	Good
Comments:	If something goes wrong must send camera to Germany or have technician come. Very sensitive to damage. No color.

(b) Model 70 & 80 TV Cameras

Built by Halliburton, a television camera with an axial viewing lens. Designed for sewer inspection. It is mounted in a three inch case which can withstand a 100 psi pressure. Ability to distinguish geologic features unknown.

Contact: Halliburton Services
Duncan, Oklahoma 73533

(c) IBAK

Manufacturer: IBAK of Germany
23 Kiel 14
Wehdenweg, 122
Germany
Cable: "IBAK KIEL"
Telex: 292824

A television camera with an axial view or a true side view. The unit has a remote focus. The image is displayed on a television screen of the European standard which has a higher density scanner than used in American televisions, allowing greater resolution. A video tape can record all pictures or a film camera attached to the screen can record the desired pictures.

The camera fits in a 4 inch (102 mm) diameter hole. The U. S. Army Corps of Engineers reports excellent reproduction of the geologic features. The Corps of Engineers owns one unit which is located at the Waterway Experimental Station Geology Department at Vicksburg, Miss.[10] IBAK claims to have the technology to build a 3 inch (76 mm) color camera.

Cost: $800 mobilization
$450/day operating
$250/day standby

(d) TV Camera

Manufacturer: Laval Corp., Fresno, California
Diameter (o. d.): 4.75 inches (121 mm)
Minimum Size Hole: 6 inches (152 mm), 3 inch (76 mm) model under development

Length of Probe:	50 inches (1,270 mm)
Weight of Probe:	40 pounds (178 N)
Power Supply:	110 volts a. c., 60 cycle
Depth Limit:	300 ft (91 m)
Film Type:	Monitoring television screen - no film
Interpretation of geologic features:	Poor

(e) TV Down-Hole Camera

Manufacturer:	Oceanographic Eng., San Diego, California
Diameter (o. d.):	3 inches (76 mm)
Minimum Size Hole:	4 inches (102 mm)
Length of Probe:	20 inches (508 mm)
Weight of probe:	20 pounds (89 N)
Power Supply:	110 volts d. c., or a. c.
Depth Limit:	4,000 ft (1,219 m)
Light Source:	Neon cell
Film Type:	Monitoring television screen.
Interpretation of geologic features:	Good

(f) Borehole Television Inspection System

Manufacturer:	Sperry Support Services 716 Arcadia Circle Huntsville, Alabama 35801 Phone: 205-533-3700 Ext. 360, Mr. R. H. Oberlies
Diameter (o. d.):	2.44 inches (62 mm)
Length of Probe:	45 inches (1,143 mm)
Weight of Probe:	30 pounds (133 N)
Power Supply:	115 $\pm$ VAC, 60 Hz at 1.5 amps
Depth Limit:	1,600 ft (488 m)

Light Source:	Miniature high intensity quartz halogen lamps
Comments:	Claimed resolution to .002 inch (.05 mm). Remote focusing. Axial and radial viewing. Can be used underwater.
Economics:	$19,140 for system.

One other potential source of equipment is:

Inspectronic Corp.
33-25 127th Street
Flushing, New York 11368.

7. Economic Considerations

Chapters 3 through 6 have identified various techniques to improve horizontal drilling capability. In this chapter, the potential for improving the economics of horizontal drilling is evaluated. Then, the economic impact of improvements in equipment and procedures are evaluated. Where a horizontal drilling costing methodology is required, the model developed in Volume II of this study is employed.

7.1 Evaluation of State-of-the-Art Economics

Before potential time and cost savings may be identified, it is necessary to obtain some idea of the division of the total drilling time among the various operations.

Tables 7, 8, and 9 present time estimates broken down by drilling operation for each of the three drilling techniques. These times were obtained using the procedures set forth in Volume II and are based on a 5,000 ft. (1,524 m) hole from Appendix A of that document.

Tables 7, 8 and 9 present time estimates for three different rock mixes:

1. The "average" rock mix assumed in the standard hole,
2. 100% soft rock, and,
3. 100% hard rock.

In addition to the time estimate breakdowns by drilling operation, i.e. full hole drilling, hole survey, etc., it is possible to break down these time estimates by component operations. These component operations are such things as wirelining, rod handling, grout setting, etc. Tables 10, 11 and 12 present these estimates also for the standard 5,000 ft. (1,524 m) hole of Appendix A, Volume II, and three different rock mixes.

TABLE 7

TIME ESTIMATES FOR DIAMOND WIRELINE CORE DRILLING

	ROCK MIX					
	100% Soft		"Average"		100% Hard	
Drilling Operation	Hours	Percentage	Hours	Percentage	Hours	Percentage
Wireline Core Drilling	645.2	19.94	1,088.3	33.14	1,521.1	44.67
Hole Survey 1 every 30'	97.3	3.01	97.3	2.96	97.3	2.86
3 every 90'	97.5	3.01	97.5	2.97	97.5	2.86
Direction Changes*	979.1	30.27	979.1	29.82	979.1	28.76
Fishing	227.2	7.02	148.4	4.51	60.8	1.78
Hole Stabilization	649.8	20.08	326.4	9.94	81.8	2.41
Subtotal:	2,696.1		2,737.0		2,837.6	
Job Efficiency	539.2	16.67	547.4	16.67	567.5	16.67
Total Time:	3,235.3	100.00	3,284.4	100.01	3,405.1	100.01

*using Wedges.

TABLE 8

TIME ESTIMATES FOR ROTARY DRILLING

	R O C K M I X					
	100% Soft		"Average"		100% Hard	
Drilling Operation	Hours	Percentage	Hours	Percentage	Hours	Percentage
Full Hole Drilling	115.1	4.04	180.7	7.39	238.5	11.30
Hole Survey						
1 every 30'	97.3	3.41	97.3	3.98	97.3	4.61
3 every 60'	146.5	5.15	146.5	5.99	146.5	6.94
Direction Change*	1,134.7	39.81	1,134.7	46.43	1,134.7	53.72
Fishing	227.2	7.97	148.4	6.07	60.8	2.88
Hole Stabilization	654.2	22.06	329.0	13.46	82.5	3.90
Subtotal:	2,375.0		2,036.6		1,760.3	
Job Efficiency	475.0	16.67	407.3	16.67	352.1	16.67
Total Time:	2,850.0	100.01	2,443.9	99.99	2,112.4	100.02

* using Dyna-Drill. Also includes time to drill core sample.

TABLE 9

TIME ESTIMATES FOR DOWN-HOLE MOTOR DRILLING

	ROCK MIX					
	100% Soft		"Average"		100% Hard	
Drilling Operation	Hours	Percentage	Hours	Percentage	Hours	Percentage
Full Hole Drilling	178.4	6.10	283.8	11.05	371.8	16.36
Hole Survey						
1 every 30'	97.3	3.33	97.3	3.79	97.3	4.28
3 every 60'	146.5	5.00	146.5	5.71	146.5	6.45
Direction Change*	1,134.7	38.78	1,134.7	44.19	1,134.7	49.94
Fishing	227.1	7.76	148.4	5.78	60.8	2.68
Hole Stabilization	654.2	22.36	329.0	12.81	378.7	3.63
Subtotal:	2,438.2		2,139.7		1,893.6	
Job Efficiency	487.6		427.9	16.67	378.7	16.67
Total Time:	2,925.8	100.00	2,567.6	100.00	2,272.3	100.01

* using Dyna-Drill. Also includes time to drill core sample.

TABLE 10

TIME ESTIMATES FOR DIAMOND WIRELINE CORE DRILLING

	ROCK MIX					
	100% Soft		"Average"		100% Hard	
Component Operation	Hours	Percentage	Hours	Percentage	Hours	Percentage
Drilling	116.3	3.59	473.5	14.42	833.3	24.47
Bit Changing	36.9	1.14	37.1	1.13	36.8	1.08
Rod Handling	1,470.8	45.47	1,375.0	41.87	1,283.3	37.69
Survey Taking						
1 every 30'	27.7	0.86	27.7	0.84	27.7	0.81
3 every 90'	27.5	0.85	27.5	0.84	27.5	0.81
Survey Handling						
1 every 30'	69.6	2.15	69.6	2.12	69.6	2.04
3 every 90'	70.0	2.16	70.0	2.13	70.0	2.06
Fishing	4.2	0.13	2.7	0.08	1.0	0.03
Wirelining	417.5	12.90	417.5	12.71	417.5	12.26
Drilling Direction Changes	18.3	0.57	18.3	0.56	18.3	0.54
Front Setting	400.0	12.36	200.0	6.09	48.0	1.41
Drilling Grout	20.0	0.62	8.7	0.26	2.0	0.06
Pumping Grout	17.3	0.53	9.4	0.29	2.6	0.08
Subtotal:	2,696.1		2,737.0		2,837.6	
Job Efficiency	539.2	16.67	547.4	16.67	567.5	16.67
Total Time:	3,235.3	100.00	3,284.4	100.01	3,405.1	100.01

TABLE 11

TIME ESTIMATES FOR ROTARY DRILLING

	ROCK MIX					
	100% Soft		"Average"		100% Hard	
Component Operation	Hours	Percentage	Hours	Percentage	Hours	Percentage
Drilling	98.0	3.44	155.1	6.35	200.0	9.47
Bit Changes	37.8	1.32	35.7	1.46	33.6	1.59
Rod Handling	1,459.9	52.49	1,325.0	54.22	1,175.0	55.63
Survey Taking						
1 every 30'	27.7	0.97	27.7	1.13	27.7	1.31
3 every 60'	41.5	1.46	41.5	1.70	41.5	1.96
Survey Handling						
1 every 30'	69.6	2.44	69.6	2.85	69.6	3.29
3 every 60'	105.0	3.68	105.0	4.30	105.0	4.97
Fishing	4.2	0.15	2.7	0.11	1.0	0.05
Drilling Cores	25.9	0.91	25.9	1.06	25.9	1.23
Drilling Direction Changes	27.7	0.97	27.7	1.13	27.7	1.31
Drilling Grout	20.0	0.70	8.7	0.36	2.0	0.09
Grout Setting	400.0	14.04	200.0	8.18	48.0	2.27
Pumping Grout	21.7	0.76	12.0	0.49	3.3	0.16
Subtotal:	2,735.0		2,036.6		1,760.3	
Job Efficiency	475.0	16.67	407.3	16.67	352.1	16.67
Total Time:	2,850.0	100.00	2,443.9	100.01	2,112.4	100.00

TABLE 12

TIME ESTIMATES FOR DOWN-HOLE MOTOR DRILLING

	ROCK MIX					
	100% Soft		"Average"		100% Hard	
Component Operation	Hours	Percentage	Hours	Percentage	Hours	Percentage
Drilling	161.3	5.51	258.2	10.06	333.3	14.67
Bit Changes	37.7	1.28	35.7	1.39	33.6	1.48
Rod Handling	1,459.9	51.13	1,325.0	51.60	1,175.0	51.71
Survey Taking						
1 every 30'	27.7	0.95	27.7	1.08	27.7	1.22
3 every 60'	41.5	1.42	41.5	1.62	41.5	1.83
Survey Handling						
1 every 30'	69.6	2.38	69.6	2.71	69.6	3.06
3 every 60'	105.0	3.59	105.0	4.09	105.0	4.62
Fishing	4.2	0.14	2.7	0.11	1.0	0.04
Drilling Cores	25.9	0.89	25.9	1.01	25.9	1.14
Drilling Direction Changes	27.7	0.95	27.7	1.08	27.7	1.22
Drilling Grout	20.0	0.68	8.7	0.34	2.0	0.09
Grout Setting	400.0	13.67	200.0	7.79	48.0	2.11
Pumping Grout	21.7	0.74	12.0	0.47	3.3	0.15
Subtotal:	2,438.2		2,139.7		1,893.6	
Job Efficiency	487.6	16.67	427.9	16.67	378.7	16.67
Total Time:	2,925.8	100.00	2,567.6	100.02	2,272.3	100.01

Study of these tables promptly identifies the following areas for potential time and cost savings. These areas of potential savings are divided into two general categories. The first is the time and cost reductions which could result from the use of alternate drilling strategies. These savings relate primarily to the drilling operations. The second category is the time and cost reductions which would result from the use of new or improved equipment. These savings relate to the component operations.

Under the first category, the prime candidate for potentially large savings is the use of the Dyna-Drill to make direction changes for diamond wireline core drilling. Section 7.2 discusses the potential of this alternate drilling strategy.

Under the second category, the prime candidate for potentially large savings is rod handling. This operation impacts all drilling techniques regardless of the type of rock encountered. Direction changes and combined coring and direction changes also offer potentially large savings for all techniques, again independent of the rock mix encountered. These areas are discussed in Section 7.3.

As a base line for the discussions in the following sections, Table 13 presents the estimated costs for drilling the standard hole of Appendix A of Volume II for each of three drilling techniques.

7.2 Cost Reductions from Alternate Drilling Strategies

A prime candidate for potentially large time and cost savings is the use, in diamond wireline core drilling, of the Dyna-Drill for drilling direction changes.

The state-of-the-art steering procedure for diamond core drilling is to use wedges. If a Dyna-Drill is employed instead, it will be posible to

TABLE 13

COST ESTIMATES FOR HORIZONTAL DRILLING

Cost Element	Diamond Wireline		Rotary		Down-Hole Motor	
	Unit Cost	Total	Unit Cost	Total	Unit Cost	Total
Total Time	-------	3,284.4	-------	2,443.9	-------	2,567.6
Labor	$36.00/hr.	118,238.	$36.00/hr.	87,980.	$36.00/hr.	92,434.
Equipment	14.87/hr.	48,839.	42.96/hr.	104,990.	34.89/hr.	89,584.
Materials	16.87/hr.	55,408.	18.20/hr.	44,479.	18.20/hr.	46,730.
	2.69/ft.	13,450.	1.83/ft.	9,150.	1.83/ft.	9,150.
Mobilization and Set-Up	-------	4,400.	-------	4,400.	-------	4,400.
Subtotal:		240,335.		250,999.		242.298.
Overhead at 15 percent	-------	36,050.	-------	37,650.	-------	36,345.
Subtotal:		276,385.		288,649.		278,643.
Profit at 15 percent	-------	41,458.	-------	43,297.	-------	41,796.
Total Cost:	-------	$317,843.	-------	$331,946.	-------	$320.439.
Average Cost:	63.57/ft		66.39/ft		64.09/ft	

save two round trips of the drill string for each required direction change. The time savings would be somewhat offset by the increased hourly equipment cost. According to Table 14, a 1.75 in. (44.5mm) Dyna Drill can be leased for $1,800./month ($\approx$ $3.50/hr.). However, the net effect of this alternate strategy would be a savings in total cost of 16%. Tables 15 and 16 present these time and cost estimates.

Other alternate drilling strategies can be evaluated in a similar fashion.

7.3 Cost Reductions from New or Improved Equipment

Improved rod handling equipment is the prime candiate for time and cost savings in horizontal drilling due to improved equipment. Other new or improved equipment which has potential for time and cost savings are core barrel guidance equipment, real time survey tools, and down-hole steering tools with real time survey tools. The first of these developments applies only to continuous core drilling techniques and the last two apply to all three techniques. The cost savings of these items of equipment are relatively independent of the type of rock encountered.

7.3.1 Rod Handling

Improved rod handling equipment is characterized as resulting in an average velocity of rod injection and extraction which is higher than the currently available 20 ft./min. (.1 m/sec). For example, equipment capable of running rods into and out of the hole at an average rate of 60 ft./min (.3 m/sec) would represent improved equipment. Table 17 illustrates the time savings which could be expected from equipment of this sort.

The potential cost savings of this improved rod handling equipment cannot be evaluated without knowing the additional hourly equipment cost of the equipment. However, the potential maximum

TABLE 14

DYNA DRILL LEASE RATES

Size	Monthly Rental	Daily Rental
1 3/4" (44.5 mm)	$ 1,800	$ 225
2 3/8" (60.3 mm)	$ 2,400	$ 300
3 3/4" (95.3 mm)	$ 2,400	$ 300
3 3/4" TANDEM (95.3 mm)	$ 3,000	$ 450
5" (127.0 mm)	$ 3,600	$ 525
6 1/2" (165.1 mm)	$ 4,200	$ 600

TABLE 15

TIME ESTIMATE

DIAMOND WIRELINE CORE DRILLING USING A DYNA-DRILL FOR DIRECTION CHANGES

Drilling Operation	Time (hours)
Wireline Core Drilling	1.088.3
Hole Survey - 1 every 30 ft.	97.3
- 3 every 90 ft.	97.5
Direction Changes	498.8
Fishing	148.4
Hole Stabilization	326.4
Subtotal:	2,256.7
Job Efficiency	451.3
Total Time:	2,708.0
Percentage Reduction:	17.55%

TABLE 16

COST ESTIMATE

DIAMOND WIRELINE CORE DRILLING USING A DYNA-DRILL FOR DIRECTION CHANGES

Cost Element	Cost
Labor at \$36.00/hr.	\$ 97,488.
Equipment at \$18.37/hr.*	49,746.
Materials at \$16.87/hr.	45,684.
at \$2.69/ft.	13,450.
Mobilization and Set-Up	4,400.
Subtotal:	210,768.
Overhead at 15 Percent	31,615.
Subtotal:	242,383.
Profit at 15 Percent	36,357.
Total Cost:	\$278,740.
Average Cost:	55.75/ft.
Percentage Reduction	16.03%

* Includes an additional \$3.50/hr. for the Dyna Drill rental.

TABLE 17

TIME SAVINGS RESULTING FROM IMPROVING DRILL ROD HANDLING VELOCITY

from 20 ft. /min. (10 cm/sec.) to 60 ft. /min. (30 cm/sec.)

	Drilling Techniques		
	Diamond Wireline	Rotary	Down-Hole Motor
Original Rod Handling Time:	1,375.0	1,325.0	1,325.0
Improved Rod Handling Time:	458.3	441.7	441.7
Reduction in Rod Handling Time:	916.7	883.3	883.3
Reduction in Job Efficiency Time	183.3	176.7	176.7
Total Reduction in Time:	1,100.0	1,060.0	1,060.0
Original Total Time:	3,284.4	2,443.7	2,567.6
Total Reduction:	1,100.0	1,060.0	1,060.0
Improved Total Time:	2,184.4	1,383.7	1,507.6
Percent Reduction:	33.49%	43.38%	41.28%

cost saving ranges from 31% for diamond drilling to 41% for rotary drilling. The maximum additional rental costs range from \$74.43/hr. for rotary drilling to \$34.11/hr. for diamond drilling. Table 18 presents these figures.

Figure 15 presents the anticipated savings in total drilling time for all three drilling techniques for rod handling velocities ranging from the current 20 ft./min (.1 m/sec) to the expected maximum of 200 ft./min. (1 m/sec). As can be seen, for rotary drilling of a 5,000 ft. (1,524 m) horizontal hole, an average rod handling velocity of 200 ft./min. (1 m/sec) would result in almost a 60% reduction in total drilling time.

7.3.2 Core Barrel Guidance

Core barrel guidance utilized in conjunction with diamond wireline core drilling would eliminate the need for taking a separate survey every 30 ft. The time estimate for this situation is presented in Table 19 which indicates that a 4 percent reduction in total drilling time would result.

The potential cost savings cannot be estimated without knowing the additional hourly equipment cost necessary to obtain such a device. However, the potential cost savings would range from 3% if the core barrel guidance could be obtained without additional cost, to 0% if the hourly cost were \$2.50/hr. These cost estimates are presented in Table 20.

7.3.3 Real Time Survey Tool

A real time survey tool would eliminate the need for making the three additional surveys which are currently required for accurately drilling the direction changes. The time estimates for each of the three drilling techniques utilizing a real time survey tool are presented in Table 21. The time savings possible range from 7% for rotary and down hole motor drilling to 4% for diamond wireline core drilling.

TABLE 18

POTENTIAL SAVINGS AND HOURLY COSTS OF 60 ft/min (30 cm/sec) ROD HANDLING EQUIPMENT

	Maximum Savings (1)	Maximum Rental Cost (2)
Diamond Wireline Core Drilling	31.00%	$ 34.11/hour
Rotary Drilling	41.04%	$ 74.43/hour
Down Hole Motor Drilling	38.98%	$ 62.64/hour

(1) The maximum savings is the savings which would result if the device could be obtained with no increase on hourly equipment costs.

(2) The maximum rental cost is the hourly cost of the device which would result in no reduction in total cost.

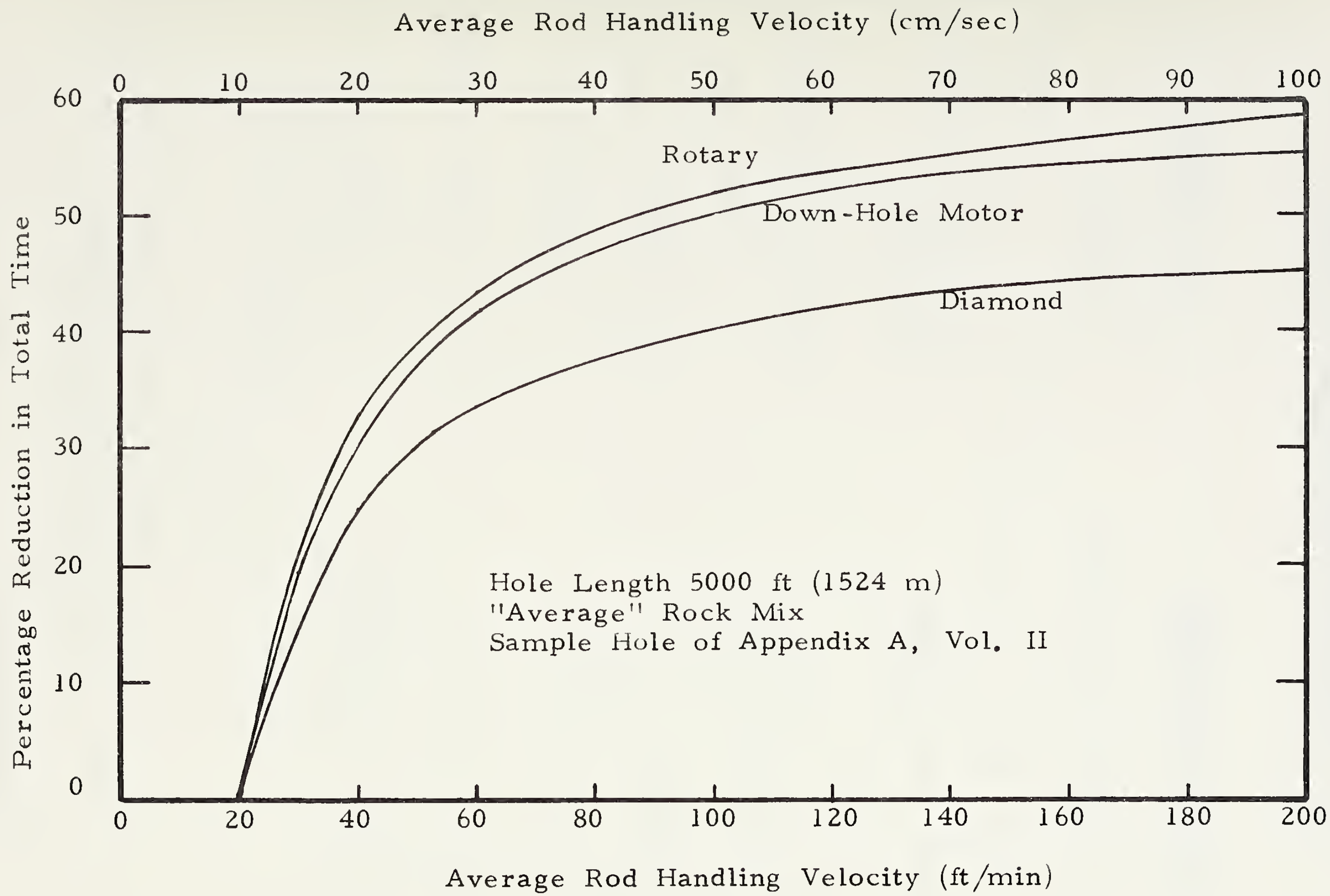


Figure 15 - Reduction in Total Drilling Time Resulting from Increased Rod Handling Velocity

TABLE 19

TIME ESTIMATES FOR DIAMOND WIRELINE CORE DRILLING WITH CORE BARREL GUIDANCE

Drilling Operation	Time (hours)
Wireline Core Drilling	1,088.3
Hole Survey - 3 every 90 ft.	97.5
Direction Changer*	979.1
Fishing	148.4
Hole Stabilization	326.4
Subtotal	2,639.6
Job Efficiency	527.9
Total Time	3,167.5
Percentage Reduction	3.56%

*using wedges

TABLE 20

COST ESTIMATES FOR DIAMOND WIRELINE CORE DRILLING WITH CORE BARREL GUIDANCE

Cost Element	Core "A"	Core "B"
Labor at $36.00/hour	$ 114,030	$ 114,030
Equipment	47,101	55,019
Material at $16.87/hour	53,436	53,436
$ 2.69/foot	13,450	13,340
Mobilization and Set-Up	4,400	4,400
Subtotal	$ 232,417	$ 240,335
Overhead at 15%	34,863	36,050
Subtotal	$ 267,280	$ 276,385
Profit at 15%	40,092	41,458
Total Cost	$ 307,372	$ 317,843
Average Cost	$ 61.47/ft.	$ 63.57/ft.
Percentage Reduction	3.30%	0%

Case "A": Equipment at $14.87/hr.

Case "B": Equipment at $17.37/hr. which includes $2.50/hr. for the core barrel guidance.

TABLE 21

TIME ESTIMATES FOR HORIZONTAL DRILLING WITH A REAL TIME SURVEY TOOL

Drilling Operation	Diamond Wireline Core Drilling	Rotary Drilling	Down-Hole Motor Drilling
	Time (hours)	Time (hours)	Time (hours)
Drilling	1,088.3	180.7	283.8
Hole Survey - 1 every 30 ft.	97.3	97.3	97.3
Direction Changes	979.1*	1,134.7**	1,134.7**
Fishing	148.4	148.4	148.4
Hole Stabilization	326.4	329.0	329.0
Subtotal:	2,639.5	1,890.1	1,993.2
Job Efficiency	527.9	378.0	398.6
Total Time:	3,167.4	2,268.1	2,391.8
Percentage Reduction:	3.56%	7.19%	6.85%

*using wedges
**and coring using a Dyna Drill

The potential cost savings of a real time survey tool cannot be evaluated without knowing the additional hourly equipment cost of such a device. However, the potential maximum cost saving ranges from 7% for rotary drilling to 3% for diamond wireline core drilling. The maximum additional rental costs range from $7.53/hr. for rotary drilling to $2.50/hr. for diamond wireline core drilling. Table 22 presents these figures.

7.3.4 Down-Hole Steering Tool and Real Time Survey Tool

Greater time and cost savings could be realized by the use of a down-hole steering tool in conjunction with a real time survey tool. The use of these two pieces of equipment would have the following effects on the time estimates: (1) eliminates the need for the three additional surveys required for accurate drilling of the direction changes, (2) eliminates the need for direction changes as a separate task, and (3) for rotary and down-hole motor drilling, requires that coring be considered as a separate task. The time estimates for each of the three drilling techniques utilizing a down-hole steering tool and real time survey tool are presented in Table 23. The time savings possible range from 39.34% diamond wireline core drilling to 24.98% for down-hole motor drilling.

The potential cost savings cannot be estimated without knowing the additional hourly equipment cost necessary to obtain these devices. However, the potential maximum cost savings ranges from 36% for diamond wireline core drilling to 24% for down-hole motor drilling. The maximum additional rental costs range from $43.92/hr. for diamond wireline core drilling to $29.67/hr. for down-hole motor drilling. Table 24 presents these figures.

TABLE 22

POTENTIAL SAVINGS AND HOURLY COSTS OF A REAL TIME SURVEY TOOL

	Maximum Savings (1)	Maximum Rental Cost (2)
Diamond Wireline Core Drilling	3.30%	$ 2.50/hr.
Rotary Drilling	6.80%	$ 7.53/hr.
Down Hole Motor Drilling	6.46%	$ 6.55/hr.

(1) The maximum savings is the savings which would result if the device could be obtained with no increase in hourly equipment costs.

(2) The maximum rental cost is the hourly cost of the device which would result in no reduction of total cost.

TABLE 23

TIME ESTIMATES FOR HORIZONTAL DRILLING UTILIZING A DOWN-HOLE STEERING TOOL AND A REAL TIME SURVEY TOOL

Drilling Operation	Diamond Wireline Core Drilling	Rotary Drilling	Down-Hole Motor Drilling
	Time (hours)	Time (hours)	Time (hours)
Drilling	1,088.3	180.7	283.8
Hole Survey - 1 every 30 ft.	97.3	97.3	97.3
Coring	*	746.7	746.7
Fishing	148.4	148.4	148.4
Hole Stabilization	326.4	329.0	329.0
Subtotal	1,660.4	1,502.1	1,605.2
Job Efficiency	332.1	300.4	321.0
Total Time	1,992.5	1,802.5	1,926.2
Percentage Reduction	39.34%	26.24%	24.98%

*included in drilling time.

TABLE 24

POTENTIAL SAVINGS AND HOURLY COSTS OF A DOWN HOLE STEERING TOOL AND A REAL TIME SURVEY TOOL

	Maximum Savings (1)	Maximum Rental Cost (2)
Diamond Wireline Core Drilling	36.41%	$ 43.92/hr.
Rotary Drilling	24.83%	$ 34.57/hr.
Down Hole Motor Drilling	23.58%	$ 29.67/hr.

(1) The maximum savings is the savings which would result if the device could be obtained with no increase in hourly equipment costs.

(2) The maximum rental cost is the hourly cost of the device which would result in no reduction of total cost.

7.4 Cost of Custom Surface Drilling Rigs

Torque and thrust requirements for surface drilling rigs are presented in Chapter 3. In this section, drill rig cost estimates are presented as a function of hole size and horizontal penetration distance.

7.4.1 Diamond Drilling Rigs

As indicated in Volume I, available off-the-shelf diamond drilling rigs should be capable of drilling B size horizontal holes to 5,000 ft (1,524 m). These rigs are catalogue items. The projected rig costs in Figure 16 have been estimated by extrapolating from available equipment costs.

7.4.2 Rotary Drilling Rigs

Drilling rigs for horizontal rotary drilling will have to be custom built. The major horizontal drilling programs conducted to date (Bureau of Mines, Seikan Tunnel, Kerr-McGee) have all employed custom built drilling rigs. Estimated rig costs have been established through consultation with blast hole drilling rig manufacturers (Gardner-Denver, Reed Tool Company, Schramm, Inc., Winter-Weiss Division of Smith Internation) and raise borer manufacturers, (Dresser, Robbins) and comparison with diamond rig costs. Repackaging of blast hole rig components to create a horizontally rotary drilling is a straight forward procedure requiring essentially no development effort. An available rig to drill angled blast holes in mines is illustrated in Figure 17. This unit is made up of standard vertical blast hole rig components and could be adopted for use as a horizontal rotary drilling rig. Figure 16 presents estimated costs for horizontal rotary drilling rigs.

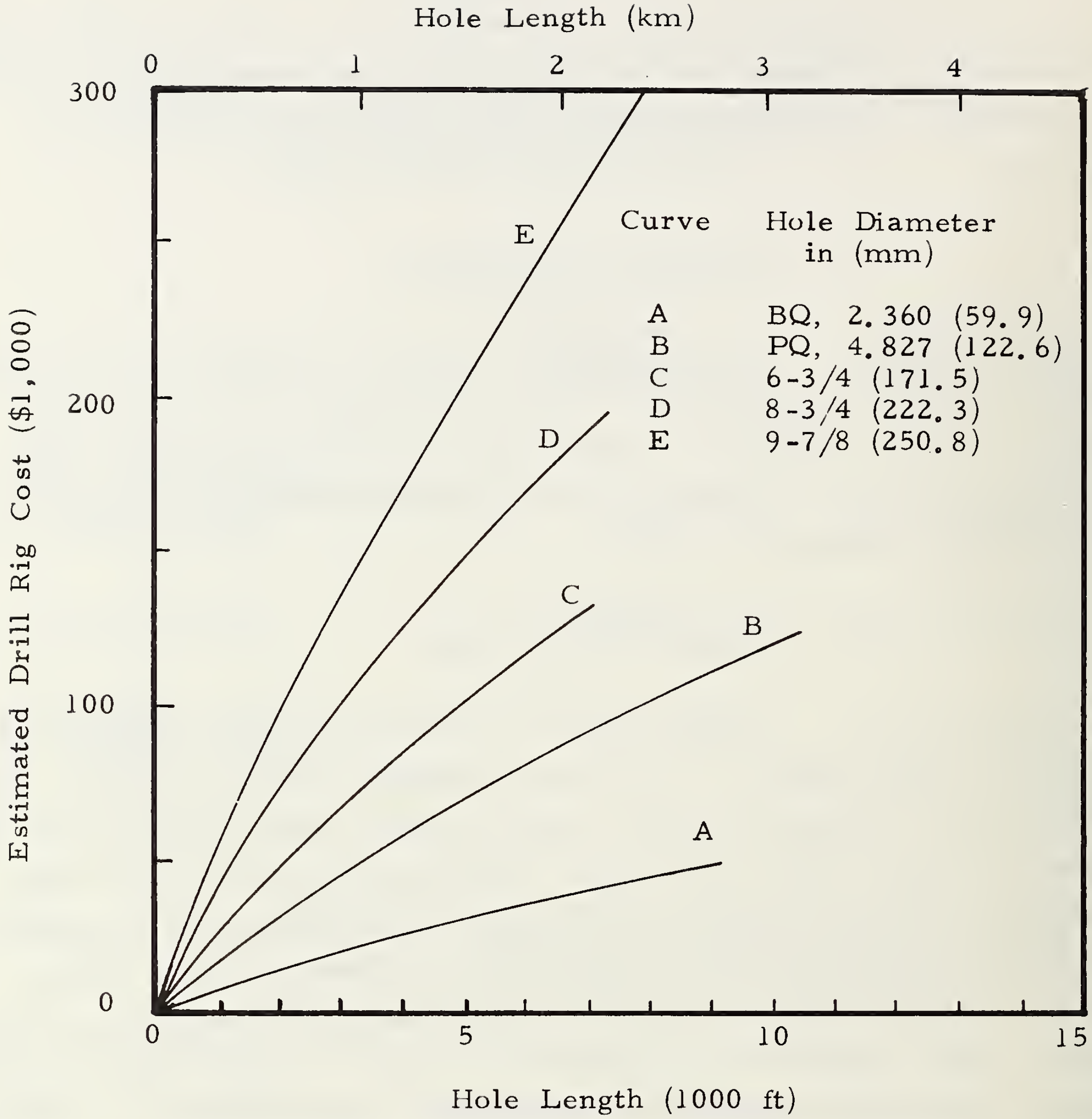


Figure 16 - Estimated Costs of Surface Rigs for Use in Horizontal Drilling

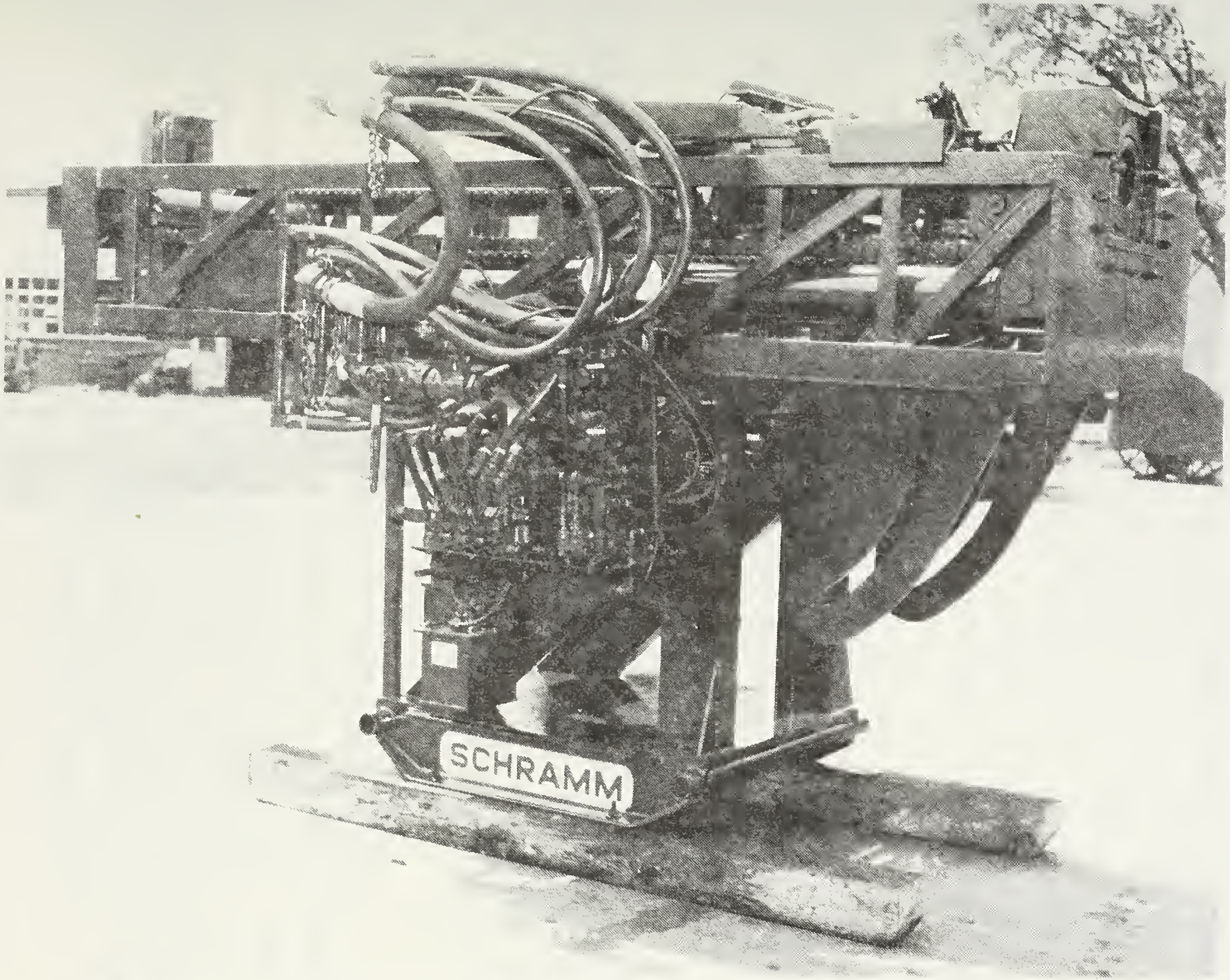


Figure 17 - Schramm High Angle Blast Hole Rig (Courtesy, Schramm, Inc.)

7.5 Improved Drill Rod Handling Methods

The most commonly used method for running drill rods in and out of a horizontal hole is to pull and break the rods in 20 ft (6.1 m) lengths. This is accomplished by means of a cable hoist and a 20 ft (6.1 m) hoist structure constructed behind the drill. A swivel hoist plug is screwed into the end of the drill rod and then the hoist is used to pull the drill rod from the hole. The rods are then broken into 20 ft (6.1 m) lengths and they are manually lifted over the hoist structure to a storage rack. The hoist plug is then walked back to the drill to be connected to the next length of rod. A reverse procedure is used to run the rods back into the hole. An optimistic estimate of round trip average rod velocity, using this method, is 20 ft per minute (.1m/sec.).

Hoists are capable of pulling drill rods at velocities up to 250 feet per minute (1.27m/sec). This velocity may cause damage to the hole or the bit or both. However, it is believed that drill rod velocities of 200 feet per minute (1.02m/sec) would not cause damages in most formations.

The horizontal drilling program conducted by Jacobs Associates of San Francisco employed a drill rod extractor which was able to move 1,000 ft (305 m) of drill rod in and out of a horizontal hole at a rate of 200 fpm (1.02m/sec).[18] The Jacobs program is described in Section 6.1.3 of Volume I and References 18-20.

The rod extractor was a hydraulically driven tool which gripped the drill rod between two counter rotating wheels, the rims of which were shaped to the approximate circular shape of the drill rod. The rapid rod extractor was designed by Jacobs and manufactured by Renstrom Gear Company. This particular device was built for NX size drill rod and was employed in a procedure which involved withdrawing and inserting the drill string in a single 1,000 ft (305 m) length. This technique could be considered for project sites which are backed by a large, obstruction free, level area.

The following conceptual design, developed by Jacobs Associates, is a much more flexible technique and should be suitable for most drill sites. This design allows the drill string to be run in and out of the hole at an average velocity of 60 fpm (.3m/sec). This velocity is computed as follows:

Running the Rods out of the Hole	Minutes per 100 ft (30.5 m)
1. Pull the rods at 200 ft/min (1.02 m/sec)	0.5
2. Break the rods in 100 ft (30.5 m) lengths.	0.2
3. Connect the hoist plug.	0.1
4. Remove the hoist plug	0.1
5. Return plug to the next length.	0.5
Total:	1.4 minutes

Running the Rods into the Hole	Minutes per 100 ft (30.5 m)
1. Make the rod connection.	0.2
2. Move the storage table.	0.1
3. Ram the rods into the hole.	1.6
Total:	1.9 minutes

The total time for running the rods in and out of the hole per 100 ft (30.5 m) is 3.3 minutes which yields an average velocity of 60 fpm (.3m/sec). No time is required for moving the storage table, prior to the rods being extracted from the hole, since this activity is taking place while the hoist plug is being returned to the drill.

Rod handling equipment considered here consists of a hydraulically movable storage table mounted on a structure behind the drill, a hoist to return the hoist plug to the drill, a hydraulic ram to run the rods back in the hole and a continuous chain rod spinner.

A movable storage table shown in Figure 18 has the capacity to store 4,000 ft (1,219 m) of NQ drill rods in 100 ft (30.5 m) lengths. The table is made up of forty 90 ft (27 m) long channels mounted on seven 4 inch (102 mm) wide flange beams at 15 ft (4.6 m) centers. This table may be moved back and forth by means of two hydraulic cylinders located at the 1/3 points of the table. The movement of this table is restricted to 4 inch (102 mm) moves to enable an empty channel to move into place to receive consecutive lengths of drill rod. When drill rod is being removed from a hole the table moves in one direction in 4 inch (102 mm) increments. To run drill rods back in the hole the direction of table movement is reversed. The table provides a supporting channel to receive 100 ft (30 m) lengths of drill rod and this channel then becomes the permanent storage rack for the length of rod.

The high speed rod spinner used to spin up and spin off drill rods is a standard off-the-shelf item. The rod spinner uses a reversible air motor and a continuous chain clamp. A hydraulic motor spinner is presently in the design phase. The spinner is designed for oil field use but it can be readily adapted to horizontal drilling. Adjustments on the unit enable it to handle drill rods ranging in diameter from 2.875 in (73 mm) to 7 in (178 mm).

Estimated costs for this unit for hole lengths from 1,000 to 5,000 ft (305 to 1,524 m) are as follows:

Hole Length; feet (meters)	Estimated Cost
5,000 (1,524)	$29,275.
4,000 (1,219)	23,420.
3,000 (914)	17,565.

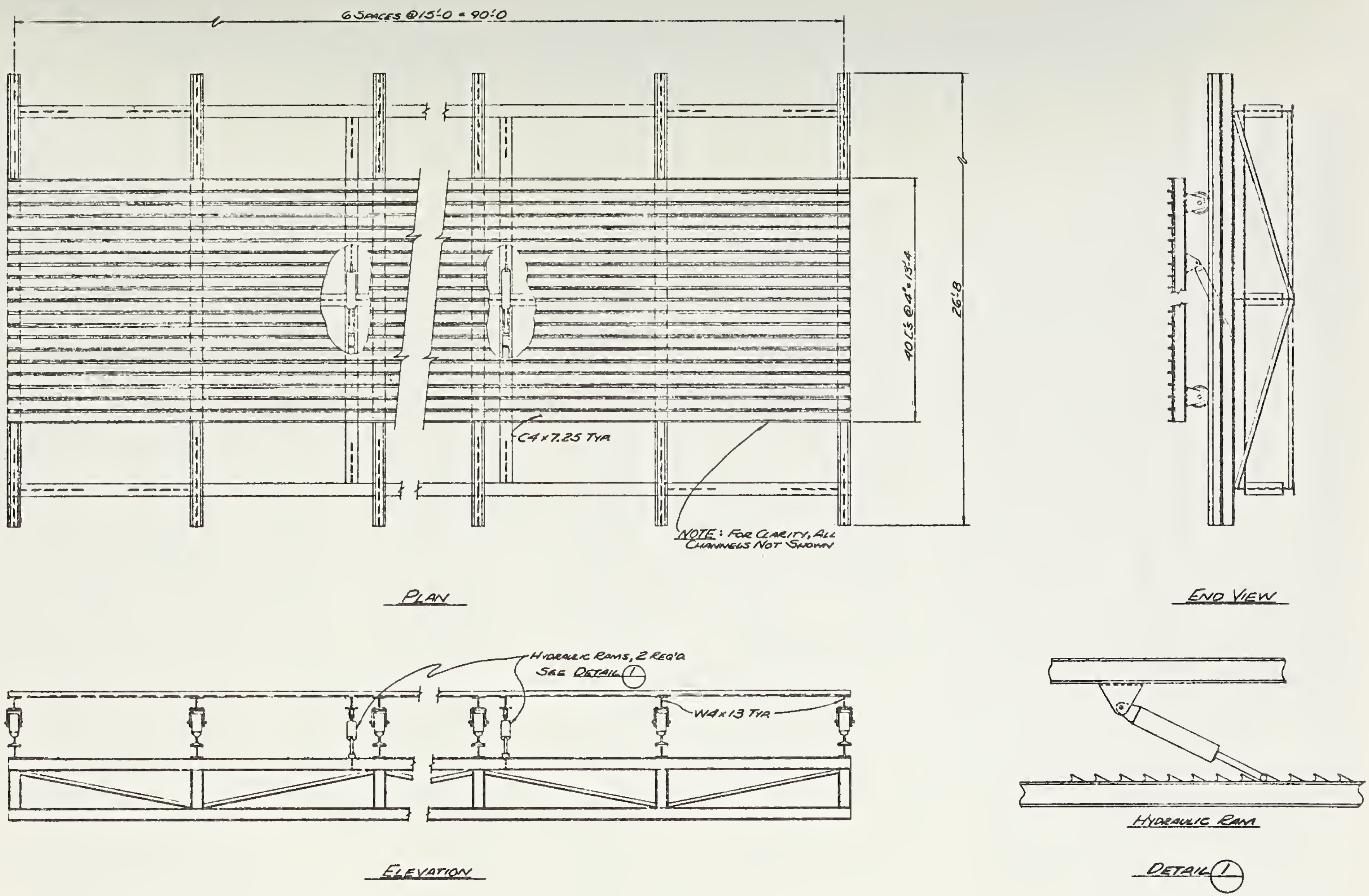


Figure 18 - Conceptual Design for Improved Drill Rod Handling

Hole Length; feet (meters)	Estimated Cost
2,000 (610)	$11,710.
1,000 (305)	5,855.

It is clear from the data presented in Section 7.3.1 that this equipment will pay for itself on one long horizontal drilling project.

8. Development Potential of Horizontal Drilling

If the existing state-of-the-art of horizontal drilling and the development potential of existing equipment and potentially cost effective new equipment are considered, a series of horizontal drilling systems can be synthesized. In the sections which follow, five potential horizontal drilling systems are presented. The systems are discussed in the order of increasing development time and development costs. Each system is comprised of equipment which has approximately the same time frame for development. The systems are characterized on the basis of the drilling technique employed as follows:

1. Diamond Wireline Core Drilling
2. Rolling Cutter Rotary Drilling
3. Rolling Cutter Core Drilling
4. Down-Hole Motor Drilling with a Down-Hole Thruster
5. Rolling Cutter Core Drilling with a Down-Hole Thruster

Each of the potential drilling systems is synthesized from equipment discussed in previous chapters. The first two techniques fit the Task B development definition and the last three are Task C development efforts.

Table 25 summarizes the equipment which makes up each of the drilling systems and indicates the potential performance capabilities of each system. The development level for each subsystem is indicated in parentheses (A, B, or C).

8.1 Diamond Wireline Core Drilling

The potential penetration capability of diamond wireline core drilling is discussed in detail in Chapter 3. Existing in-hole equipment (bits, drill rod, core barrels, etc.) is capable of penetrating to 10,000 ft (3,048 m). B thru P size equipment could be employed (2.36-4.827 inch, 36.5-85 mm hole diameter), although B and N size equipment would probably be used for most work.

TABLE 25

POTENTIAL IMPROVED HORIZONTAL DRILLING SYSTEMS

Drill Bit	Energy	Transmission	Guidance		Hole Specifications			Coring	Comments
	Thrust	Torque	Survey	Steering	Diameter	Length	Deviation		
Diamond wireline core bit (A)	Surface rig (B)	Surface rig (B)	Core barrel guidance system (B) Gyroscopic wireline survey tool (B).	Down-hole motor (A) to 3000 ft (914 m) Wedging (A) beyond 3000 ft (914 m)	2.360-4.827 inches (48 - 123 mm)	10,000 ft (3,048 m)	± 10 ft (3 m) per 1000 ft (305 m)	Continuous	Automated rod handling recommended (B/C)
Rolling cutter bit (A) Diamond core bit (A)	Surface rig (B)	Surface rig (B)	Magnetic survey tool (A). Gyroscopic wireline survey tool(B).	Down-hole motor (A) to 5,000 ft (1,524 m) *	6.75 - 10+ ins. (171 - 254 mm)	7,500 ft (2,134 m)	± 10 ft (3 m) per 1000 ft (305 m)	Intermittent	Automated rod handling recommended (B/C0
Rolling cutter coring bit (B/C)	Surface rig (B)	Surface rig (B)	Core barrel guidance system (B). Gyroscopic wireline survey tool (B)	Down-hole motor (A) to 5,000 ft. (1,524 m).* OR Remote steering tool (C).	6.75 - 10+ ins. (171 - 254 mm).	7,500 ft (2,134 m)	± 10 ft (3 m) per 1000 ft (305 m)	Continuous	Automated rod handling recommended (B/C)
Rolling cutter bit (A) or diamond plug bit (A)	Down-hole thruster (C)	Down-hole motor (A)	Magnetic and/or gyroscopic wireline (B).	Steering shoe (C)	≈ 3 - 10 inches (76 - 254 mm)	15,000 ft (4,572 m)	± 10 ft (3 m) per 1000 ft (305 m)	None	Flexible drill string can be rolled on drum.
Rolling cutter coring bit (B/C)	Down-hole thruster (C).	Surface rig (B)	Core barrel guidance system (B). Gyroscopic wireline survey tool (B).	Remote steering tool (C).	6.75 - 10+ 10 + ins. (171 - 254 mm)	15,000 ft. (4,572 m)	± 10 ft (3 m) 1000 ft (305 m)	Continuous	Automated rod handling recommended (B/C)

*Whip stocking (A) beyond 5,000 ft (1,524 m)

It should be noted that the maximum hole size for this technique is well below the hole sizes which are anticipated as being necessary for geophysical sensing equipment being developed by FHWA. Wireline coring equipment employed for vertical (petroleum) drilling is available for hole sizes up to 12.25 inches (311 mm). However, this equipment has never been employed for horizontal drilling and adapting the equipment to horizontal drilling will not be cost effective. Therefore, if the use of potential FHWA developed sensing equipment is anticipated, a technique other than diamond wireline core drilling should be employed for horizontal penetration.

An equipment list for the major components of the proposed drilling system is indicated in Table 26. The excavation equipment requires little or no development effort as discussed previously. The core barrel guidance system is made up of equipment now employed for oriented core sampling and should not involve any significant development effort. A wireline gyroscopic survey tool can be made available on a custom order basis. Surveys conducted with the unit would meet accuracy requirements and provide a calibration reference for the core barrel guidance system. The down-hole motor should be employed in conjunction with the wireline survey tool. Both gyroscopic and magnetic wireline survey tools meet this requirement. The best choice for this application will depend on accuracy requirements, economics, and field operating experience.

The time and costs savings which can be achieved with more efficient drill rod handling techniques make the development of automatic, semi-automatic, or continuous rod handling equipment a desirable goal. This option is recommended for long range horizontal drilling.

8.2 Rolling Cutter Rotary Drilling

Existing rolling cutter bits, drill rods, and associated in-hole equipment should be suitable for horizontal penetration to about

TABLE 26

MAJOR EQUIPMENT AND MATERIALS LIST FOR AN IMPROVED DIAMOND WIRELINE CORE DRILLING HORIZONTAL DRILLING SYSTEM

Function	Equipment	Development	Comments
Excavation	(a) Bits, overshots drill rod, etc.	State-of-the-art	
	(b) Drill.	Custom built (Task B)	
Guidance	(a) Core barrel guidance system.	Task B development.	Reduces time.
	(b) Wireline gyro survey tool.	Task B development.	Achieves accuracy requirements.
Steering	(a) Down-hole motor. [Out to 3,000 ft (914 m)]	State-of-the-art	Reduces time.
	(b) Wedging [To 10,000 ft. (3,048 m)].	State-of-the-art.	
	(c) Wireline magnetic survey tool.	Task B development	Considered essential to employ down-hole motor.
	(d) Wireline gyroscopic survey tool.	Task B development.	See text.
Rod Handling (Optional)	Automatic or semi- automatic rod handling device.	Task B/C development	Substantial time savings.

7,500 ft (2,286 m). A suitable surface rig will have to be custom made but this does not involve any significant development effort. Specifications for rigs are developed in Chapter 3. Hole size should be at least 6.75 inches (171 mm) to ensure acceptable bit life in hard rock. Diameters up to 9.875 inches (251 mm) will encompass the anticipated size range for FHWA developed geophysical sensing equipment. If intermittent core sampling is required a conventional diamond core drilling assembly would be employed at the interval specified.

A major equipment list for a rolling cutter rotary drilling horizontal drilling system is given in Table 27. Rotary drilling is the technique of choice among the Task B techniques where core samples are not required or when larger hole sizes are required. If intermittent coring is required, the extra rod handling burden which this imposes, makes the development of improved rod handling equipment and techniques especially important.

8.3 Rolling Cutter Core Drilling

For information gathering value the development of rolling cutter core bits for horizontal drilling provides an ideal system. The technique would provide continuous coring and large hole size to accomodate geophysical sensing instrumentation. Insert rolling cutter bits represent the most sophisticated rock drilling technology and improvement in bit performance is continuing at an impressive rate. Use of this technology to satisfy the requirement for exploratory horizontal drilling would connect horizontal drilling to the mainstream of drill bit development.

Other elements of a rolling cutter bit coring system would be similar to components employed for full hole rotary drilling and diamond wireline core drilling (See Table 28).

The drilling rig required for rolling cutter coring drilling should require less power than the rig used for full hole rolling cutter drilling since core drilling removes less material. As hole length

TABLE 27

MAJOR EQUIPMENT AND MATERIALS LIST FOR AN IMPROVED ROLLING CUTTER BIT ROTARY DRILLING HORIZONTAL DRILLING SYSTEM

Function	Equipment	Development	Comments
Excavation Full Hole	(a) Bits, stabilizers, drill collars, drill rod, etc.	State-of-the-art	When intermittent core samples are required.
	(b) Drill	Custom built (Task B)	
Coring	Convention diamond coring equipment	State-of-the-art	
Guidance Survey	(a) Magnetic survey instrument.	State-of-the-art	
	(b) Wireline gyroscopic survey tool.	Custom order (Task B)	Achieves accuracy requirement.
Guidance	(a) Down-hole motor.	State-of-the-art	
	(b) Wireline magnetic survey tool.	Custom order (Task B)	Considered essential to employ down-hole motor.
	(c) Wireline gyroscopic survey tool.	Custom order (Task B)	
Rod Handling (Optional)	Automatic, semi-automatic or continuous rod handling device.	Task B/C development	Of added importance for intermittent coring.

TABLE 28

MAJOR EQUIPMENT AND MATERIALS LIST FOR A ROLLING CUTTER CORE DRILLING HORIZONTAL DRILLING SYSTEM

Function	Equipment	Development	Comments
1. Excavation	(a) Bits	Task B or C development effort required.	Deep sea drilling project experience should simplify development effort.
	(b) Core barrels.	Should be simple adaptation of state-of-the-art core barrels (Task B).	Rely on deep sea drilling project experience.
	(c) Drill rod, stabilizers, drill collars, etc.	State-of-the-art.	
	(d) Drill Rig.	Custom built (Task B).	Should require less power than full hole rotary rig.
2. Guidance Survey	(a) Core barrel guidance system.	Task B development.	Larger space envelope than diamond wireline application.
	(b) Wireline gyroscopic survey tool.	Task B development.	See 2(a) above. Necessary to meet accuracy requirements.

Table 28 (continued)

Function	Equipment	Development	Comments
Steering	(a) Down hole motor.	State-of-the-art.	Task B development. Considered essential to employ down hole motor. Packaging problem eased by larger packaging envelope.
	(b) Wireline magnetic survey tool.		
	(c) Wireline gyroscopic survey tool.	Task B development.	
*Steering (Optional)	Remote steering tool	Task C development.	
3. Rod Handling (Optional)	Automatic, semi-automatic or continuous rod handling device.	Task B/C development.	

increases and friction forces consume an increasing percentage of the drill rig output, this difference will decrease in significance.

The increased hole size resulting from the use of rolling cutter coring bits will provide increased space in which to package instrumentation and core recovery equipment.

An optional development with this system could be a remote steering tool to replace the down-hole motor and whip stocking procedures.

8.4 Down-Hole Motor Drilling with a Down-Hole Thruster

The development of a suitable down-hole thruster device is necessary to achieve horizontal penetrations beyond 10,000 ft (3,048 m) in length. A thruster device is also required if the down-hole motor is to be used to drill hole deviations beyond a 5,000 ft (1,524 m) depth. The down-hole thruster has additional advantages listed below:

1. The thruster eliminates the need for a rigid drill string.

2. The use of a flexible, non-rotating connection between the drilling assembly and the surface allows simple "hard wired" instrumentation telemetry.

3. The combination of down-hole motor, thruster, and steering shoe gives a true long range, maneuverable horizontal penetration system.

A system such as that described in Table 29 could be assembled from components which have been tested experimentally. However, considerably more development work would be required to

TABLE 29

MAJOR EQUIPMENT AND MATERIALS LIST FOR A DOWN HOLE MOTOR/THRUSTER/STEERING SHOE HORIZONTAL DRILLING SYSTEM

Function	Equipment	Development	Comments
1. Excavation	(a) Bits	Task A.	
	(b) Drill	Task A or B/C.	A state-of-the art hydraulic down hole motor could be employed (A) or an electric drill (B/C).
	(c) Drill String	Task B.	Hydraulic lines and/ or electrical cable.
2. Guidance Survey	Magnetic and/or gyroscopic wireline survey tool.	Task B.	
Steering	Steering shoe.	Task C.	

turn such a system into a practical reality. The system also has some serious disadvantages. Two of the most notable being:

1. Lack of coring capability.
2. Inability to penetrate severely broken ground.

If developed, this system would meet all study requirements for non-cored horizontal penetration.

8.5 Rolling Cutter Core Drilling with a Down-Hole Thruster

A system to perform core drilling to 15,000 ft (4,572 m) will have to employ some sort of down-hole thruster device. The development of such a device will be particularly difficult since the thruster will have to have an annular configuration to allow the core to pass out of the hole. If such a device were to be developed it could be employed with the rolling cutter core drilling system, with torque provided from a surface rig, to core drill well beyond the projected 7,500 ft (2,286 m) limit projected for the surface thrusted system. (See Chapter 3).

9. Development Plans to Improve Horizontal Drilling Capability

In the preceding chapters developments with the potential to improve horizontal drilling capability have been identified. In each case these developments have been identified as either Task B (short-term) or Task C (long-term) developments. Task B developments have been further defined as involving modifications to "conventional" equipment, while Task C developments consist of "new, conceptual design alternatives."

In the following sections potential Task B and C developments are summarized and the cost effectiveness of government support in each of the development areas is discussed. Then, development strategies to promote selected developments are outlined.

9.1 Task B Developments

The definition of Task B developments has been expanded somewhat over the simple "modifying conventional equipment" in an attempt to further clarify the distinction between Task A, B, and C developments. Task B developments involve proven equipment and/or procedures which are not generally applied to horizontal drilling. The term "proven" in this case indicates that the developments involve no new technology. This implies that Task B developments will involve off-the-shelf hardware and that little or no design or development effort will be involved other than, perhaps, repackaging. The term further implies that Task B developments will be short term, relatively low cost developments. Experimental hardware is not included in this category because it cannot be considered proven. Even with this expanded definition, the distinction between Task B and C developments can sometimes be ambiguous. Where such ambiguities exist they will be pointed out.

Table 30 summarizes the potential Task B developments identified previously. The items are listed by functional classification.

TABLE 30

POTENTIAL TASK B

HORIZONTAL DRILLING DEVELOPMENTS

Functional Classification	Development	Comments
1. Penetration	Upgraded diamond and rotary drilling drill rigs.	Can be custom built.
2. Guidance	(a) Magnetic wireline survey tools.	Can be custom built.
	(b) Gyroscopic wireline survey tools.	Can be custom built.
	(c) Core barrel guidance systems.	Some development may be required.
	(d) Utilize down hole motor to drill hole deviations for diamond wireline drilling systems.	The down hole motor is state-of-the-art. Either development 2(a) or 2(b) is a prerequisite for this procedure.
	(e) Remotely actuated kick subs.	Some development required. Of interest mainly for down hole motor drilling.
3. Hole Stability	Non-metallic casing technique.	
4. Information Gathering Techniques	None recommended.	
5. Cost Savings.	(a) Core barrel guidance system.	See 2(c)

Table 30 (continued)

Functional Classification	Development	Comments
5. Cost Savings (continued)	(b) Application of the down hole motor as a steering tool for diamond wireline core drilling.	See 2(d)
	(c) Wireline survey tool.	See 2(a) and 2(b)
	(d) Improved rod handling	Can be either a B or C development effort depending on the technical sophistication employed.

9.2 Task B Development Plans

By definition, Task B developments involve adapting existing equipment and/or procedures so that they may be applied to horizontal drilling. The fact that equipment which exists and has the capability to improve horizontal drilling performance has not already been applied to horizontal drilling suggests either a lack of communication or the lack of a horizontal drilling market. In truth, both of these inferences are true to some degree. The objectives of this three volume study include upgrading the state of knowledge on horizontal drilling potential and, in so doing, stimulating greater use of horizontal drilling.

The most effective technique to promote Task B horizontal drilling development is to stimulate the market for such development. This stimulation could be provided by a horizontal drilling demonstration project, conducted as a part of the preliminary site investigation for an underground construction project.

Either the diamond wireline drilling system, or the rotary drilling system described in Chapter 8 should be employed, depending on coring and hole size requirements for the project. Specifications for potential horizontal drilling projects employing each of the Task B horizontal drilling systems are presented below.

9.2.1 Diamond Wireline Core Drilling Horizontal Drilling Demonstration Project

(a) State-of-the-Art Demonstration Project

The least expensive diamond wireline demonstration project would employ state-of-the-art equipment as outlined in Volume I. A 4,000-5,000 foot (1,219-1,524 m) demonstration hole in BX or NX size would cost approximately \$300-\$500 thousand. Actual drilling time will take approximately 6 months, so a total contract period of one year to allow for planning, mobilization, and demobilization would be reasonable.

(b) Task B Demonstration Project

A Task B demonstration project for diamond wireline core drilling should be conducted using the state-of-the-art demonstration project as a baseline and considering various Task B options. A Task B demonstration project will be much more expensive than a state-of-the-art (Task A) project. This is due to the fact that the Task A project can be contracted without significant non-expendable purchases, while Task B equipment will be custom made and will, in all likelihood, have to be purchased.

Possible Task B options are considered below:

- Custom Drill Rigs

The main objective of developing a special horizontal drill rig is to increase penetration capability. A custom rig will cost from \$50,000 to \$150,000 and this total will be added to the cost of the project.

- Application of a Down-Hole Motor for Steering

As indicated in Chapter 7, the use of a down-hole motor for drilling hole corrections will reduce overall drilling costs. However, a wireline survey tool should be employed with the down-hole motor and this will add \$20,000 to \$40,000 to project costs.

- Core Barrel Guidance System

A magnetic core barrel guidance system (two units) should cost from \$10,000 to \$20,000 per unit. For a single 5,000 ft (1,524 m) hole approximately \$1,000 to \$1,500 of this cost would be recovered in reduced drilling costs.

- Wireline Gyroscopic Survey Tool

A wireline gyroscopic survey tool would add $20,000 to $40,000 to project costs. This is essentially the cost penalty for achieving the desired survey accuracy and ranges from 4 percent to 13 percent of total hole cost for a 5,000 ft (1,524 m) hole.

- Improved Rod Handling

A carefully considered development program to improve drill rod handling could recover the equipment costs on a single 5,000 ft (1,524 m) hole. For example, a rod handling machine to increase the average rod handling speed from 20 ft/min (.10m/sec) to 60 ft/min (.30 m/sec) is estimated to cost $50,000 for a 5,000 ft (1,524 m) capacity device. The estimated hole cost savings for increasing average rod handling speed from 20 to 60 ft/min (.10 to .30m/sec) ranges from $50,000 to $90,000 for a 5,000 ft (1,524 m) hole.

9.2.2 Rotary Drill (Rolling Cutter Bits) Horizontal Drilling Demonstration Project

A rotary drilling horizontal drilling demonstration project should only be considered if hole sizes of 6.75 inches (171 mm) or larger are desired. Specifically, rotary drilling will be required if the FHWA developed geophysical sensing equipment is to be employed. Strictly speaking, a horizontal rotary drilling project can not be conducted with state-of-the-art (Task A) equipment, since the surface drilling rig will have to be custom made. The cost of the rig is likely to range from $100,000 to $150,000 for a unit capable of drilling a 6.75 inch (171 mm) diameter hole to 5,000 ft (1,524 m), to $200,000 to $350,000 for a unit capable of drilling a 9.875 inch (251 mm) hole to 7,500 ft (2,286 m). Since the unit will be custom built, the cost will have to be charged to the drilling project.

(a) Base Demonstration Project

A baseline horizontal rotary drilling demonstration project to drill a 6.75 inch (171 mm) hole to 5,000 ft (1,524 m), with core samples and direction changes at 60 ft (18 m) intervals, will cost approximately $500,000. The job would take 3 - 4 months.

(b) Task B Demonstration Project Options

The key options to be considered for the demonstration project would be:

- A wireline magnetic and/or gyroscopic survey tool.

- Improved rod handling equipment.

A wireline magnetic survey tool is considered essential to efficient employment of the down-hole motor for steering. This device will add $20,000 to $40,000 to the project cost.

A wireline gyroscopic survey tool will be necessary to ensure that hole deviation is less than $\pm$ 30 ft (9 m).

Improved rod handling equipment should pay for itself on a rotary drilling demonstration project.

9.3 Task C Developments

Task C developments require the development of "new, conceptual design alternatives." Included in this category are original concepts, experimental concepts, and concepts involving extensive modification (modification requiring new technology) of conventional equipment. Generally Task C developments will require more time and money than Task B developments.

Table 31 lists Task C developments identified previously. The developments are listed by functional classification. These potential developments are discussed in more detail below.

(a) Down-Hole Thruster Development

Drilco down-hole thrust applicators are built in 3 inch (76 mm) and 6 inch (152 mm) diameters. The 3 inch (76 mm) model has a claimed thrust output of 7,000 lbs (3.1 kN). The 3 inch (76 mm) unit has been used to drill to 800 ft (244 m) in soft coal in the CONOCO proprietary horizontal drilling program. This unit will require much more extensive development to be suitable for long horizontal drilling in rock.

A concept for a down-hole thruster unit designed specifically for the objectives of this study is presented in Appendix C. This concept would also require extensive development effort to bring to proven hardware.

The primary objectives of down-hole thruster development would be:

(1) To enable horizontal penetration to 15,000 ft (4,572 m).

(2) To provide a down-hole anchor which will increase the range for which a down-hole motor can be applied to drill hole deviations.

(b) Annular Down-Hole Thruster

The objective of an annular down-hole thruster development would be to create a drilling system which could core drill to 15,000 ft (4,572 m). This would be a technically challanging, long-term, expensive development effort.

TABLE 31

POTENTIAL TASK C HORIZONTAL DRILLING DEVELOPMENTS

Functional Classification	Development	Comments
1. Penetration	(a) Down-hole thruster units	Exist as experimental hardware. Drilco thrust applicator. ("Creepy Crawler")
	(b) Down-hole thruster units with an annular geometry to allow coring	Advanced development
2. Guidance	(a) Wireless telemetry	Extensive commercial development effort
	(b) Remote steering tool for rotary drilling	High pay off mid-term development effort
	(c) Steering shoe for use with down-hole motors and thrusters	Developed for CONOCO experimental horizontal drilling program
	(d) External reference guidance systems	Advanced development
3. Information Gathering	Rolling cutter coring bits	Employed successfully on Deep Sea Drilling Project[2,3]
4. Cost Savings	Advanced drill rod handling equipment	

(c) Wireless Telemetry

Wireless telemetry is a development which is being pursued by several commercial companies. Success in this area will benefit all forms of long range drilling activities.

(d) Remote Steering Tool for Rotary Drilling

A remotely activated steering tool which could be employed with either a diamond wireline system or a rolling cutter rotary drilling system would substantially reduce drilling times. Potential time reductions exceed 39 percent for diamond wireline core drilling. A prototype development effort for such a device is projected to cost between $250,000 and $500,000 and require 1.5 to 2 years. This cost could be recovered in three 5,000 ft (1,524 m) horizontal drilling projects. However, the development of such a device would have a significant impact on all types of guided rotary drilling.

(e) Steering Shoe for Down-Hole Motor/Thruster Drilling Systems

This potential development would be part of an advanced, full hole (non-cored) drilling system to penetrate to 15,000 ft (4,572 m).

(f) External Reference Guidance Systems

External reference guidance systems have the potential for achieving a very high order of survey accuracy. The "Hyperbolic Homing Guidance" concept presented in the FMA proposal was conceived as a very high accuracy survey system.(14) It is now apparent that developments of this type are not necessary in order to achieve specified hole accuracy requirements.

(g) Rolling Cutter Coring Bits

Rolling cutter coring bits could be termed either a Task B or Task C development. The bits developed for the Deep Sea Drilling Project have performed very well in that application, but without some field experience, it is difficult to evaluate how much development effort will be required to apply the bits to horizontal drilling. Core barrels and other supporting equipment will definitely be Task B development efforts as the equipment can be custom made and involves no new technology.

Rolling cutter bit development will eliminate the requirement for "dual mode" drilling when core sampling is required for a rotary drilling project. A rotary drilling system employing rolling cutter full hole and coring bits, as required, would be an optimum drilling system to meet the objectives of this study.

9.4 Task C Development Plans

Task C improvements will generally require extensive hardware development efforts prior to any field demonstration of the techniques. In our opinion, most Task C developments are already receiving commercial support consistant with the need for the equipment. Two developments which are especially relavent to the needs of this study which are potential targets for support are: (1) a remote steering tool for rotary drilling and (2) rolling cutter coring bits.

Development strategies to provide this support are described below.

9.4.1 Remote Steering Tool for Rotary Drilling

The development of a remote steering tool for rotary drilling will allow substantial time and cost savings for guided rotary drilling. An effort to develop such a device could be undertaken as a relatively straight-forward hardware development program. A program requiring $250,000 to $500,000 conducted over a 1.5 to 2 year period should be sufficient to develop prototype hardware.

9.4.2 Rolling Cutter Coring Bits

The development of rolling cutter coring techniques for horizontal drilling could be promoted most effectively by field testing the technique in conjunction with a rotary drilling demonstration program. Initial tests could be conducted with hardware adapted from the Deep Sea Drilling Project. Further evaluation of the utility of the technique would await the results of the test program.

10. Conclusions and Recommended Development Efforts

The primary objectives of this program are to (1) investigate the performance of horizontal drilling as an alternative to pilot tunneling in pre-excavation site investigations for proposed tunneling projects and (2) to evaluate the potential for improving horizontal drilling capabilities. We can now conclude that:

1. Horizontal drilling has an order of magnitude cost advantage over pilot tunneling for horizontal penetrations out to 5,000 ft. (1,524 m).

2. The economic advantage of horizontal drilling over pilot tunneling is likely to increase, even without substantial development, since horizontal drilling is essentially a mechanized technique while plot tunneling is a more labor intensive technique.

3. There is a substantial potential to decrease the cost and/or increase the performance capability of horizontal drilling.

10.1 Conclusions on Horizontal Drilling Development

In drawing conclusions on the cost effectiveness of a variety of potential development efforts it is essential to have some knowledge of the market for such developments. Table 32 summarizes market estimates from a recent study for horizontal drilling and related guided drilling activities.[15.] The table is abridged to indicate significant market segments only. From this data and other information gained during this study, the following conclusions can be drawn:

1. The market for horizontal drilling as a site investigation technique for transportation tunnels is small relative to other guided drilling

TABLE 32

POTENTIAL MARKETS FOR HORIZONTAL (DIRECTIONAL) DRILLING[15]

Market	Potential Customers	Drilling (x 1000 ft) 1974	Drilling Potential (x1000 ft/yr) (domestic) 1975-80	1980-85	Typical Lengths Present-Future (ft)	Material Penetrated
ENERGY RESOURCE RECOVERY						
Coal Degassification	Conoco Peabody Exxon Etc. (ERF)*	2-5	2-8000		800-2000	Soft coal
EXPLORATION						
Minerals	Homestaker Bunnkerhill Amax (MRF)**	1,000			1000-1500	Metamorphic/ Sedimentary Rock
Energy Resources (Directional Drilling)***	ERF	>16,000			15,000	Sedimentary Rock
Transportation Tunnels	Federal and Municipal Governments	5-10 (Japan)	25-30 - soil 30-35 - rock		5000-10,000	Soil Residual Soil Hard Rock

* Energy Resource Firms

** Mineral Resource Firms

*** Hole trajectory typically 20° or less from vertical applications. This suggests that developments to improve horizontal drilling capability should also be applicable to other guided drilling applications to increase the market for such development.

2. The study requirement for horizontal penetration to 15,000 ft. (4,572 m) is not representative of actual requirements. Given a typical maximum tunnel length of 10,000 ft. (3,048 m) a maximum horizontal penetration depth of 5,000 ft. (1,524) should be sufficient to meet most requirements.

Another conclusion, which is at odds with some views on horizontal drilling as a site investigation technique, is that non-cored drilling will be of little or no utility. Geophysical techniques can supplement the information gathered by core drilling but they are not likely to replace core drilling. This contrasts sharply with exploration drilling for petroleum, where logging procedures have supplanted core drilling as the primary means of gathering geological information. This is consistent with the less detailed, "area" type investigation requirements of petroleum drilling exploration. This fact also explains why the excellent performance of rolling cutter coring bits on the Deep Sea Drilling project has not stimulated more development of this technique in petroleum exploration drilling. The rolling cutter coring bit has not been developed further for mineral exploration either, since this application does not require the larger hole size given by the rolling cutter coring bit.

On the basis of the preceding discussion, ground rules can be established for evaluating potential horizontal drilling developments:

1. There is little need for developments to increase penetration capability.

2. Guidance Developments should stress the achievement of desired accuracy requirements and reduced cost for guidance activities.

3. Cost saving developments should offer rapid payback. Recovery of costs on one 5, 000 ft. (1, 524 m) project is a desirable goal. Developments peculiar to horizontal drilling have a very limited market over which to amortise development costs. Developments relevant to the entire guided drilling market justify higher development costs than those developments limited to horizontal drilling activities.

10.2 Recommended Horizontal Drilling Development

Recommended horizontal drilling development activites are summarized in the following sections.

10.2.1 Diamond Wireline Core Drilling Horizontal Drilling Demonstration Project.

A state-of-the-art demonstration project is recommended as an alternative to pilot tunneling for an actual pre-excavation tunnel site investigation. Task B options which are recommended as a part of the project include:

1. Application of a Down-Hole Motor for Steering. - Potential cost savings should be about equal to wireline survey tool costs.

2. Improved Rod Handling - Development costs should be limited to potential cost savings on the project.

Total cost estimates for this program are $500,000. with a 1 to 1.5 year duration.

A wireline gyroscopic survey tool could be employed if value analysis shows that the increased survey accuracy is worth the $20,000 to $40,000 cost premium.

The use of a core barrel guidance system is also recommended to decrease the time required for the project and increase the utility of the data obtained. This development would add $18,000 to $37,000 to the cost of a 5,000 ft (1,524 m) hole.

10.2.2 Rotary Drilling (Rolling Cutter Bits) Horizontal Drilling Demonstration Project

This program should be considered if there is a requirement for a 6.75 inch (171 mm) or larger hole size. This minimum hole size will be required for the geophysical sensing equipment being developed for FHWA under contract FH-11-8602.[1,16,17]

Task B options recommended include:

1. A Wireline Survey Tool. (Essential to employing a down-hole motor for steering).

2. Improved Rod Handling Equipment. (Potential time savings are especially attractive with required intermittent coring).

A total contract cost of approximately $750,000 to $1,000,000 with a duration of 1.5 to 2 years is estimated for this project.

The use of a wireline gyroscopic survey tool should be considered if increased accuracy is required, as for the previous project.

A rolling cutter core drilling test should be conducted as a subtask of this project. The increase in cost due to this activity is not known but it should not exceed $100,000.

10.2.3 Development of a Remote Steering Tool for Rotary Drilling

A remote steering tool for rotary drilling is the only potential Task C development effort which warrants consideration for a hardware development program. A successful remote steering tool would provide rapid payback (in excess of $100,000 for a 5,000 ft (1,524 m) diamond wireline hole) and would be applicable to the entire guided drilling market.

It is estimated that $250,000 to $500,000 will be required over a 1.5 to 2 year period to develop prototype hardware.

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APPENDIX A

ANALYSIS OF THRUST AND TORQUE REQUIREMENTS IN HORIZONTAL HOLES

In the drilling of horizontal holes, there are two primary energy uses. One is the actual energy required at the rock face by the drill bit and the other is the energy required to supply torque and thrust to the drill bit, i. e., the energy lost between the surface rig and the drill bit. For the techniques currently employed for horizontal drilling, this second area requires the greatest expenditure of energy.

The loss of energy between the surface rig and the drill bit is primarily due to friction between the drill string and the hole wall. These friction losses arise because of the contact force between the hole wall and the drill string. In a horizontal hole, this contact force is the sum of the force of the drill string weight and the side support forces necessary to support the drill string against buckling. (The drill string tends to buckle due to compressive loading.)

These friction losses also account for the major differences between horizontal and vertical drilling. In drilling a vertical hole, the drill string supports its own weight which results in the drill string being in tension. Since the drill string is in tension, there is no buckling tendency and the total wall contact force is negligibly small. Hence there is less energy loss due to friction in a vertical hole.

This appendix analyzes the torque and thrust requirements for the drilling of horizontal holes by surface drilling, down-hole motor drilling, and down-hole thruster drilling. The analysis includes the drill string to hole wall friction, the resulting contact and resistance forces, the thrust and torque analyses, and the limits imposed by yield of the drill pipe. Table A. 1 presents specifications for the drill pipe currently used in each of these techniques.

TABLE A.1

DRILL PIPE SPECIFICATIONS

Hole Diameter D_h, in (mm)	Outside Dia. D_p, in (mm)	Inside Dia. D_i, in (mm)	Wt./Unit Lgh. W, lbf/ft (N/m)	Stiffness EI, lbf-in^2 (N-m^2)	Yield Stress Ψ, lbf/in^2(N/m^2
SURFACE DRILLING					
BQ, 2.360 (59.9)	2.188 (55.6)	1.813 (46.1)	4.0 (58.4)	1.744×10^7 (5.007×10^6)	8.0×10^4 (5.5×10^6)
PQ, 4.827 (122.6)	4.500 (114.3)	4.063 (103.2)	10.3 (150.3)	1.981×10^8 (5.687×10^7)	8.0×10^4 (5.5×10^6)
6-3/4 (171.5) (171.5)	4.500 (144.3)	3.958 (100.5)	13.75 (200.7)	2.371×10^8 (6.807×10^7)	7.5×10^4 (5.2×10^6)
8-3/4 (222.3)	5.500 (139.7)	4.778 (121.4)	21.9 (319.7)	5.672×10^8 (1.628×10^8)	7.5×10^4 (5.2×10^6)
9-7/8 (250.8)	6.625 (168.3)	5.965 (151.5)	25.2 (367.8)	9.509×10^8 (2.730×10^8)	7.5×10^4 (5.2×10^6)
DOWN HOLE MOTOR DRILLING					
3 (76.2)	1.750 (44.5)	1.219 (31.0	4.4 (64.2)	1.033×10^7 (2.966×10^6)	7.5×10^4 (5.2×10^6)
6-3/4 (171.5)	3.500 (88.9)	2.992 (76.0)	9.5 (138.7)	1.007×10^8 (2.891×10^7)	7.5×10^4 (5.2×10^6)
8-3/4 (222.3)	4.500 (114.3)	3.958 (100.5)	13.75 (200.7)	2.371×10^8 (6.807×10^7)	7.5×10^4 (5.2×10^6)
9-7/8 (250.8)	4.500 (114.3)	3.958 (100.5)	13.75 (200.7)	2.371×10^8 (6.80×10^7)	7.5×10^4 (5.2×10^6)

A.1 Drill String to Hole Wall Friction

The friction coefficient, f, is the ratio of the shear force, S, between two surfaces to the normal force, N, holding the two surfaces in contact or:

$$f = \frac{S}{N}$$

In situations where both the friction coefficient and the normal force are known, the shear force may be calculated. The direction of this shear or resistive force is always opposite to the direction of relative motion.

The friction coefficient for drill string to hole wall friction is a function of the flushing fluid used and whether or not the drill string is moving relative to the hole wall. For long, horizontal holes, water or bentonite-water mud are the most likely drilling fluids. The Baroid Oil Field Products Laboratory has measured the friction coefficient for various drilling fluids. Table A.2 lists the values measured for three of the most likely horizontal drilling fluids - water, bentonite-water mud, and bentonite-water mud with a special additive designed to enhance lubricating properties. In this table, the static values apply to cases where the drill string and hole wall are stationary relative to one another. Once the drill string is moving relative to the hole wall, either rotating or moving in or out of the hole, the dynamic values apply.

The special lubricating additives, such as Bovoid Torq-Trim or EP Mudlube are relatively expensive and are included here to provide lower limits on the values of the friction coefficients. Used in the recommended amounts, approximately \$4. worth of the additive is required for each \$1. worth of a 15 lb/barrel bentonite-water mud. The total cost of using the additive depends on the frequency that lost circulation zones are encountered. For field applications of the mud with the lubricating additive, 0.1 is a realistic value for both the static and dynamic friction coefficients.

TABLE A.2

VALUES FOR FRICTION COEFFICIENTS*

Drilling Fluid	Friction Coefficient	
	Static, f_s	Dynamic, f_D
Water	0.47	0.38
Bentonite-Water Mud	0.38	0.28
Bentonite-Water Mud with Lubrication Additive	$\sim$0.1	0.06-0.1

* Measured by Baroid Oil Field Products Laboratory

For the purpose of evaluating the thrust and torque requirements of the various horizontal drilling configurations under consideration, the friction coefficient values listed in Table A. 2 will be used. In particular, thrust and torque requirements are presented for friction coefficient values of 0. 1 and 0. 38 for both dynamic and static friction. However, the recommended coefficient values are 0. 1 for dynamic friction and 0. 38 for static friction.

A. 2 Drill String to Hole Wall Contact Force

Long, slender members loaded in compression will buckle when the compression load exceeds the critical load for the member. In the case of a drill string several thousand feet long, the applied thrust will be many times greater than this critical load. Therefore, the total contact force of the drill string against the hole wall will be the sum of the drill string weight and the side support force necessary to support the drill string against the buckling tendency. The total drill string to hole wall contact force will vary along the length of the drill string, being smallest at the drill bit and increasing toward the surface.

The side support force per unit length of drill string, R, required to support the drill string buckling is a function of the drill string stiffness, EI, the local thrust force being transmitted, F, and the difference between the hole diameter, D_h, and the drill pipe outside diameter, D_p, and may be expressed as:

$$R = \frac{(D_h - D_p)\, F^2}{2\pi^2\, EI} \tag{A. 1}$$

The total contact force per unit length, N, between the drill string and the hole wall is the sum of the drill string weight per unit length, W, and the side support force, R.

$$N = W + R \tag{A. 2}$$

If we assume dimensions of N in lbf, W in lbf/ft, D_h and D_p in inches, F in lbf, and EI in lbf-in^2, then:

$$N = W + \frac{6\,(D_h - D_p)\,F^2}{\pi^2\,EI} \qquad (A.3)$$

The drill string stiffness is expressed as EI where E is Young's Modulus and I is the moment of inertia and may be expressed as:

$$I = 0.048\,(D_p^4 - D_i^4)$$

where D_i is the inside diameter of the drill pipe in inches. For steel, $E = 3.0 \times 10^7$ psi and thus the drill string stiffness is expressed by:

$$EI = 1.44 \times 10^6\,(D_p^4 - D_i^4) \qquad (A.4)$$

If the buckling tendency of the drill string could be eliminated, the drill string to hole wall contact force could be decreased substantially. The additional side support force required to support the buckling tendency could be eliminated by placing stabilizers at appropriate locations along the drill string. The stabilizer spacing required to support the drill string without buckling can be calculated on the basis of the critical compressive load for a column with hinged supports at both ends. This critical load is:

$$P_{crit} = \frac{\pi^2\,EI}{L_c^2} \qquad (A.5)$$

or:

$$L_c = \pi \left[\frac{EI}{P_{crit}}\right]^{1/2}$$

Since the drill string will be loaded with a thrust force, F, the spacing between stabilizers, L_s, must be less than the critical length, L_c, when $P_{crit} = F$. In other words:

$$L_s < L_c = \pi \left[\frac{EI}{F}\right]^{1/2}$$

or:

$$L_s < \pi \left[\frac{EI}{F}\right]^{1/2} \qquad \text{(A. 6)}$$

Thus, if stabilizers are located along the entire drill string in such a fashion that their spacing is always less than the local critical length, then the side support force will be eliminated and the weight of the drill string will be the only drill string to hole wall contact force.

The use of stabilizers sounds very inviting. However, it does raise a number of new questions. Such things as how the stabilizer affects insertion force, drill string to hole wall coefficient of friction, hole wear, etc. are currently unanswered and would have to be investigated before the use of stabilizers would be a viable possibility. For these reasons, the use of stabilizers is not considered here.

A. 3 Analysis of Thrust Requirements

In horizontal drilling, thrust is required for the insertion and removal of the drill string and for drilling. The thrust requirements for each of these operations is analyzed below.

A. 3. 1 Drill String Removal

During removal, the drill string is always in tension. Thus, the only contact force is the weight of the drill string and the maximum friction force which must be overcome, F_R, is expressed by:

$$F_R = f_s WL \qquad \text{(A. 7)}$$

where f_s is the static friction coefficient, W is the drill string weight per unit length (lbf/ft), and L is the length of the hole (ft). A static coefficient of friction is used because the drill string is not always in motion relative to the hole wall.

The surface forces required for drill string removal for each of the different drilling techniques are presented as a function of hole length and hole diameter in Figures A. 1 and A. 2. For any drilling technique and length and diameter of hole the maximum removal force required may be obtained from these curves. The surface rig should be sized to provide at least 10-20 percent more than this maximum force.

A. 3. 2 Drill String Insertion

Drill string insertion may be performed in either of two ways - a down-hole thruster may pull the drill string into the hole or a surface rig may push the drill string into the hole.

If a down-hole thruster is used, then the drill string is pulled into the hole and is in tension all the time. The thrust required for this operation is exactly the same as that required for removal of the drill string and may be obtained from Figures A. 1 and A. 2 for the various drilling techniques, hole diameters, and hole lengths. The down-hole thruster should be sized to provide at least 10-20 percent more than the required thrust obtained from these figures.

When a surface rig is used, the drill string is pushed into the hole and is in compression. In this case, the drill string to hole wall contact force is composed of both the drill string weight and the side support force required to support the buckling. The total friction force in this case is expressed by:

$$F_I = \left[\frac{\pi^2 EIW}{6\,(D_h - D_p)}\right]^{1/2} \tan\left\{\left[\frac{6\,(D_h - D_p)\,W}{\pi^2 EI}\right]^{1/2} f_s L\right\} \qquad (A.8)$$

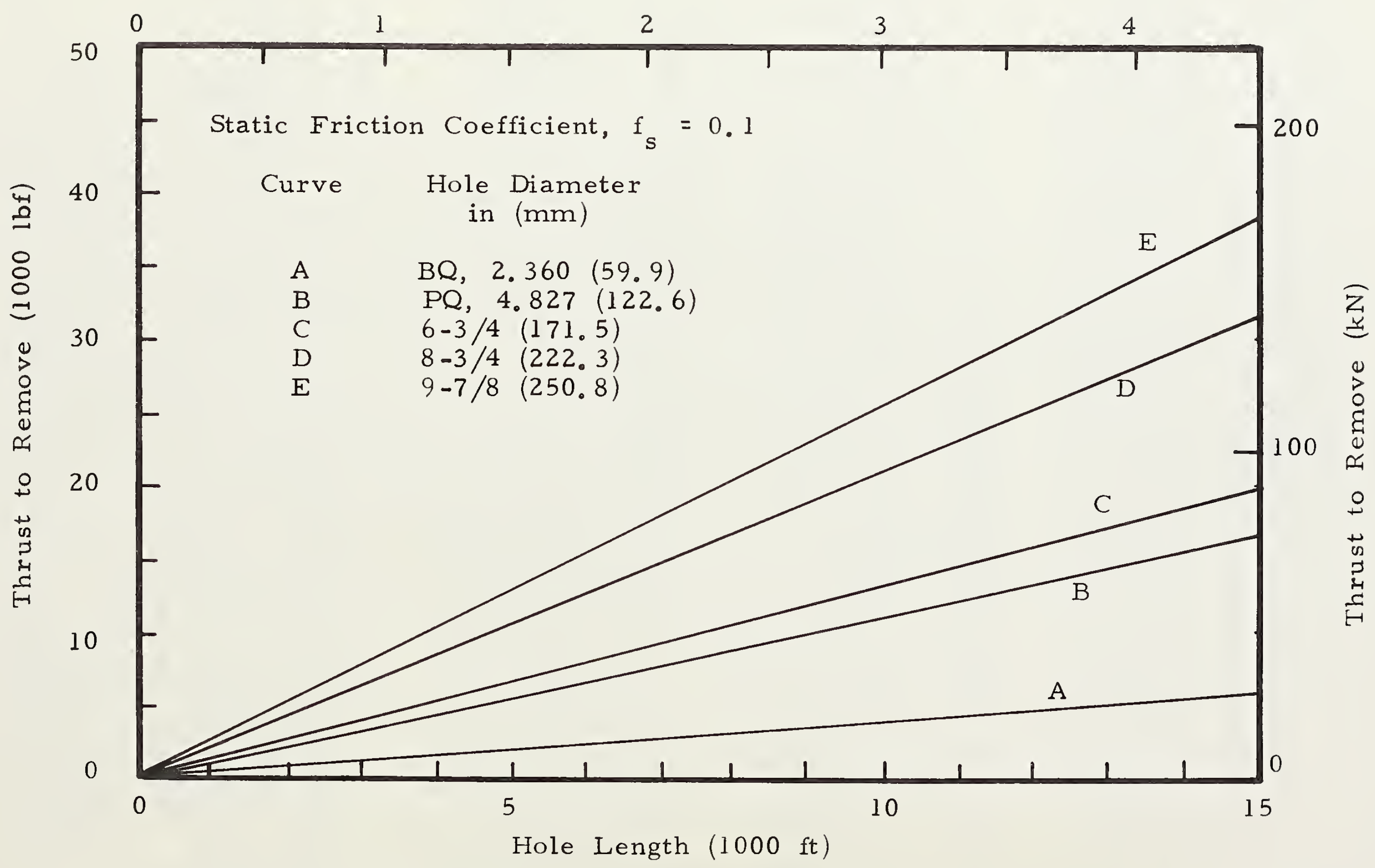


Figure A.1a - Thrust Required to Remove Drill String in Surface Drilling

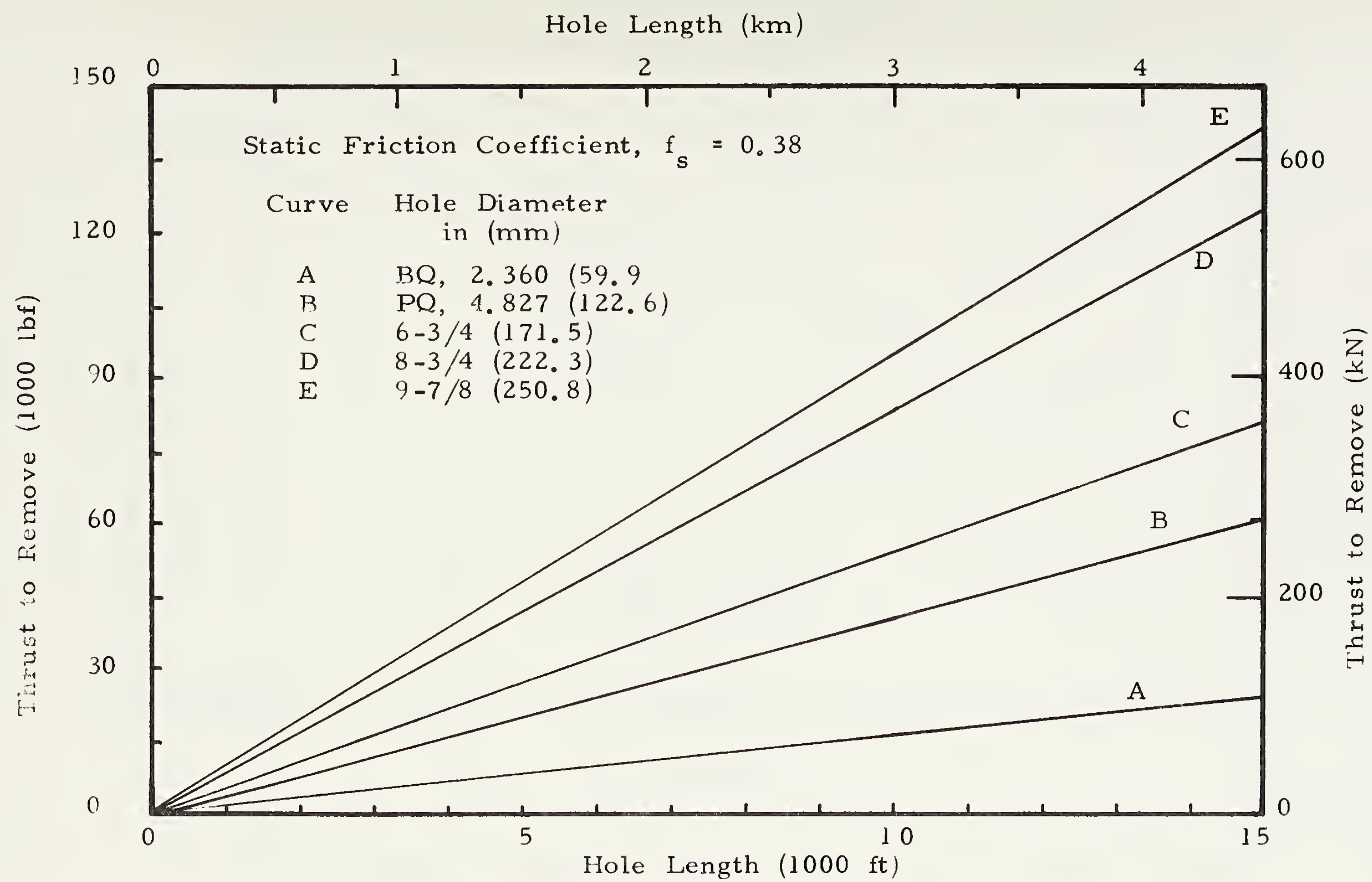


Figure A.1b - Thrust Required to Remove Drill String in Surface Drilling

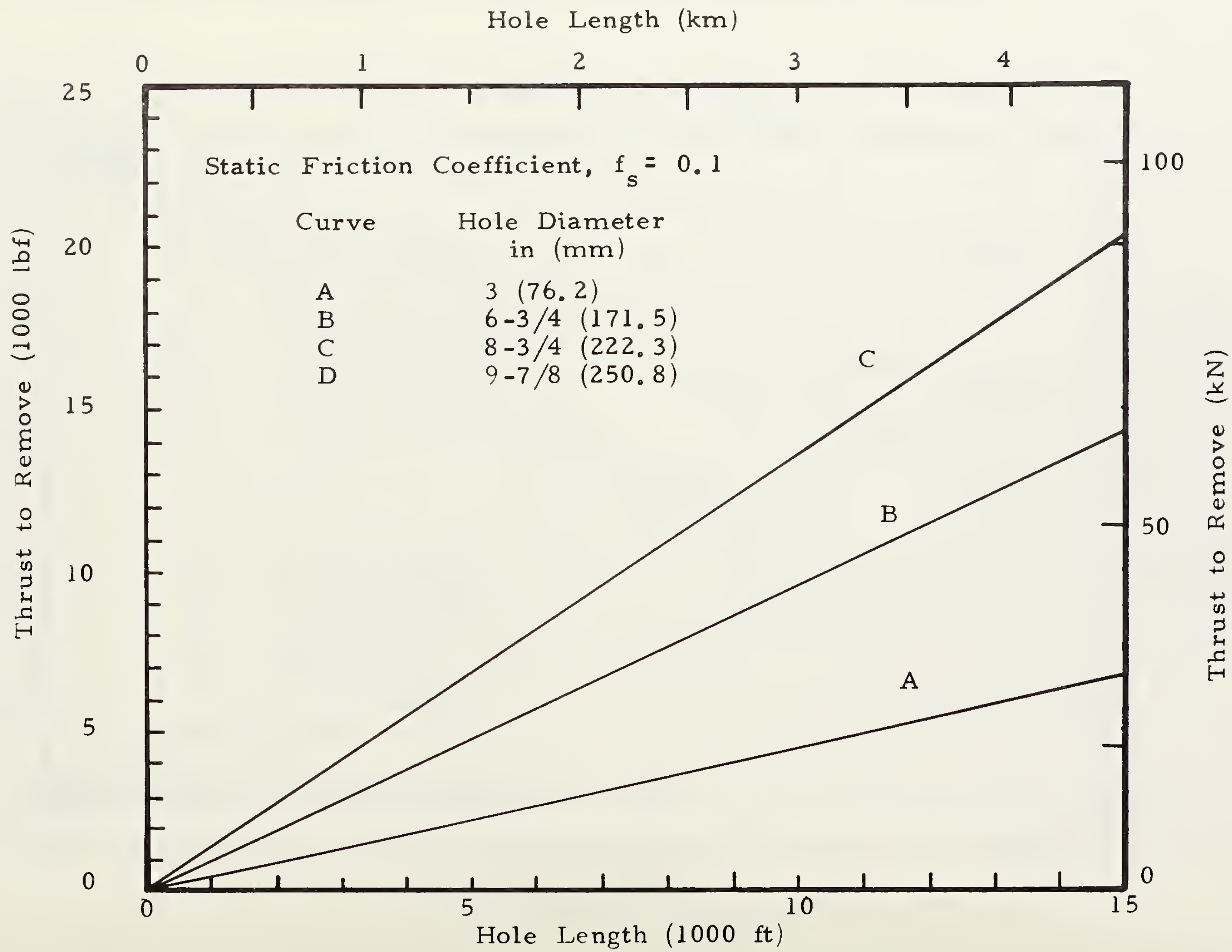


Figure A.2a - Thrust Required to Remove Drill String in Down-Hole Motor Drilling

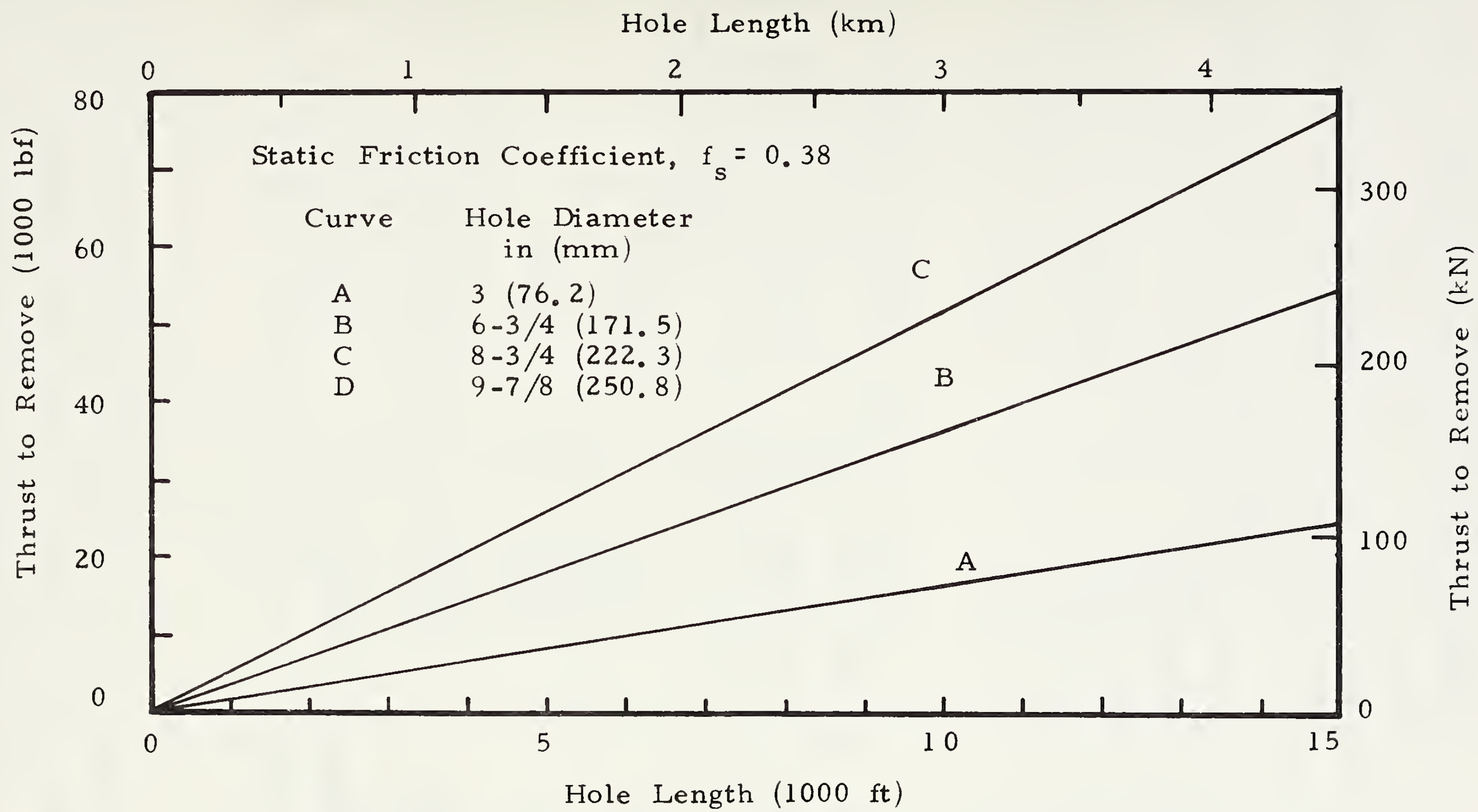


Figure A.2b - Thrust Required to Remove Drill String in Down-Hole Motor Drilling where EI is the drill string stiffness (lbf-in^2), W is the drill string weight per unit length (lbf/ft), D_h is the hole diameter (in), D_p is the drill pipe outside diameter (in), f_s is the static friction coefficient, and L is the length of the hole (ft). A static coefficient of friction is used because the drill string is not always in motion relative to the hole wall.

The surface forces required for drill string insertion for the different drilling techniques are presented as a function of hole length and hole diameter in Figures A.3 and A.4. For any given drilling technique, hole length and hole diameter, the maximum insertion force can be obtained from these curves. The surface rig should be sized to provide at least 10-20 percent more than this maximum force.

It should be noted that the required insertion force becomes infinite at some hole length. However, the drill string will fail prior to reaching this length. The length at which the drill string fails is the maximum length that the drill string can be inserted. Yield of the drill pipe under an axial load is discussed in Section 5 of this Appendix.

A.3.3 Drilling Thrust

In horizontal drilling, a certain amount of thrust must be applied at the drill bit for efficient penetration. Table A.3 presents values for this drill bit thrust, F_{bit}, required by the various drilling techniques and hole diameters. This thrust may be supplied in either of two ways - by means of a down-hole thruster or by means of a drill string driven by a surface rig.

When a down-hole thruster is used, the drill string is in tension all the time and the thruster must supply both the drill bit thrust, F_{bit}, required and the thrust required to advance the drill string. Since the drill string is in tension, the only contact force is the drill string weight and the thrust required to advance the

TABLE A.3

DRILL BIT THRUST AND TORQUE

Hole Diameter D_h, in (mm)	Type of Drill Bit	Thrust F_{BIT}, lbf (N)	Torque T_{BIT}, ft-lbf (N-m)
Surface Drilling			
BQ, 2.360 (59.9)	Diamond	5,000 (22,250)	180 (245)
PQ, 4.827 (122.6)	Diamond	12.000 (53,400)	700 (952)
6-3/4 (171.5)	Rotary	35,000 (155,750)	3,500 (4,760)
8-3/4 (222.3)	Rotary	50,000 (222,500)	5,000 (6,800)
9-7/8 (250.8)	Rotary	58,000 (258,100	5,800 (7,890)
Down Hole Motor Drilling			
3 (76.2)	Diamond	6,000 (26,700)	10 (14)
6-3/4 (171.5)	Rotary	14,000 (62,300)	400 (544)
8-3/4 (222.3)	Rotary	18,000 (80,100)	625 (850)
9-7/8 (250.8)	Rotary	20,000 (89,000)	625 (850)

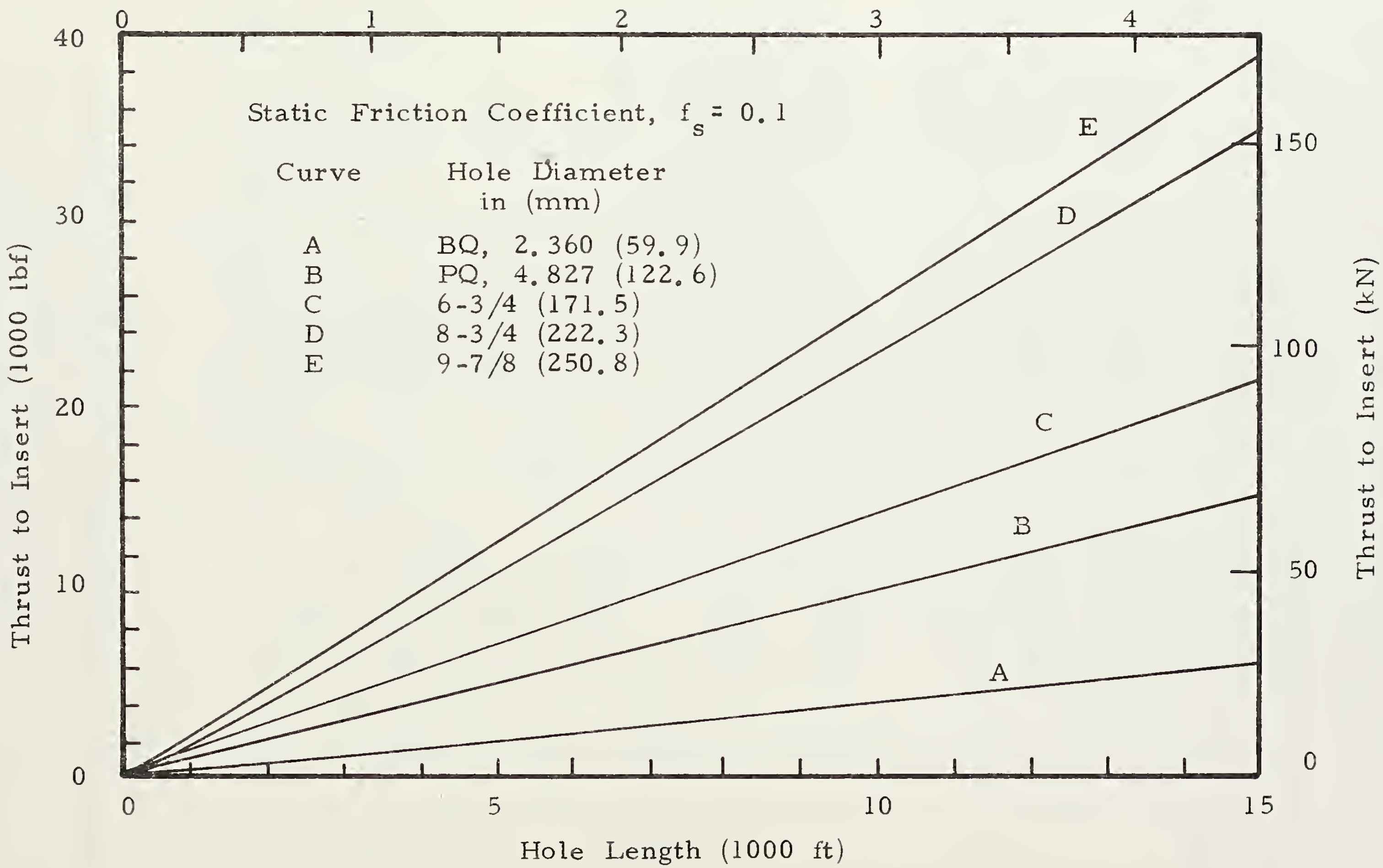


Figure A.3a - Thrust Required to Insert Drill String in Surface Drilling

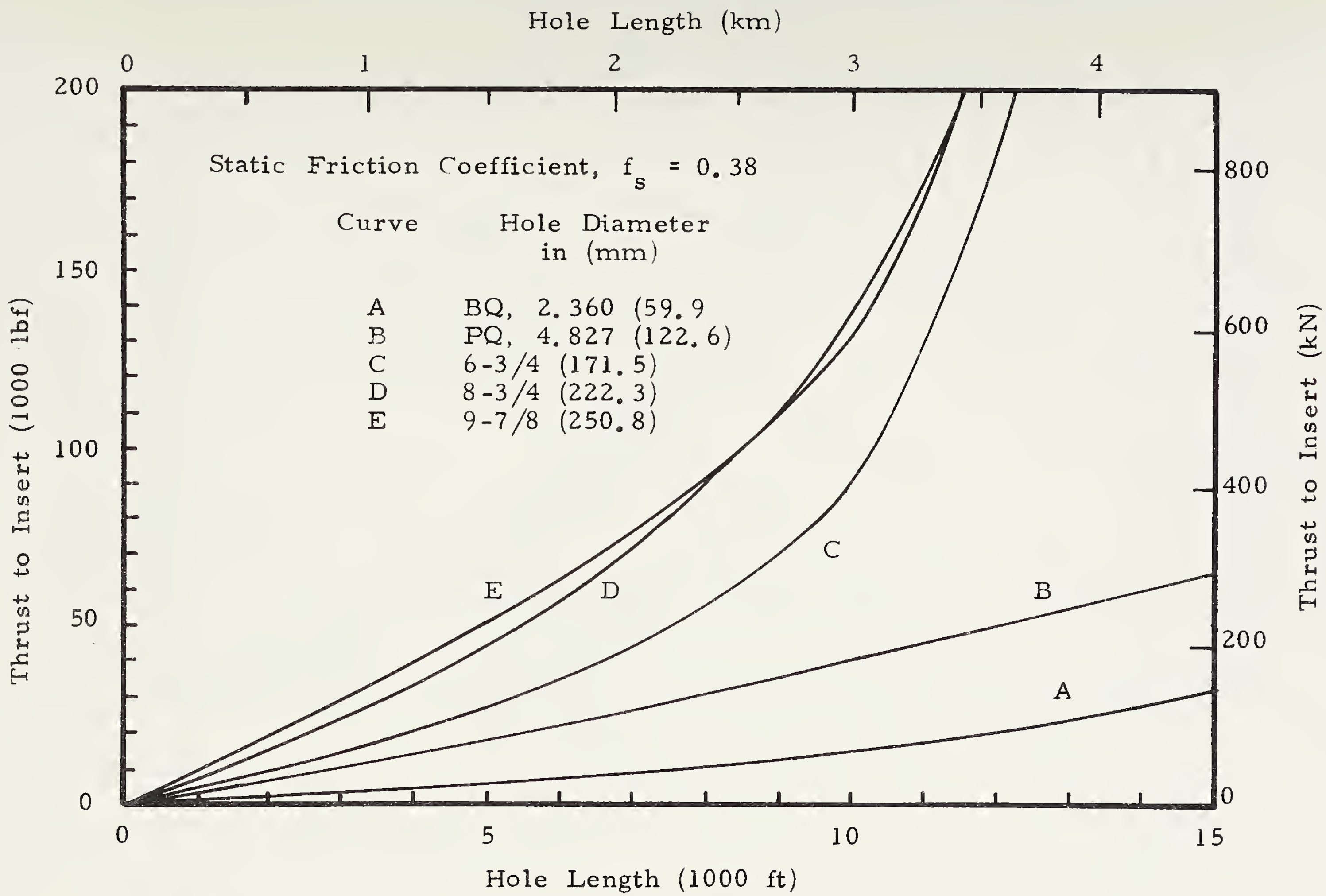


Figure A.3b - Thrust Required to Insert Drill String in Surface Drilling

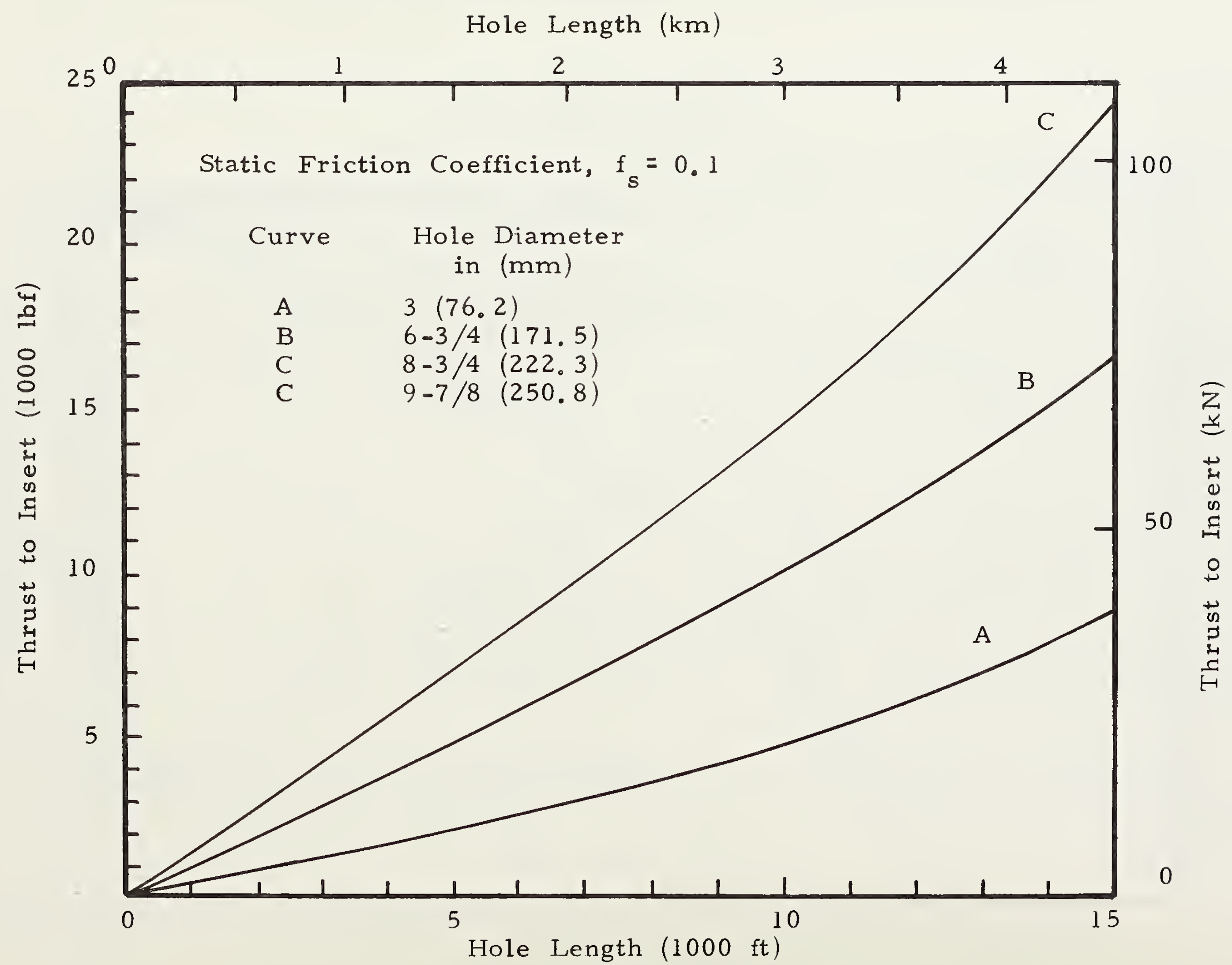


Figure A.4a - Thrust Required to Insert Drill String in Down-Hole Motor Drilling

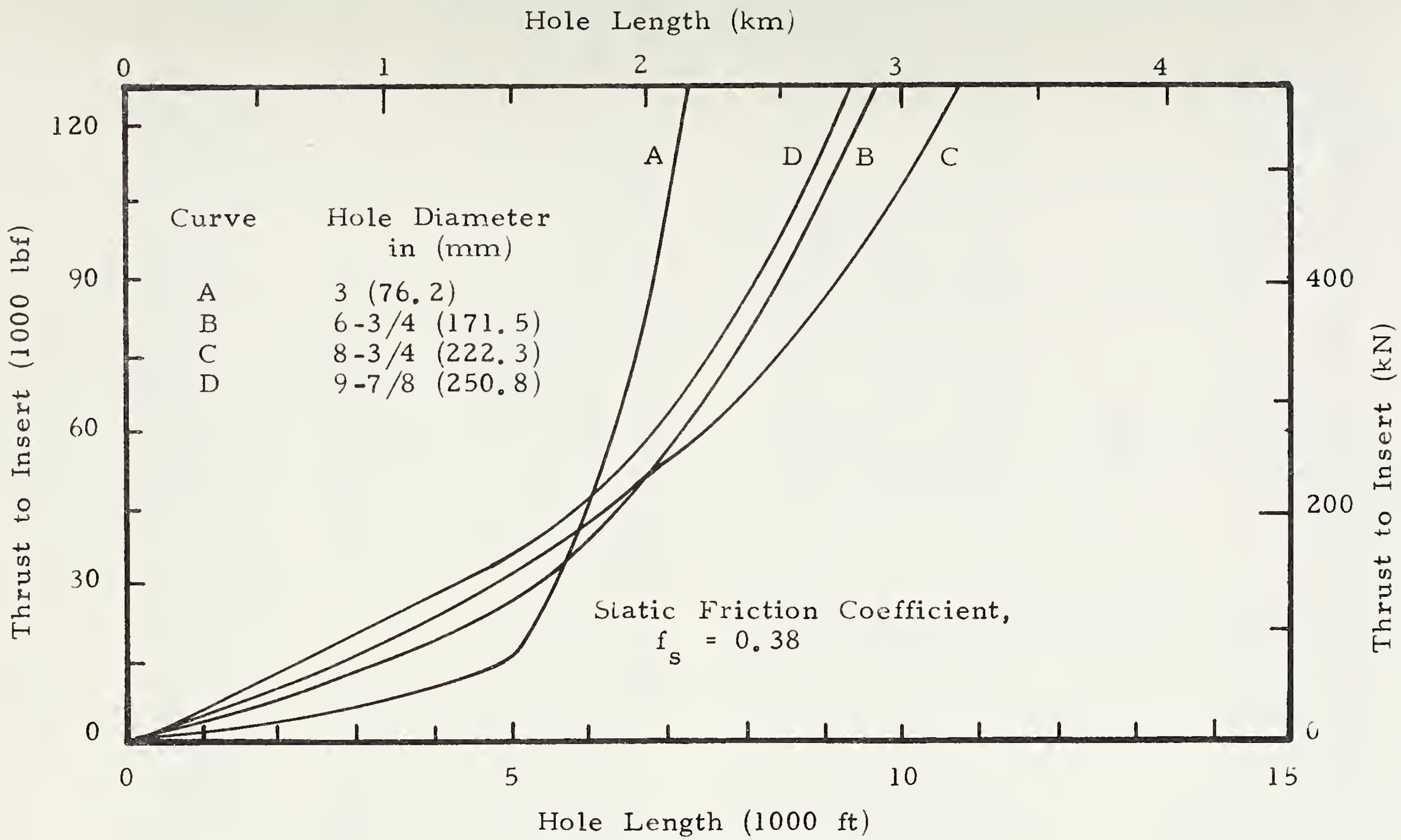


Figure A.4b - Thrust Required to Insert Drill String in Down-Hole Motor Drilling drill string may be expressed by:

$$F = f\,WL \tag{A.8}$$

where f is the coefficient of friction, W is the drill string weight per unit length (lbf/ft), and L is the hole length (ft). The total drilling thrust which must be supplied by a down-hole thruster may therefore be expressed as:

$$F_D = F_{bit} + fWL \tag{A.9}$$

The drilling thrust for each of the different drilling techniques is presented as a function of hole length and hole diameter in Figures A.5 and A.6. These figures assume a dynamic coefficient of friction for the surface drilling and a static coefficient of friction for the down-hole motor drilling. The down-hole thruster should be sized to provide at least 10-20 percent more than the required thrust obtained from these figures.

When a surface rig is used to supply the drilling thrust, the drill string is in compression. In this case, the contact force is composed of both the drill string weight and the side support force. The total thrust which must be supplied at the surface to provide the required drill bit thrust, F_{bit}, to the drill may be expressed as:

$$F_D = \left[\frac{\pi^2 EIW}{6\,(D_h - D_p)}\right]^{1/2} \tan\left\{\left[\frac{6\,(D_h - D_p)\,W}{\pi^2 EI}\right]^{1/2} fL_{eq}\right\} \tag{A.10}$$

where EI is the drill string stiffness (lbf/f-in^2), W is the drill string weight per unit length (lbf/ft), D_h is the hole diameter (in), D_p is the drill pipe outside diameter (in), f is the coefficient of friction, and L_{eq} (ft) is:

$$L_{eq} = L + L_{bit} \tag{A.11}$$

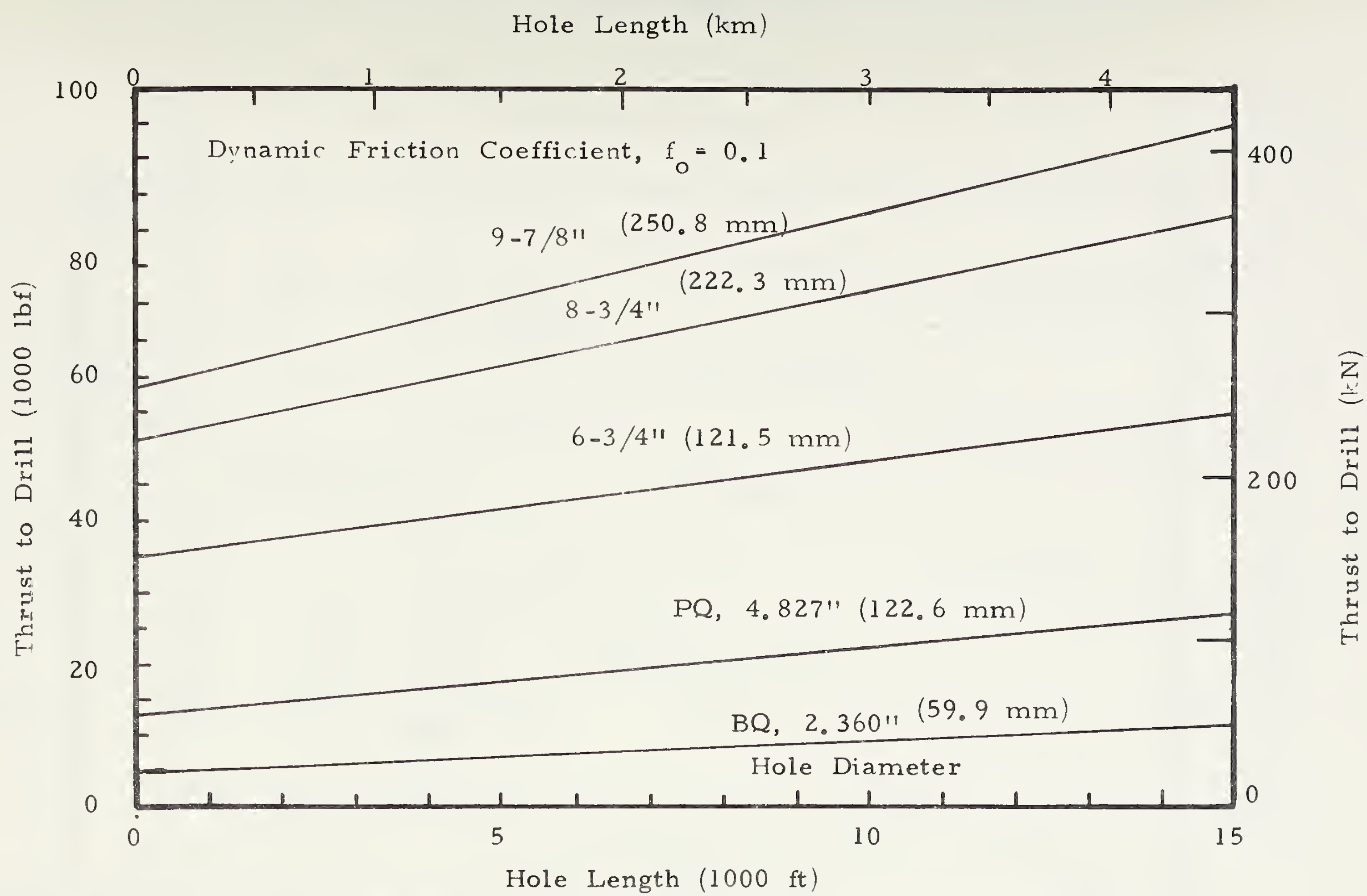


Figure A.5a - Thrust Required to Drill in Surface Drilling with a Down-Hole Thruster

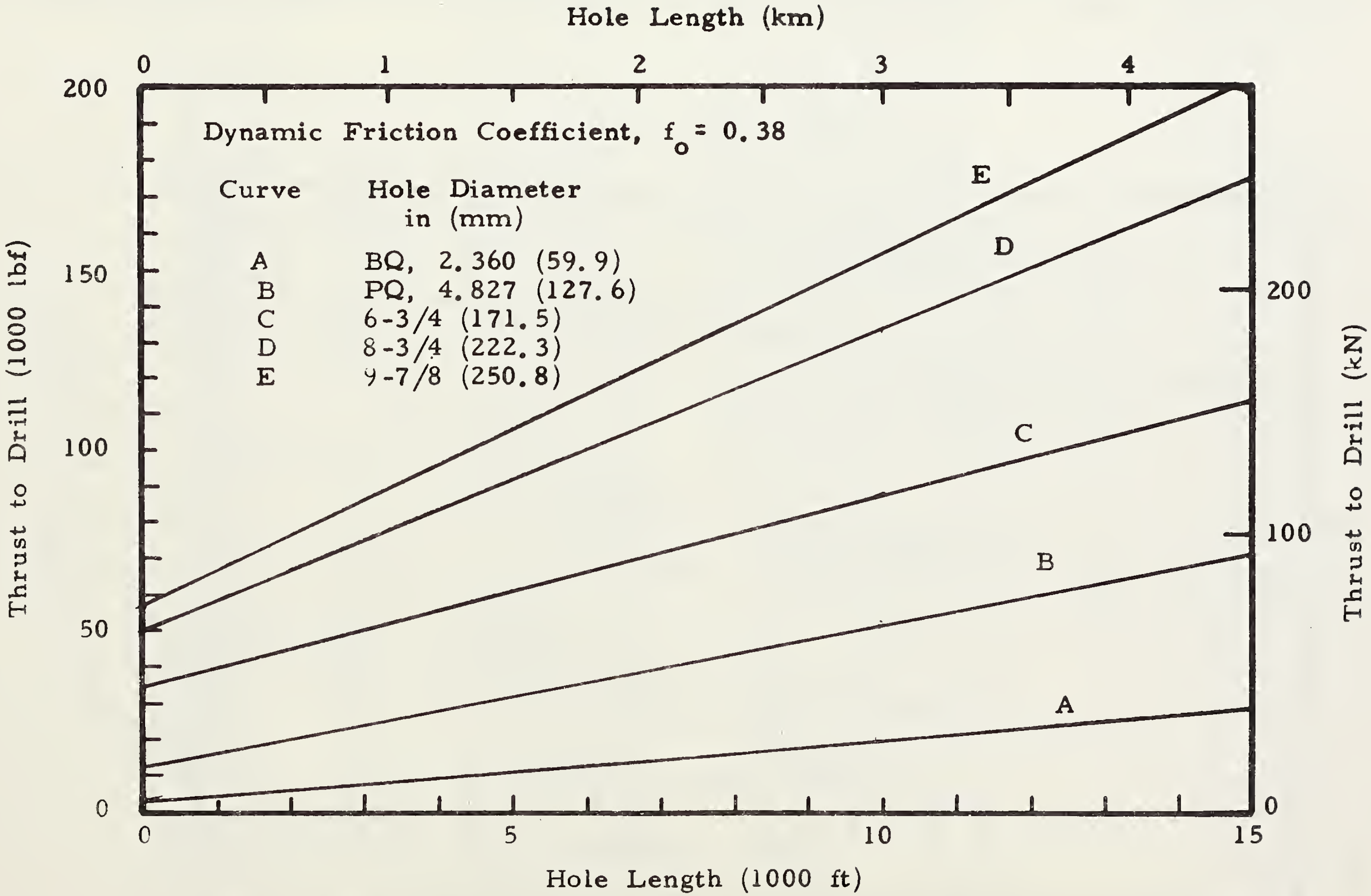


Figure A.5b - Thrust Required to Drill in Surface Drilling with a Down Hole Thruster

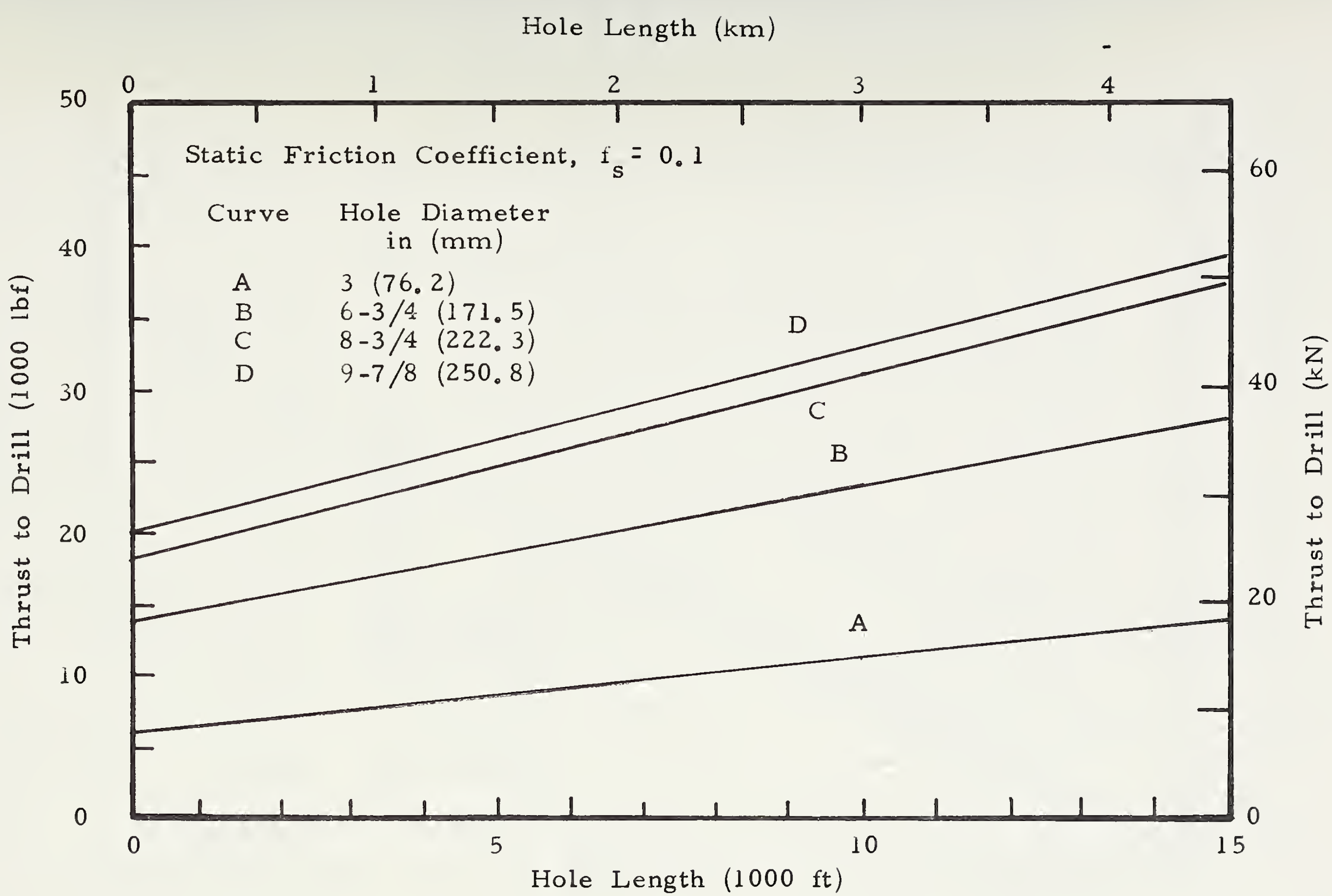


Figure A.6a - Thrust Required to Drill in Down Hole Motor Drilling with a Down Hole Thruster

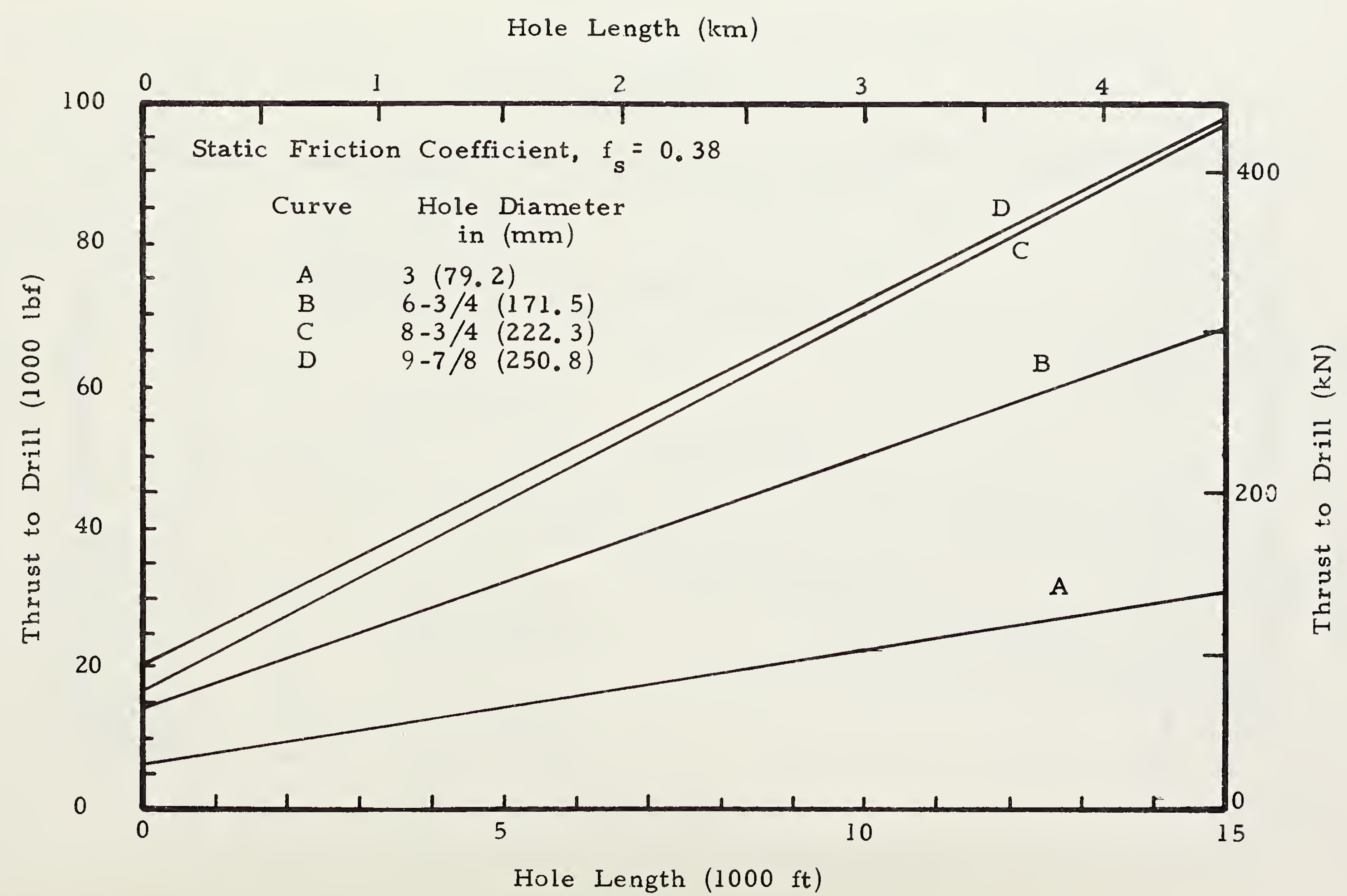


Figure A.6b - Thrust Required to Drill in Down Hole Motor Drilling with a Down Hole Thruster

where
$$L_{bit} = \left[\frac{\pi^2 EI}{6\ (D_h - D_p)\ W}\right]^{1/2} \frac{1}{f} \tan^{-1}\left\{\left[\frac{6\ (D_h - D_p)}{\pi^2 EIW}\right]^{1/2} F_{bit}\right\} \quad (A.12)$$
and L is the hole length (ft) and F_{bit} is the drill bit thrust (lbf) from Table A.3.

The drilling thrust required for each of the drilling techniques is presented as a function of hole length and diameter in Figures A.7 and A.8. These figures assume a dynamic coefficient of friction for surface drilling and a static coefficient of friction for down-hole motor drilling. For any given drilling technique, hole diameter, and hole length, the maximum drilling thrust can be obtained from these curves. The surface rig should be sized to provide at least 10-20 percent more than this maximum force.

It should be noted that the required drilling thrust becomes infinite at some hole length. However, the drill string will fail prior to reaching this length. The length at which the drill string fails is the maximum length to which the required drill bit thrust can be provided. Yield of the drill pipe under an axial load is discussed in Section 5 of this Appendix.

A.4 Analysis of Torque Requirements

In horizontal drilling, a certain amount of torque is required at the bit for efficient penetration. Table A.3 presents values for this drill bit torque, T_{bit}, required by the various drilling techniques and hole diameters. This torque may be supplied in one of two ways - by means of a down-hole motor or by means of a drill string driven by a surface rig.

When a down-hole motor is used to provide the torque, it need supply only the actual drill bit torque required. These torques are presented in Table A.3.

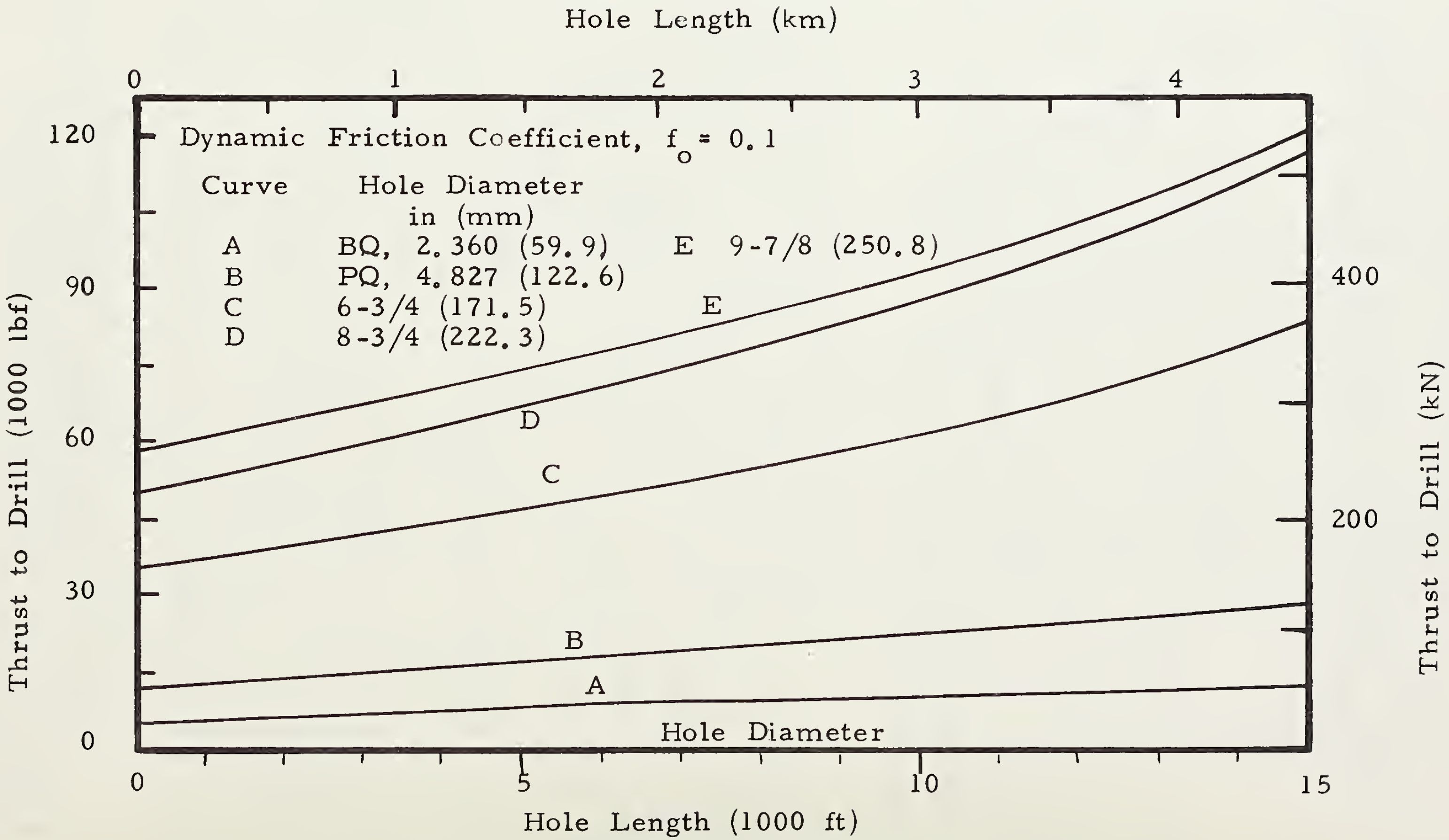


Figure A.7a - Thrust Required to Drill in Surface Drilling

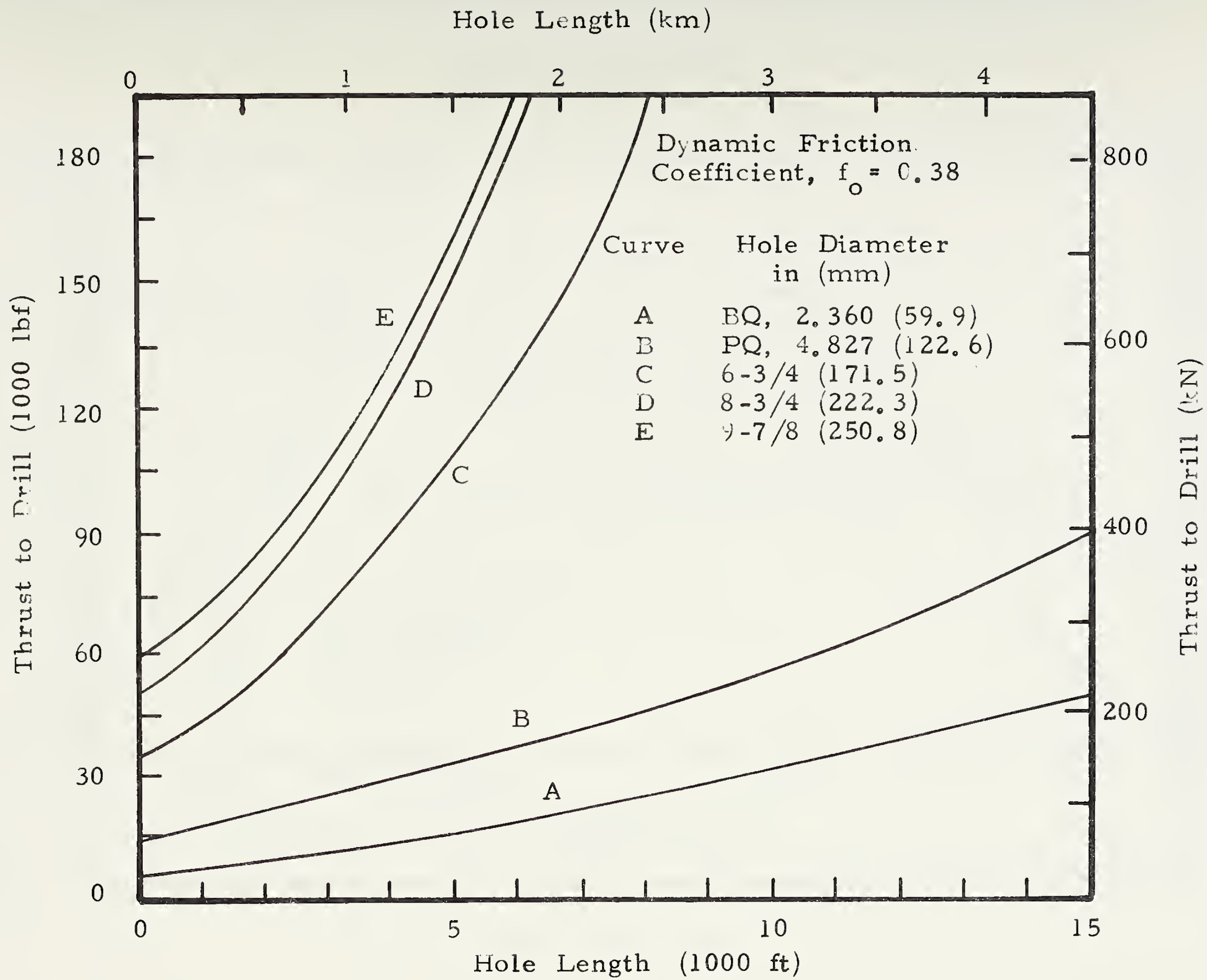


Figure A.7b - Thrust Required to Drill in Surface Drilling

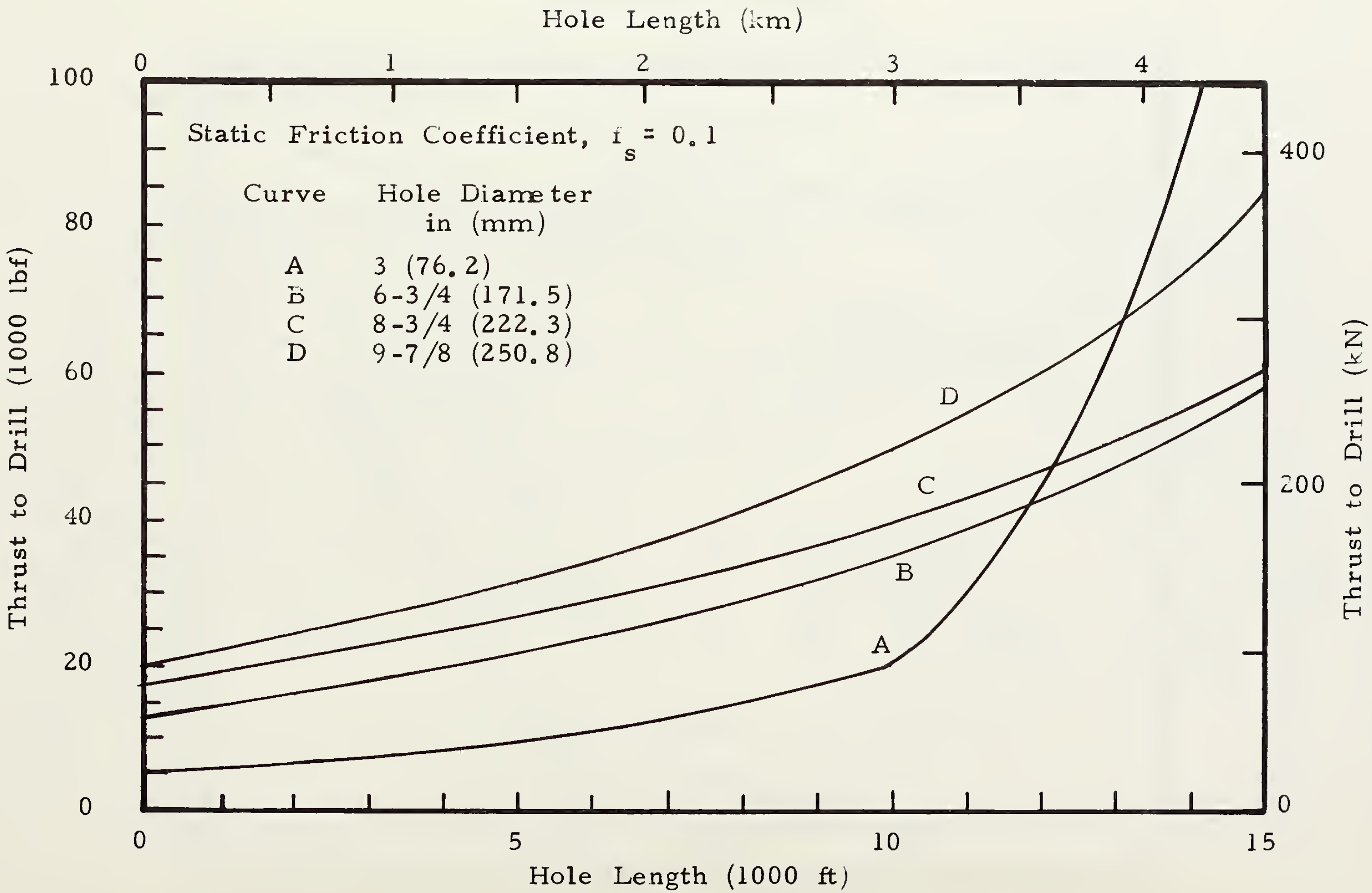


Figure A.8a - Thrust Required to Drill in Down Hole Motor Drilling

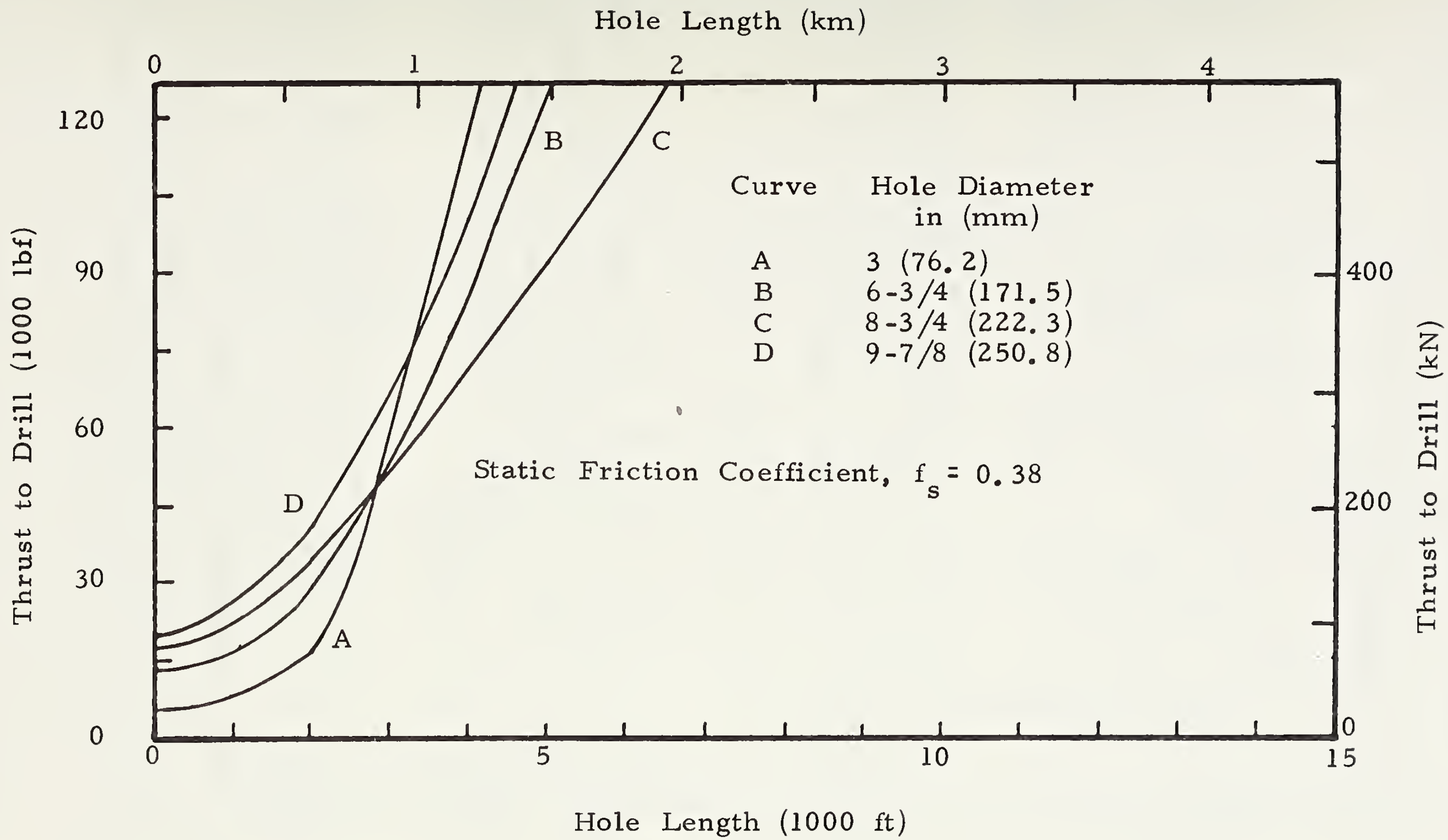


Figure A.8b - Thrust Required to Drill in Down Hole Motor Drilling

When a surface rig is used to provide the torque, it must provide not only the torque required to supply the drill bit torque, T_{bit}, but also the torque required to start the drill string rotating. The torque requirements for each of these operations are discussed below.

A. 4. 1 Drilling Torque

When a surface rig and drill string are used to provide the torque required for drilling, the surface rig must supply both the drill bit torque, T_{bit}, and the torque required due to friction along the length of the drill pipe. When drilling is taking place, there is a thrust, F_{bit}, being applied to the drill bit and depending on how this thrust is supplied, the drill string may be in tension or compression.

If a down-hole thruster is supplying the drilling thrust, then the drill string is in tension and the only drill string to hole wall contact force is that due to the weight of the drill string. In this case, the drilling torque may be expressed as:

$$T_D = T_{bit} + \frac{1}{24} f_D WLD_p \tag{A. 13}$$

where T_{bit} is the drill bit torque (ft lbf) from Table A. 3, f_D is the dynamic coefficient of friction, W is the drill string weight per unit length (lbf/ft), L is the length of the hole (ft), and D_p is the drill pipe outside diameter (in). A dynamic coefficient of friction is used because the drill string is rotating.

The torques required for drilling with a surface rig and a down-hole thruster are presented for the various drilling techniques as a function of hole length and hole diameter in Figure A. 9. For any given drilling technique, hole length, and hole diameter, the maximum drilling torque may be obtained from these curves. The surface rig should be sized to provide at least 10-20 percent more than this maximum torque.

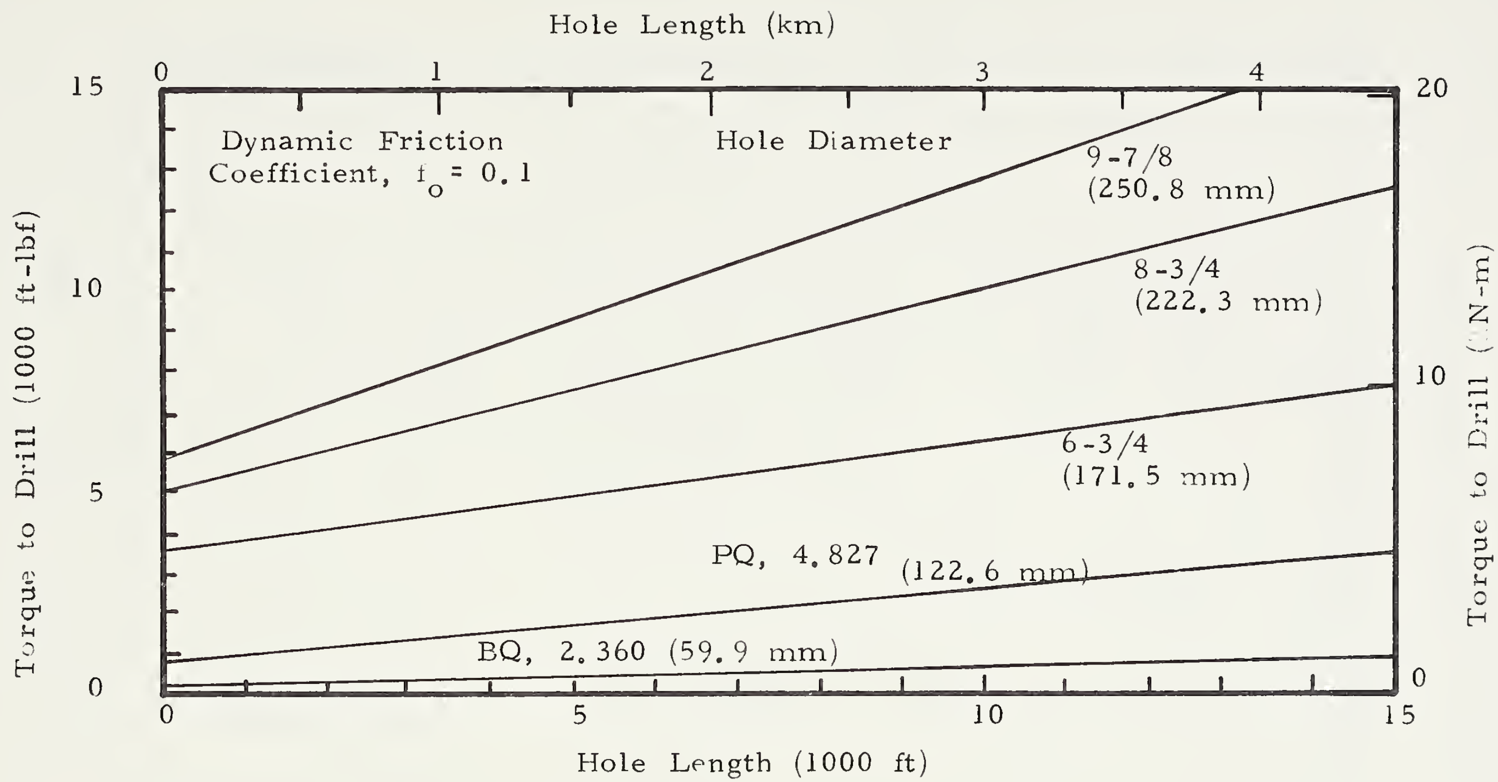


Figure A.9a - Torque Required to Drill in Surface Drilling with a Down Hole Thruster

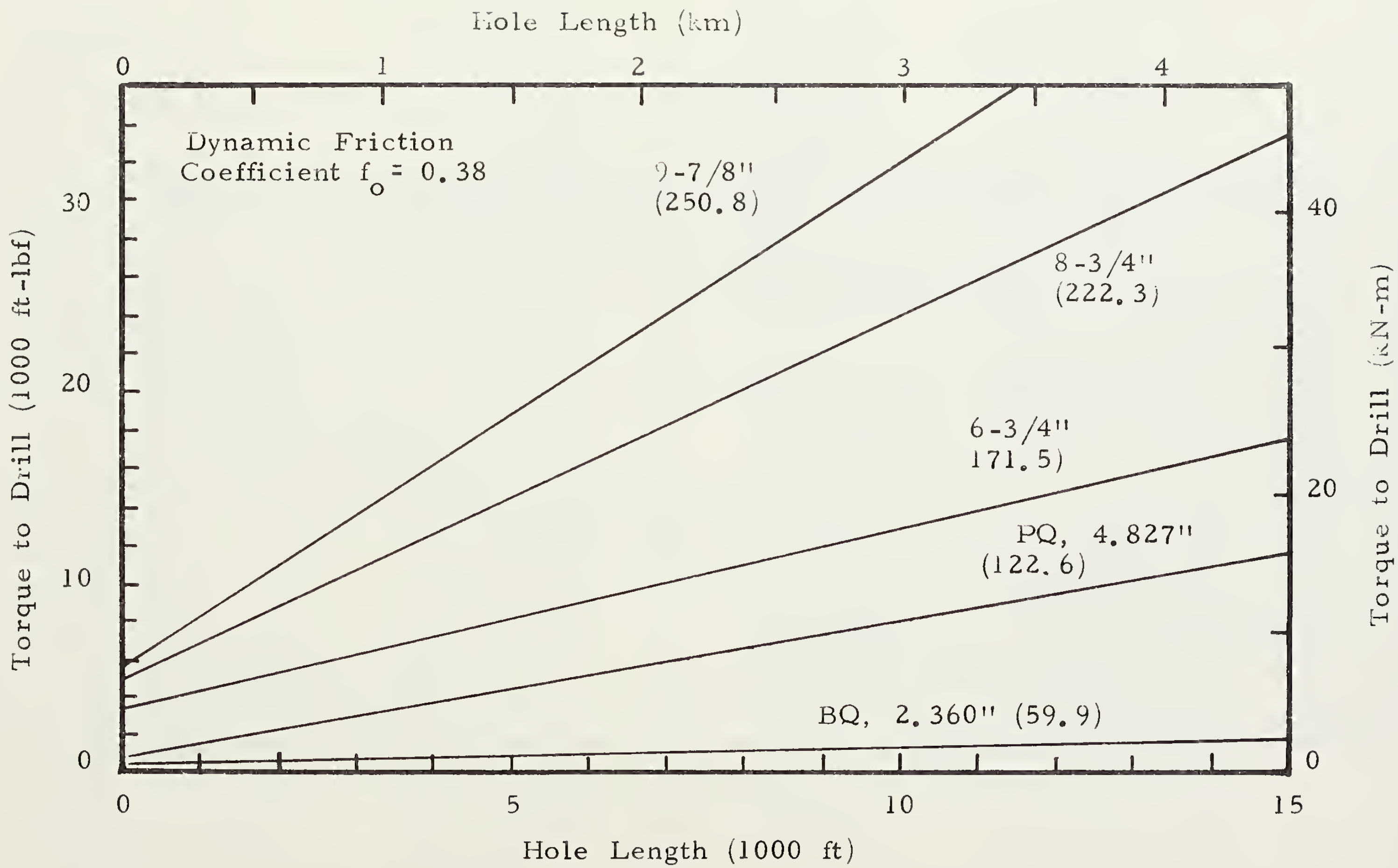


Figure A.9b - Torque Required to Drill in Surface Drilling with a Down Hole Thruster

If a surface rig is supplying the drilling thrust, then the drill string is in compression and the drill string to hole wall contact force is composed of both the drill string weight and the side support force due to buckling. In this case, the drilling torque may be expressed by:

$$T_D = T_{bit} + \frac{D_p W}{24B} \left\{ \tan\left(Bf_D L_{eq}\right) - \tan\left(Bf_D L_{bit}\right) \right\} \quad (A.14)$$

where:

$$B = \left[\frac{6(D_h - D_p)\ W}{\pi^2\ EI} \right]^{1/2}$$

$$L_{eq} = L + L_{bit}$$

$$L_{bit} = \frac{1}{Bf_D} \tan^{-1} \left(\frac{F_{bit}}{A} \right)$$

$$A = \left[\frac{\pi^2\ EIW}{6\ (D_h - D_p)} \right]^{1/2}$$

In these equations, T_{bit} is the drill bit torque (ft-lbf) from Table A.3, F_{bit} is the drill bit thrust (lbf) from Table A.2, W is the drill string weight per unit length (lbf/ft), EI is the drill string stiffness (lbf-in^2), and L is the hole length (ft). A dynamic coefficient of friction is used because the drill string is rotating.

The torques required for drilling with a surface rig are presented in Figure A.10 for the various drilling techniques as a function of hole length and hole diameter. For any given drilling technique, hole length, and hole diameter, the maximum drilling torque may be obtained from these curves. The surface rig should be sized to provide at least 10-20 percent more than this maximum torque.

It should be noted that this required drilling torque becomes infinite at some hole length. However, the drill string will fail prior to reaching this length. The length at which the drill string fails is the maximum length that the drill string can be used for drilling.

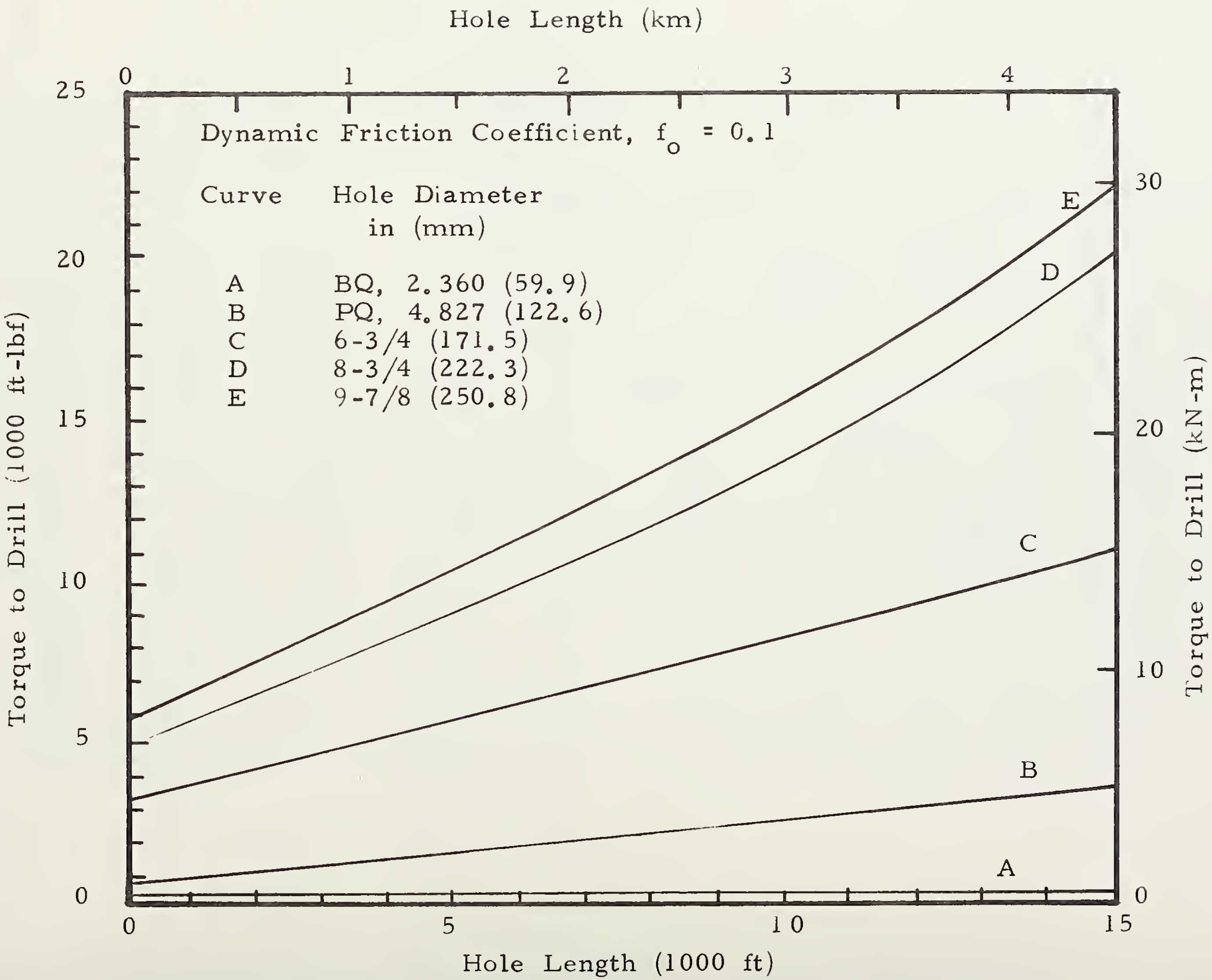


Figure A.10a - Torque Required to Drill in Surface Drilling

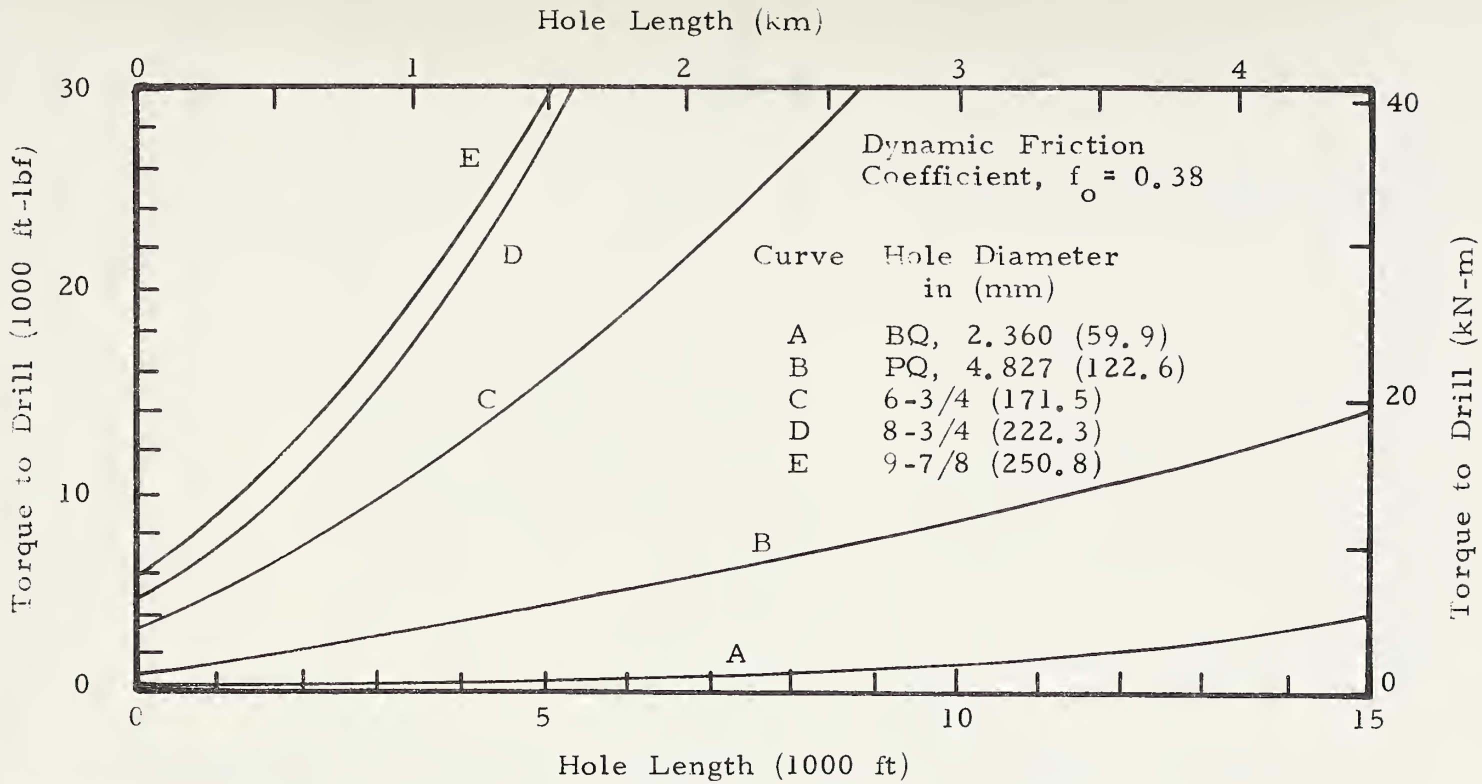


Figure A.10b - Torque Required to Drill in Surface Drilling

Yield of the drill pipe under a torsional load is discussed in Section 5 of this Appendix.

A.4.2 Torque to Start Drill String Rotating

When a surface rig and drill string are used to provide the torque for horizontal drilling operation, the surface rig must be able to supply the torque required to start the drill rod rotating. This torque is solely due to friction along the length of the drill pipe. The exact value of this spin-up torque depends on the recent history of the drill string, i.e., did it just reach the bottom, did it just stop drilling, etc.? For the purposes of this analysis, it will be assumed that the drill string has just been inserted to the bottom of the hole and will be spun-up prior to having the bit pressed against the drilling face with the required drill bit thrust.

If a down-hole thruster has been used to insert the drill string, then the drill string is in tension and the only drill string to hole wall contact force is that due to the weight of the drill string. In this case, the spin-up torque may be expressed by:

$$T_s = \frac{1}{24} f_s WLD_p \qquad \text{(A. 15)}$$

where f_s is the static coefficient of friction, W is the drill string weight per unit length (lbf/ft), L is the hole length (ft) and D_p is the drill pipe outside diameter (in). A static coefficient of friction is used because the drill string is stationary.

The torques required for drill string spin-up using a surface rig and a down-hole thruster are presented for the various drilling techniques as a function of hole length and hole diameter in Figure A.11. For any given drilling technique, hole length, and hole diameter, the maximum spin-up torque may be obtained from these curves. The surface rig should be sized to provide at least 10-20 percent more than this maximum torque.

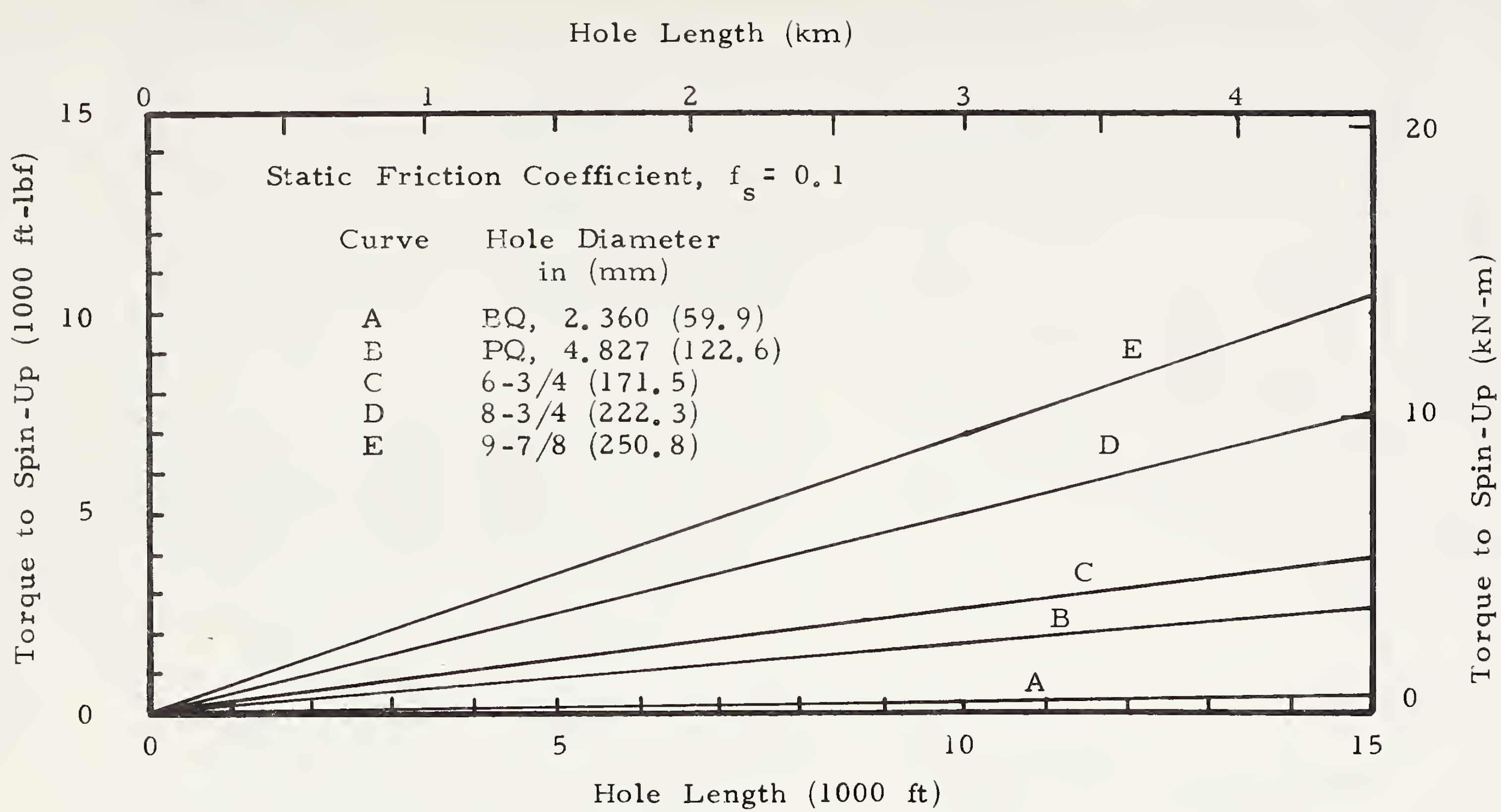


Figure A.11a - Torque Required to Spin-Up Drill String in Surface Drilling with a Down Hole Thruster

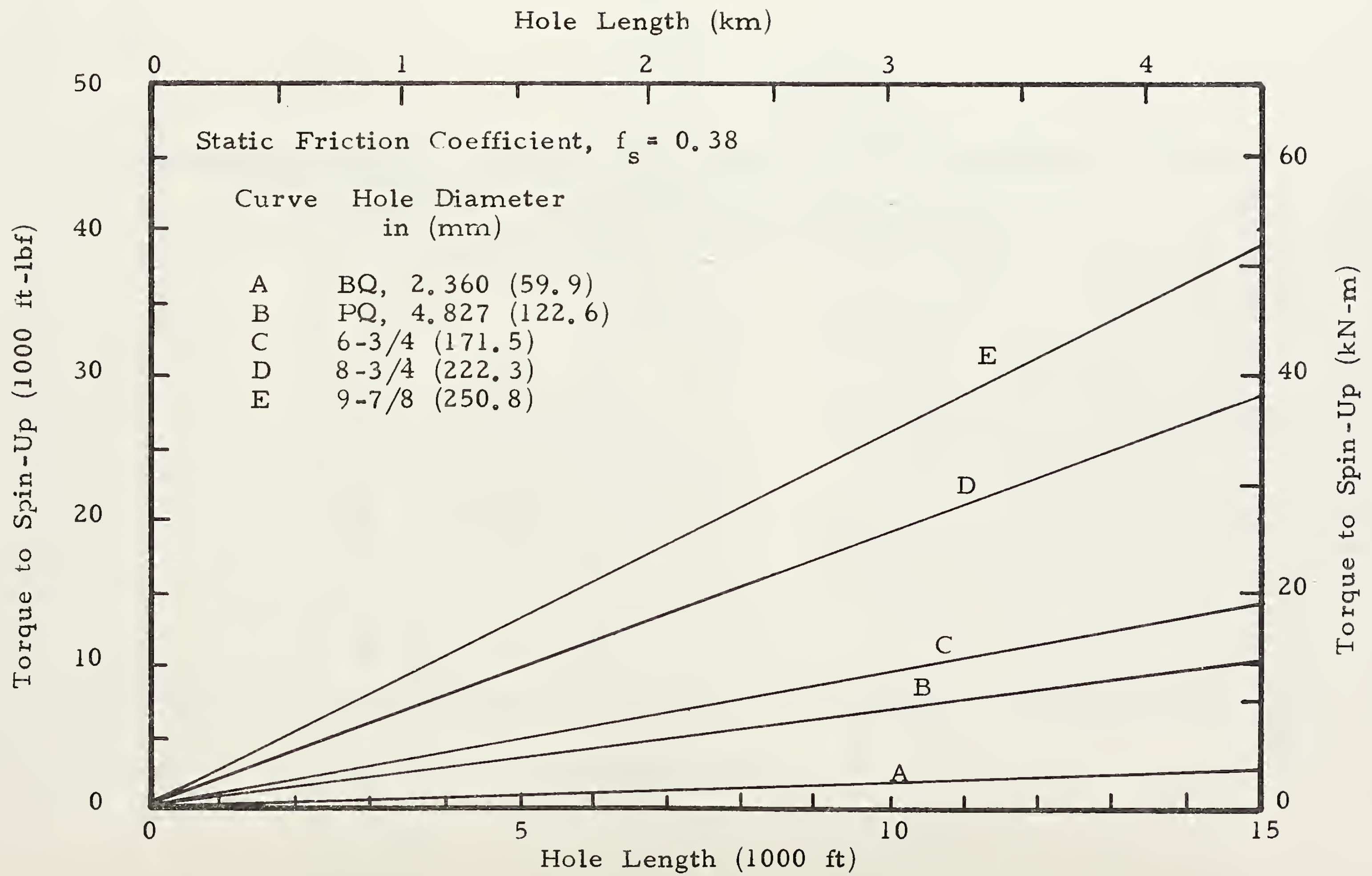


Figure A.11b - Torque Required to Spin-Up Drill String in Surface Drilling with a Down Hole Thruster

If a surface rig has been used to insert the drill string, then the drill string is in compression and the drill string to hole wall contact force is composed of both the drill string weight and the side support force due to buckling. In this case, the spin-up torque may be expressed by:

$$T_s = \frac{D_p W}{24B} \tan (Bf_s L) \qquad (A.16)$$

where $$B = \left[\frac{6(D_h - D_p)W}{\pi^2 EI} \right]^{1/2}$$

and D_p is the drill pipe outside diameter (in), W is the drill string weight per unit length (lbf/ft), f_s is the static coefficient of friction, L is the hole length (ft), D_h is the hole diameter (in), and EI is the drill string stiffness (lbf-in^2). A static coefficient of friction is used because the drill string is stationary.

The torques required to spin-up the drill string using a surface rig are presented for the various drilling techniques as a function of hole length and hole diameter in Figure A.12. These figures assume a static coefficient of friction. For any given drilling technique, hole length, and hole diameter, the maximum spin-up torque may be obtained from these curves. The surface rig should be sized to provide at least 10-20 percent more than this maximum torque.

It should be noted that the required spin-up torque becomes infinite at some hole length. However, the drill string will fail prior to this. The maximum length at which a surface rig can be used to spin-up the drill string is determined by the length at which the drill string fails. Yield of the drill pipe under a torsional load is discussed in Section 5 of this Appendix.

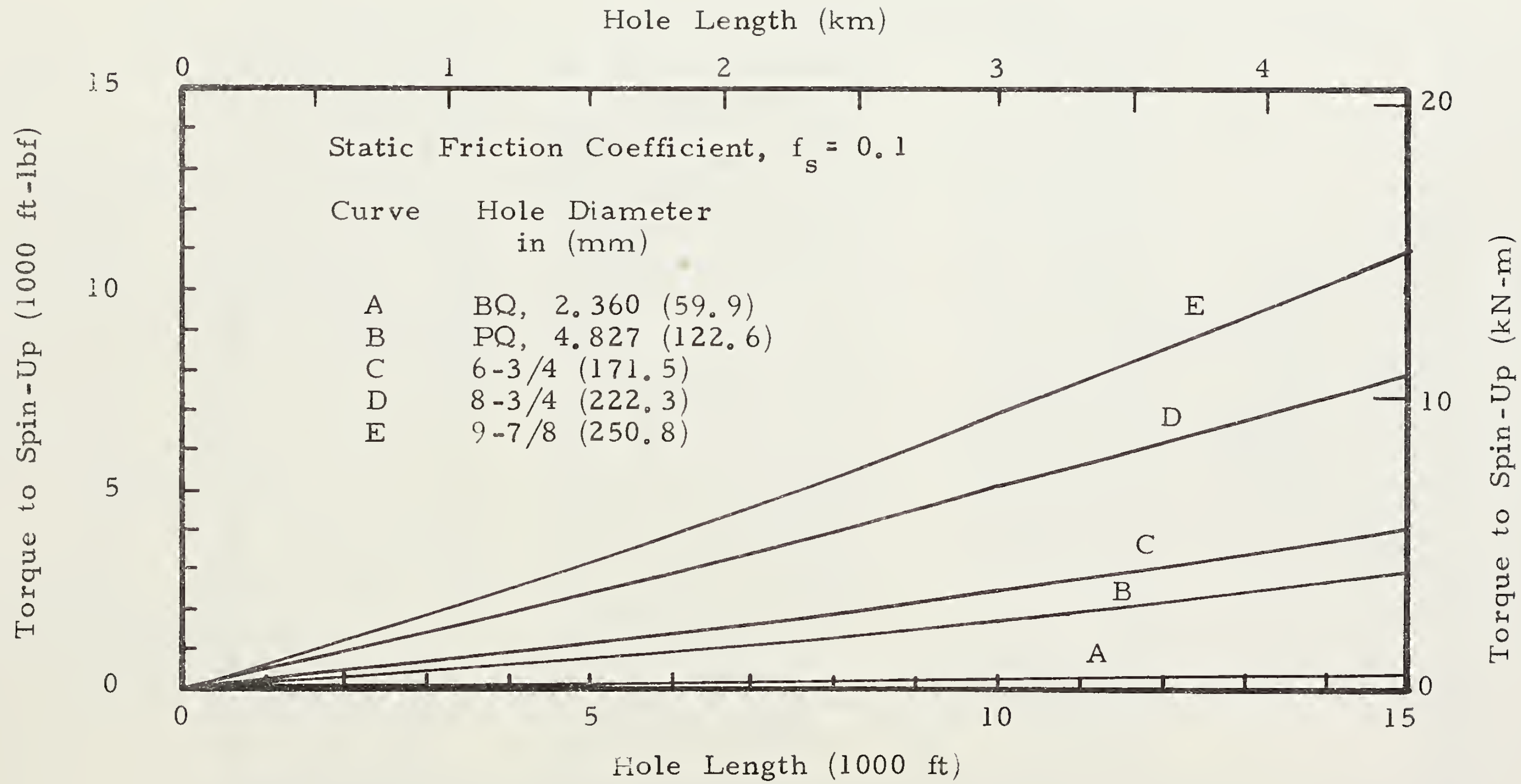


Figure A.12a - Torque Required to Spin-Up Drill String in Surface Drilling

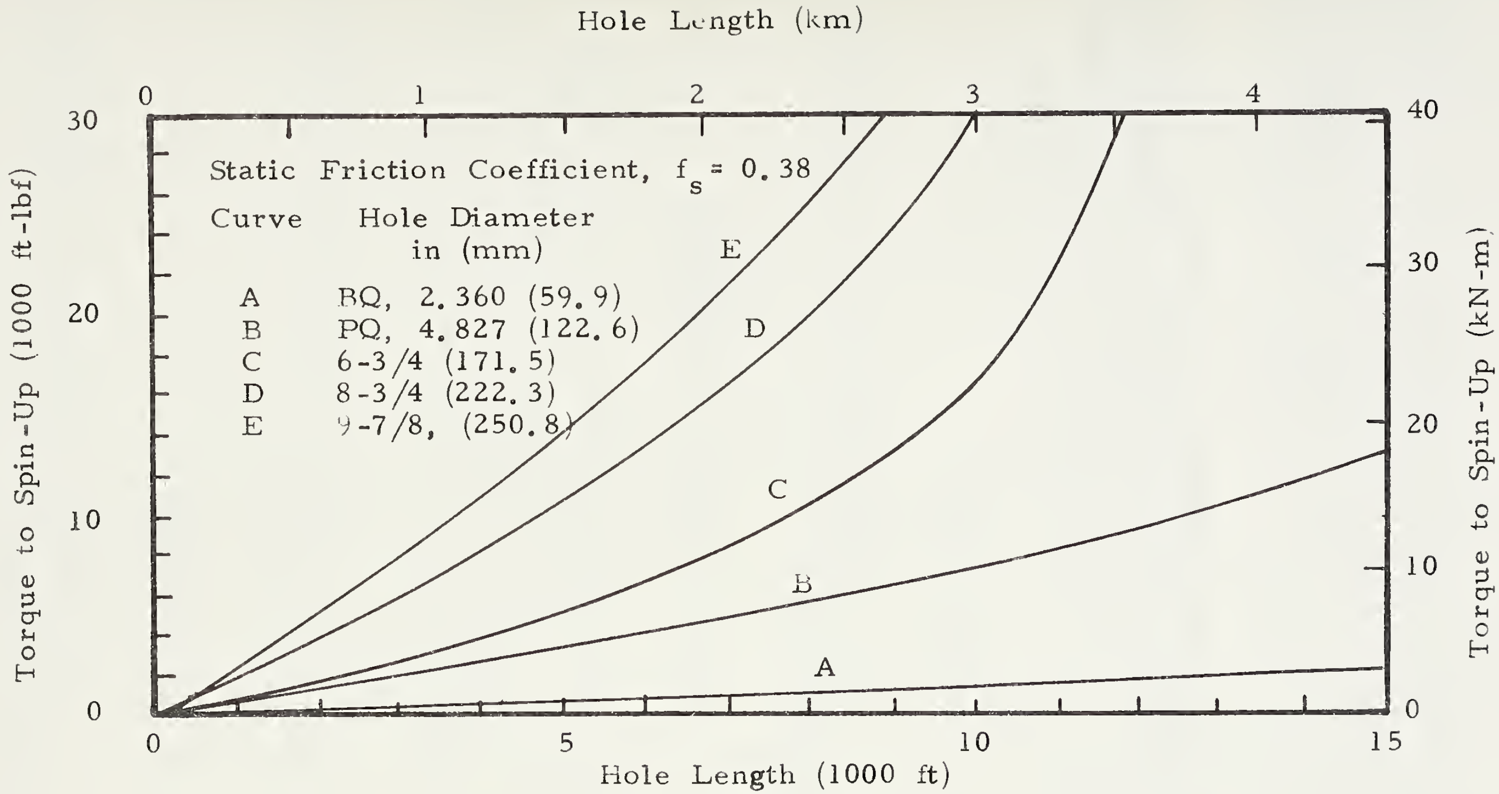


Figure A.12b - Torque Required to Spin-up Drill String in Surface Drilling

A.5 Analysis of Drill String Failure Due to Yield

Previous sections of this Appendix have dealt with the thrusts and torques which are required to perform the various operations which are necessary to drill a horizontal hole. None of these sections were concerned with the ability of the drill string to withstand these thrusts and torques. In fact, the major factor limiting penetration capability in horizontal drilling is the strength of the drill string.

Depending on the drilling technique being employed, the strength of the drill rod may be first exceeded by either excessive thrust or excessive torque. This section analyzes the maximum thrust and the maximum torque which the drill string is capable of handling.

A.5.1 Thrust Limits

The maximum thrust which a drill string is capable of handling may be expressed by:

$$F_{max} = \frac{\pi}{4} D_p^2 \left[1 - \left(\frac{D_i}{D_p}\right)^2\right] \frac{Y}{S} \qquad \text{(A. 17)}$$

where D_p is the drill pipe outside diameter (in), D_i is the drill pipe inside diameter (in), Y is the drill pipe yield stress (lbf-in^2), and S is a safety factor. Values of the yield stress, for the drill pipe used by the different drilling techniques are presented in Table A. 1.

Table A.4 presents values of the maximum thrust for the drill pipe used by the various drilling techniques and hole diameters. This table assumes a safety factor of 2.5.

A.5.2 Torque Limits

The maximum torque which a drill string is capable of handling may be expressed by:

$$T_{max} = \frac{\pi}{192} D_p^{3} \left[1 - \left(\frac{D_i}{D_p} \right)^4 \right] \frac{Y}{2S} \qquad \text{(A. 18)}$$

where D_p is the drill pipe outside diameter (in), D_i is the drill pipe inside diameter (in), Y is the drill pipe yield stress (lbf-in^2), and S is a safety factor. Values of the yield stress, Y, for the various drill pipes are presented in Table A. 1.

Table A. 4 presents values of the maximum torque for the drill pipe used by the various drilling techniques and hole diameters. This table assumes a safety factor of 2. 5.

TABLE A.4

MAXIMUM SAFE DRILL PIPE THRUSTS AND TORQUES

Hole Diameter D_n, in (mm)	Maximum Thrust* F_{MAX}, lbf (N)	Maximum Torque* T_{MAX}, ft-lbf (N-m)
Surface Drilling		
BQ, 2.360 (59.9)	37,700 (167,800)	1,450 (1,970)
PQ, 4.827 (122.6)	94,000 (418,000	8,000 (10,900)
6-3/4 (171.5)	108,000 (481,000)	8,980 (12,200)
8-3/4 (222.3)	174,500 (776,500)	17,580 (23,900)
9-7/8 (250.8)	195,800 (871,300)	24,460 (33,300)
Down Hole Motor Drilling		
3 (76.2)	24,240 (107,900)	1,010 (1,400)
6-3/4 (171.5)	77,720 (345,900)	4,900 (6,670)
8-3/4 (222.3)	108,000 (481,000)	8,980 (12,200)
9-7/8 (250.8)	108,000 (481,000)	8,980 (12,200)

* Safety Factor S = 2.5

APPENDIX B.

LIMITATIONS OF CONVENTIONAL HORIZONTAL DRILLING

B.1 Introduction

Conventional horizontal drilling techniques apply force to the bit from the surface through the drill spring. Thus, the drill string itself is always in compression.

Experience in vertical drilling has established, almost as a dogma, that a drill string must always be operated in tension. Weight on the bit is applied through heavy drill collars directly behind the bit. Drilling forces are balanced so that the drill string supports about 25% of the weight of the drill collars. Thus the string itself is always in tension.

Brantly, in his handbook, repeatedly emphasizes the danger of using the drill string in compression.[12] He quotes the results of early drilling in the mid-continent area. At this time it was the practice to use only one ton of drill collar to 15 tons of weight on the bit. He states:

> "This subjected the relatively thin wall of the drill pipe in the bottom of the string to excessive movements and motions, which, together with excessive pressure caused metal fatigue. promoted corrosion and eventually caused fatigue failure."..."It may readily be understood from this procedure why the useful life of drill pipe in these areas was so brief in relation to the feet of hole drilled. Many strings of pipe were junked after only five or ten thousand feet of hole had been drilled with them, and 25,000 to 30,000 feet was considered excellent service. Such performance was entirely too brief and costly in view of the possible useful life of the tool. Where adequate drill collars were used, and by 'adequate' is meant sufficient drill collars that all the weight on the bit was in the drill collars, with sufficient amount above to hold the drill pipe in tension, the useful life of a string of drill pipe was doubled or tripled."[12]

Problems of drill string stability, and directional control, can also be traced to the operation of the drill string in compression, yet in horizontal drilling, the practice continues. There does not seem to be a practical alternative available at present.

B.2 Summary

This study explores the problems of operating the drill string in compression. It uses the buckling of the drill string as the test criteria, and establishes that there is a critical length, which can be calculated, beyond which the drill string cannot function.

It projects this length to be in the order of 5,000 feet for hard rock, and possibly 7,000 to 10,000 feet in softer materials.

Although the study recognizes the possibility of earlier limitations due to secondary failures, it does not address itself to them. It concludes that "The full potential of horizontal drilling cannot be achieved by conventional techniques."

B.3 Compressive Forces on the Drill String

The linear forces acting on the drill string are:

- The force delivered to the bit, $F_o = CD$
- Fluid pressure forces, F_p
- Friction forces, WLf
- Buckling forces delivered as friction, F_B
- Fotal force = $F_T = F_o + F_p + (WL + F_B)f$

Euler's long column buckling formula is:

$$1 = \left(\frac{EA}{F_T}\right)^{1/2} K \qquad \text{(B.1)}$$

where:

l = the buckling length - inches

E = modulus of elasticity - 30×10^6 PSI

A = the structural area

K = least radius of gyration, $\left(\frac{D_o^2 + D_i^2}{8}\right)^{1/2}$

W = weight - pounds/ft

L = Length in feet

f = Coefficient of friction

C = The Bit Load in Pounds Per Inch of Diameter

When the drill string is loaded to buckling, the number of pressure points will be

$$n = \frac{L}{l} \tag{B.2}$$

for increased friction due to loading to be significant, n will have to be a large number. Thus, although n should only assume integer values, little error is introduced if equation (B.2) is taken to be a continuous function.

When the drill string buckles, it will apply force to the wall of the borehole at the pressure point. This will be seen as added frictional weight. $F_B = n \sin F_T \qquad \sin = \frac{D_h}{l}$ (B.3)

Thus by combining B.1, B.2, and B.3

$$F_B = \frac{LF_T D_h}{l^2} = \left(\frac{LF_T^2 D_h}{K^2 EA}\right) \tag{B.4}$$

$$F_B = \frac{12LD_h}{K^2EA}\left[F_B f + (WLf + F_o + F_p)\right]^2$$

Let

$$X = F_B^{1/2}$$

$$C_1 = \left(\frac{12LD_h}{K^2EA} \right)^{1/2}$$

$$C_2 = WLf + F_o + F_p$$

Then, by taking the square root of (B.4) and rearranging

$$C_1 fx^2 - X + C_1 C_2 = 0$$

$$X = \frac{1}{2C_1 f} \left(1 \pm \sqrt{1 - C_1{}^2 C_2 f} \right)$$

or

$$F_B = \frac{K^2EA}{48LD_h f} \left(1 - \sqrt{1 - \frac{12LD_h}{K^2EA} \left(WLf + F_o \; 3 \; F_p\right)} \right)^2 \qquad \text{(B.5)}$$

Since F_B must equal zero, when L = 0 the minus sign in front of the radical is selected.

It can be seen that F_B becomes complex when the negative term inside the radical becomes greater than one. This would be the point where the frictional drag due to buckling becomes so great that the drill string can no longer transmit the force required for drilling.

Most of the parameters can be expressed empirically as direct functions of the size of the borehole. Other studies have developed the following empirical formulas.

$W = .86D_h^{1.44}$ pounds/foot

$F_o = 2000D_h$ pounds, force on the bit

$D_o = .6D_h$ inches, outside diameter of drill string.

$D_i = .425D_h^{1.11}$ inches, inside diameter of drill string

$K^2 = \dfrac{D_o^{\,2} + D_i^{\,2}}{8} = .31D_h^{1.39}$ in.^{2}, square of least radius of gyration

$A = \frac{\pi}{4}(D_o^{\,2} + D_i^{\,2}) = .207D_h^{1.39}$ in.^{2}, cross sectional area

The curves for K^2 and A are shown in Figure B.1. The pressure force, F_p, has two components.

- o The pressure force due to flow in the drill string

  $F_D = P_D A_i$

- o The pressure force due to the return flow in the annulus between the drill string and the hole

  $F_a = P_a A_n$

The return flow in the drill string is taken to be 150 ft./min.

$$P_a = \frac{1.52 \times 10^{-6} V^{1.86} L}{(D_h - D_o)^{1.14}} = \frac{4.8 \times 10^{-2} L}{D_h^{1.14}}$$

$$F_a = P_a A_n = 4.82 \times 10^{-2} \frac{\pi}{4} \frac{D_h^{\,2} L}{D_h^{1.14}} = 3.79 \times 10^{-2} D_h^{.86} L$$

$$P_D = 1.52 \times 10^{-6} \frac{\left(150 \frac{A_a}{A_i}\right) L^{1.86}}{(D_i)^{1.14}} = \frac{1.59L}{D_h^{1.49}}$$

Thus

$$F_D = .159 \times \frac{\pi}{4} \frac{(.425D_h^{1.11})^2 L}{D_h^{1.49}} = .125D_h^{.73} L$$

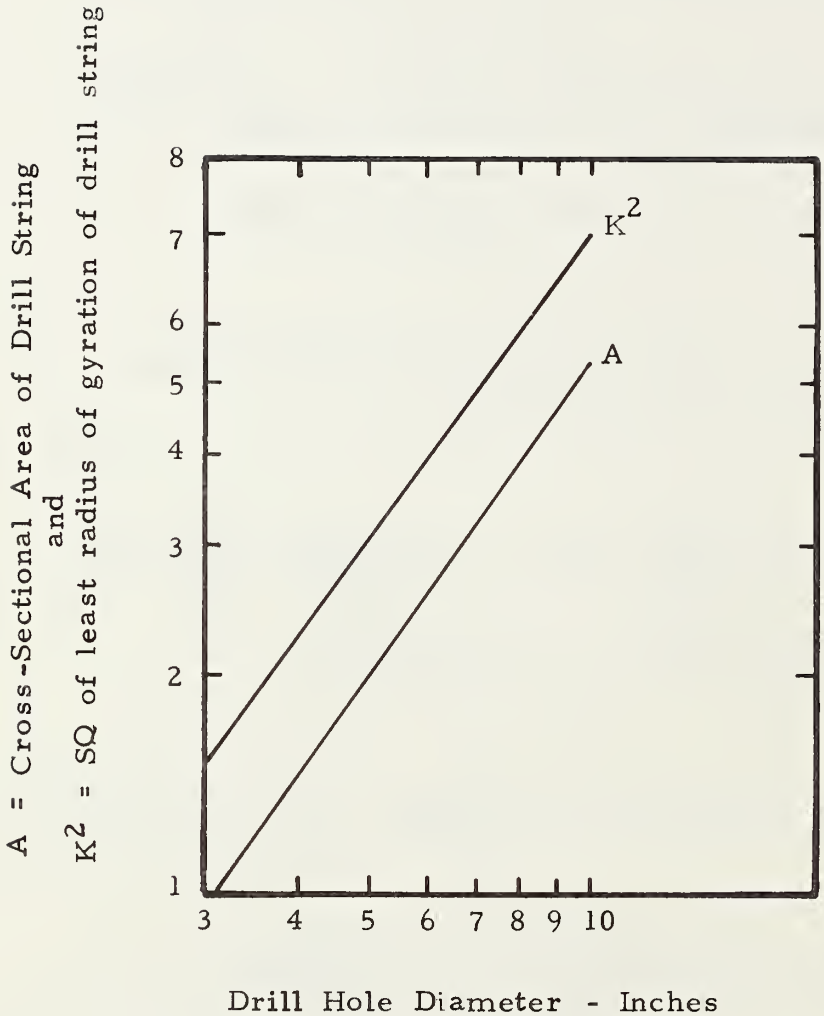


Figure D.1 - Empirical Fit of Equations for Drill String Diameter and Radius of Gyration to Drill Hole Size

Figure B.2 shows the power law approximation of F_p. It can be seen that

$$F_p = F_a + F_D + .17D^{.74}$$

provides an excellent fit.

Equation B.5 can now be simplified by converting all parametric variables to power functions of drill hole diameter and known constants. It reduces to

$$F_B = 4 \times 10^5 \frac{D_h^{1.78}}{L_f} \left(1 - \left[1 - 1.07 \times 1.07 \times 10^{-7} \frac{L^2}{D_h} (5.06 D_h^{.72} f^2 + \frac{(1.18 \times 10^4 D^{.26} + 1) f}{L} \right]^{1/2} \right)^2 \quad (B.6)$$

Figure B.3 is a plot of equation 6 for:

$f = .1$, $D_h = 4''$ and $D_n = 10''$

It can be seen that F_B never becomes excessive compared to the other forces involved. However, at the critical length:

$$\frac{\partial F_B}{\partial L} \rightarrow \infty$$

Further attempts to increase the output force by increasing the input would simply result in more buckling without force transmission.

The functional relationships which cause F_B to go critical can be examined at the point where the radical of B.5 or B.6 goes to zero. This occurs when

$$\frac{12D_n}{{}^2K\ {}^2EA} \left[(Wf^2 + F_{p1} f) L^2 + F_o\ fL) \right] = 1 \quad (B.7)$$

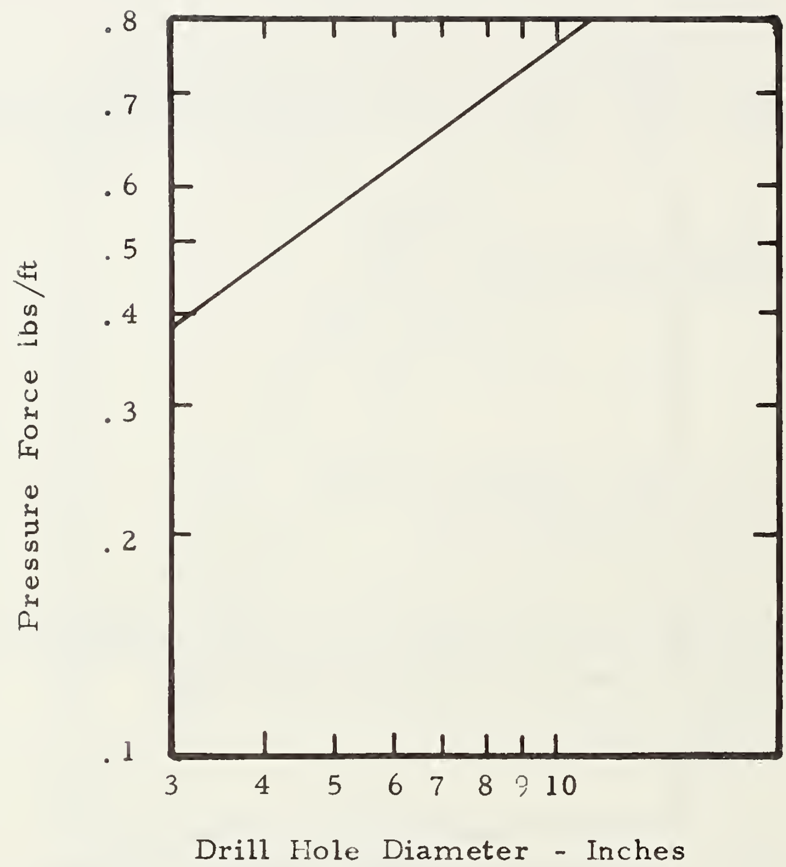


Figure B. 2 - Empirical Power Law Approximation of Pressure Force

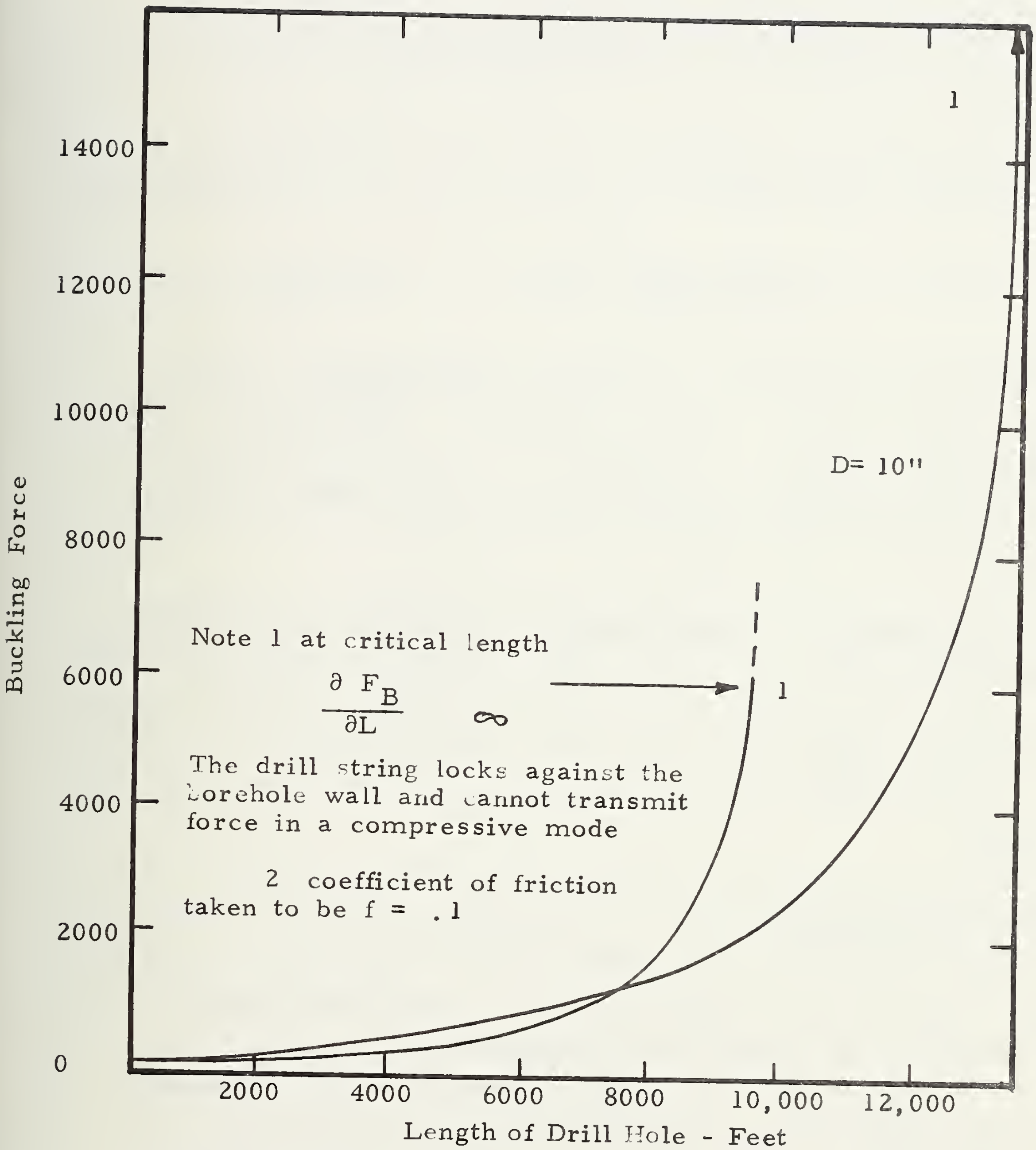


Figure B. 3 - Force Required to Overcome Added Friction Due to Drill String Buckling where

$$F_{p1} = \frac{F_p}{L} = .125 D_h^{.73}$$

Equation B.7 can be solved as a quadratic in either f or L.

F_o is the force delivered to the drill bit. The limiting condition would be to determine the critical length for:

$F_o = 0$

Equation B.7 then becomes

$$L_o(\text{crit}) = K \left(\frac{EA}{12D_h(Wf+F_{p1})f} \right)^{1/2} \qquad \text{(B.8)}$$

Equation B.8 represents the absolutely limiting case. It can allow no force on the bit. Thus it represents a length which can only be approached in theory. It is therefore of no practical interest. However, its evaluation is enlightening as an aid to understanding the lock-up conditions which occur.

Note the similarity between Equation B.8 and Euler's long column buckeling Equation B.1

$$L_o(\text{crit}) = K\left(\frac{EA}{F_{eq}}\right)^{1/2}$$

where

$$F_{eq} = 12D_h\,(Wf+F_{p1})f$$

The units are D_h in inches and Wf and F_{p1} in pounds per foot. Thus the constant 12 is merely the conversion factor. Recognize that:

$Wf+F_{p1} = \frac{\partial F}{\partial L}$, the rate of buildup of compressive force along the drill string.

It is now possible to define the critical length, $L_o(\text{crit})$. $L_o(\text{crit})$ is the length at which a weightless drill string would buckle if an axial force, $F_{(eq)}$, were applied.

Where:

$F_{(eq)}$ is equivalent to the frictional force which would be generated by a weight equal to the force buildup in the drill string in a distance equal to one hole diameter.

$F_{(eq)}$ can now be converted to be a parametric function of drill hole diameter as was done for Equation B.6

$$F_{(eq)} = 12\,(.86D_n^{2.44}f + .125D_h^{1.75})f$$

$$L_o(\text{crit}) = \frac{1}{12}\left(\frac{K^2AE}{F_{eq}}\right)^{1/2} \text{ ft}$$

$$L_o\text{crit} = 3570\left(\frac{D_n}{(6.88D_n^{.71}f + 1)\,f}\right)^{1/2} \qquad \text{(B.9)}$$

Figure B.4 is a graphical representation of Equation B.9 for three coefficients of friction. There seems to be no data available on the frictional characteristics of the hole. However, from review of other frictional data it would seem that the range $.1 < f < .3$ would cover the extremes from optimistic to pessimistic projections.

It would seem that the ultimate limit of horozontal drilling with conventional techniques using compressive forces on the drill string is probably in the range of 8000 to 12000 feet. The practical limit would be considerably less.

Equation B.7 can be rearranged to be

$$L^2 + \frac{F_o}{Wf + F_{pl}}L - \frac{K^2EA}{12D_h(Wf+F_{pl})f} = 0 \qquad \text{(B.10)}$$

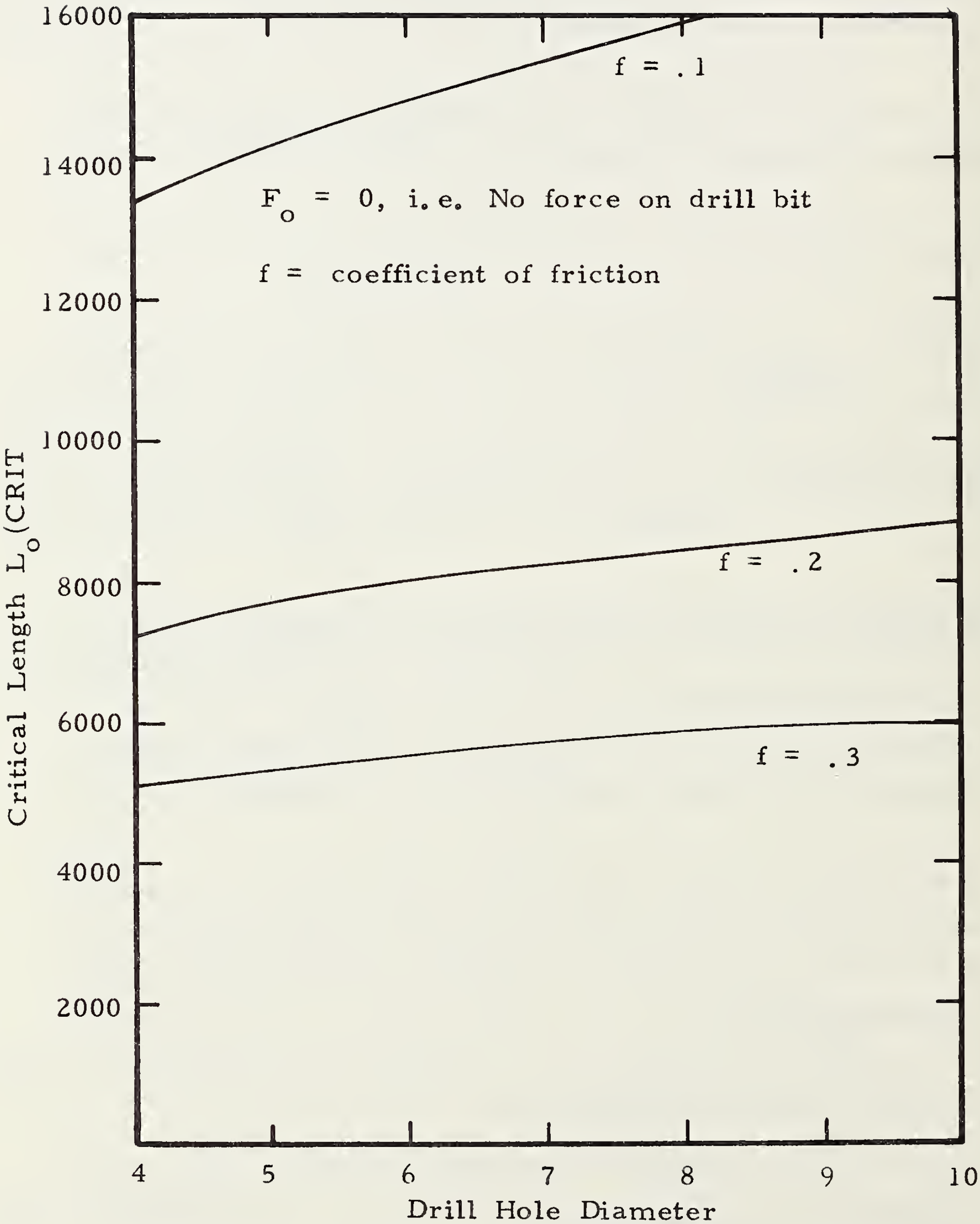


Figure E.4 - Ultimate Critical Length for Buckling

Let:

$$R = \frac{F_o}{Wf+F_{p1}}$$

$$\frac{L^2}{R} - L - \frac{L_o^2(crit)}{R} = 0$$

$$L_p(crit) = \frac{R}{2}\left(\sqrt{\frac{1+4L_o^2 crit}{R^2}} -1\right) \qquad (B.11)$$

$L_p(crit)$ = The practical critical length

Using the empirical approximations for parametric variations in terms of D_h, R becomes:

$$R = \frac{8CD^{.27}}{6.88D^{.71}f+1} \text{ feet} \qquad (B.12)$$

Where: C = the force on the bit in pounds per inch of diameter.

C may vary from as little as 500 to as high as 8000 pounds per inch of hole diameter.

R is simply the ratio of the delivered force on the bit, to the rate of compressive stress build up along the drill string. Figure B.5 presents the variation of R with hole size for the three coefficients of friction, f, considered.

Figures B.6a, B.6b, and B.6c present the practical critical lengths for these values of f over the range of practical drilling weights.

It must be remembered that f is, in reality, a random variable. Unless the drill string is continuously rotated, f will show up as coulomb friction or as it is more commonly called, "sticktion."

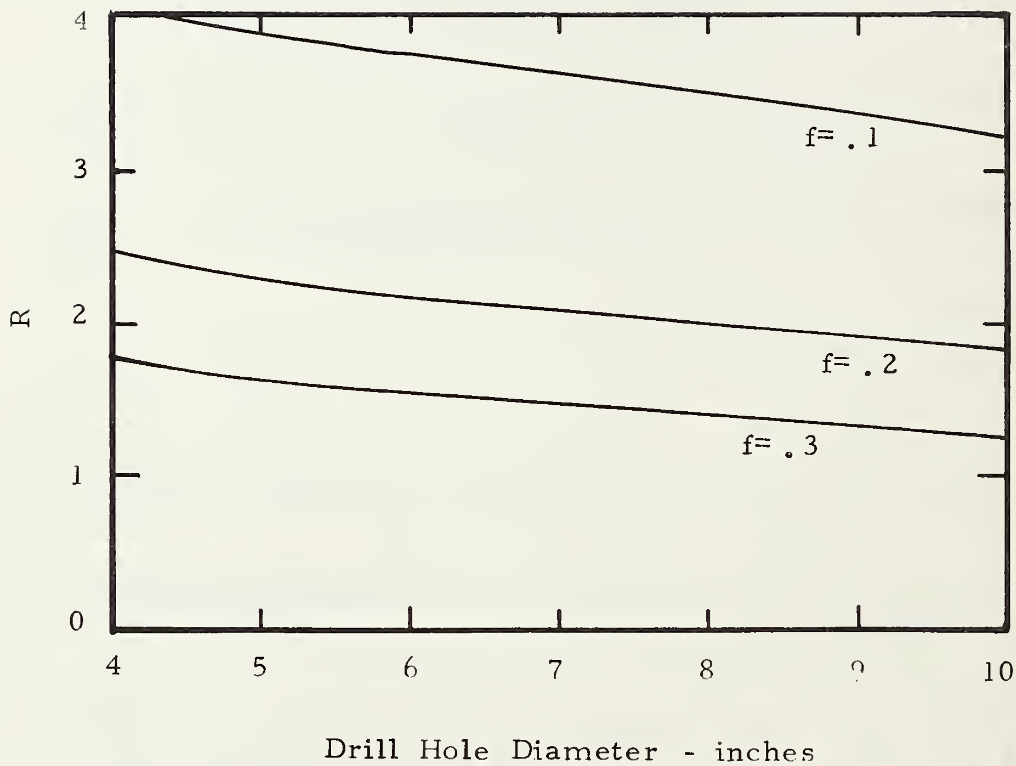


Figure D.5 - R vs. Hole Diameter

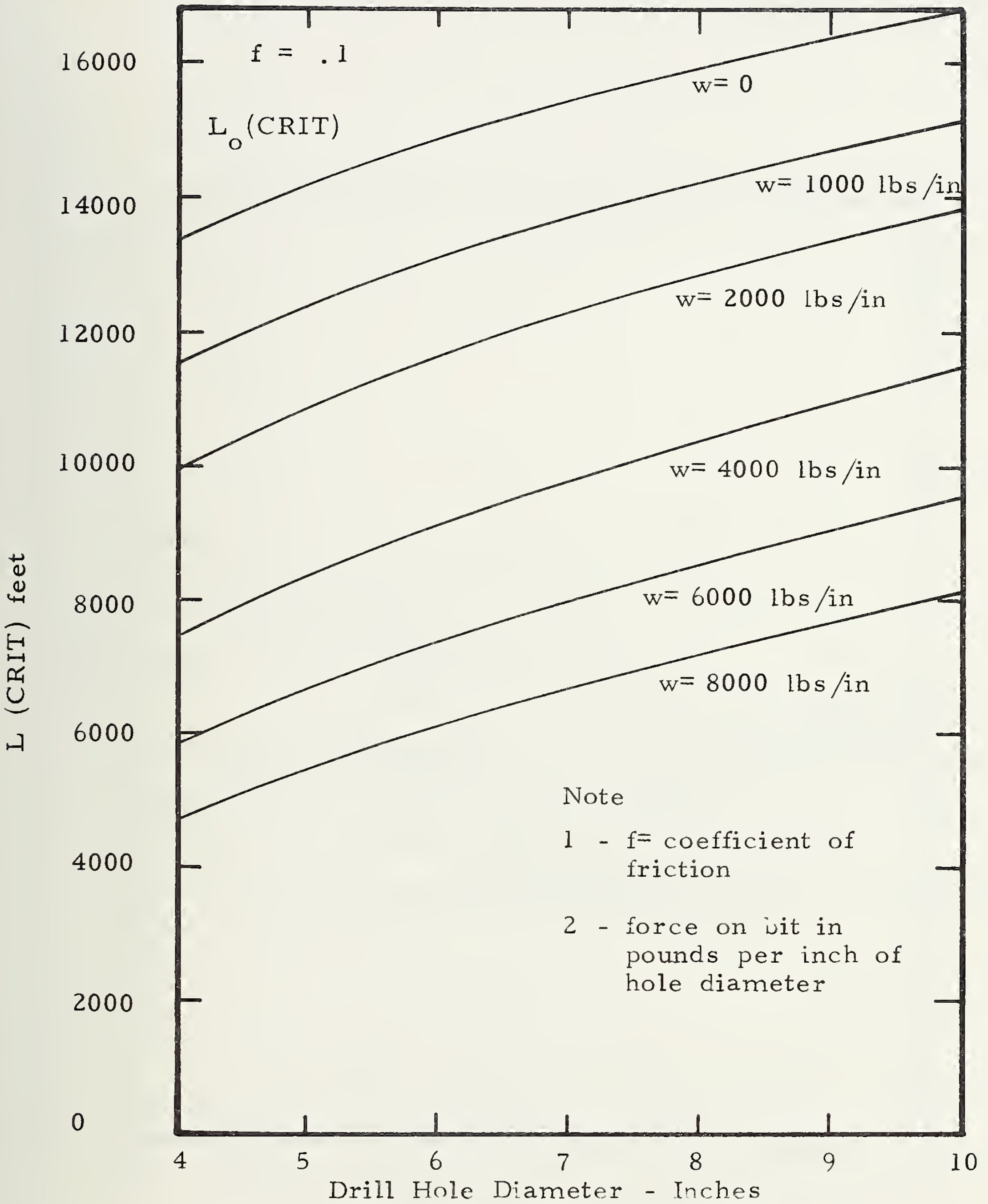


Figure B. 6a - Critical Length for Buckling vs. Hole Size

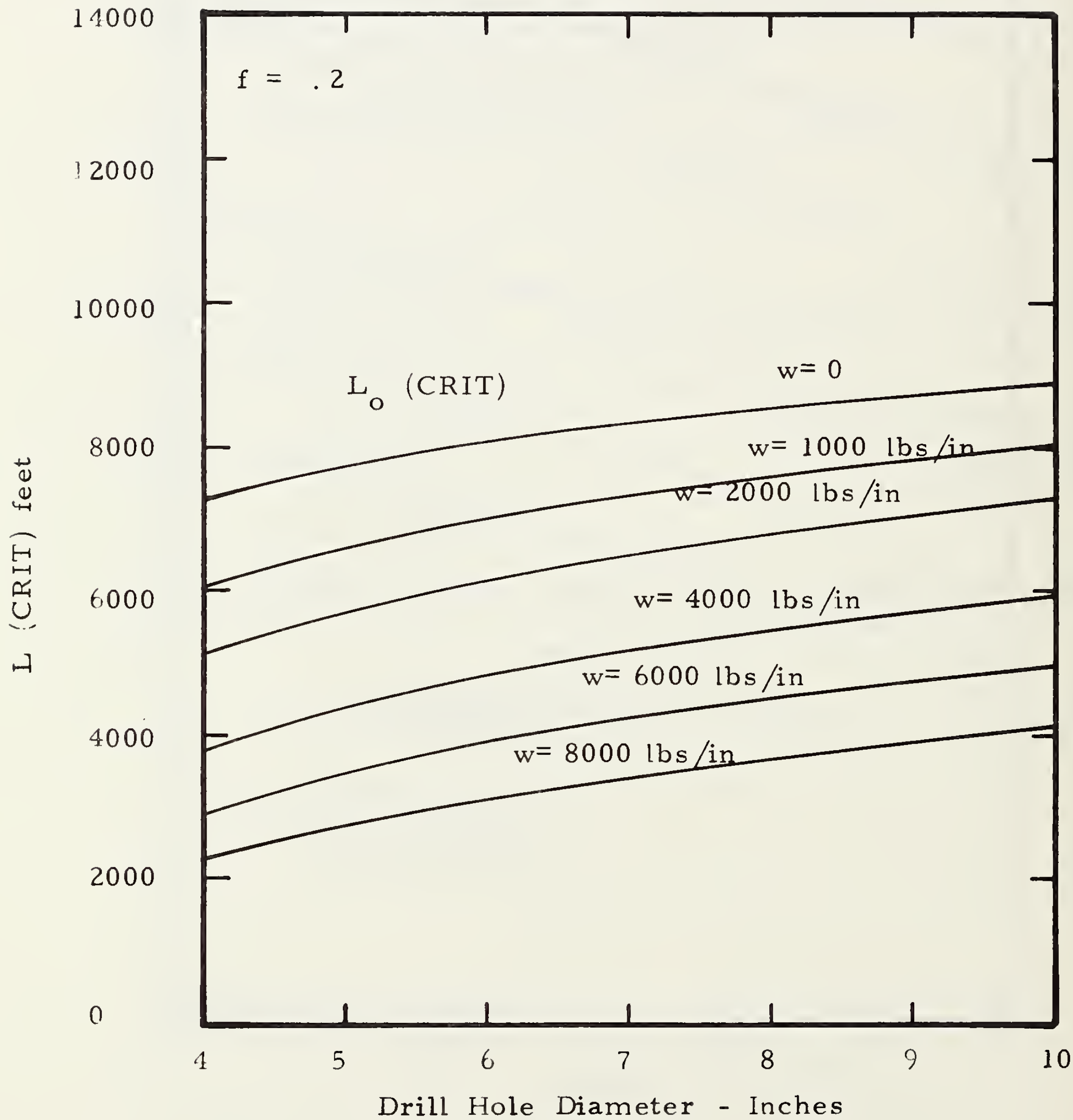


Figure B. 6b - Critical Length for Buckling vs. Hole Size

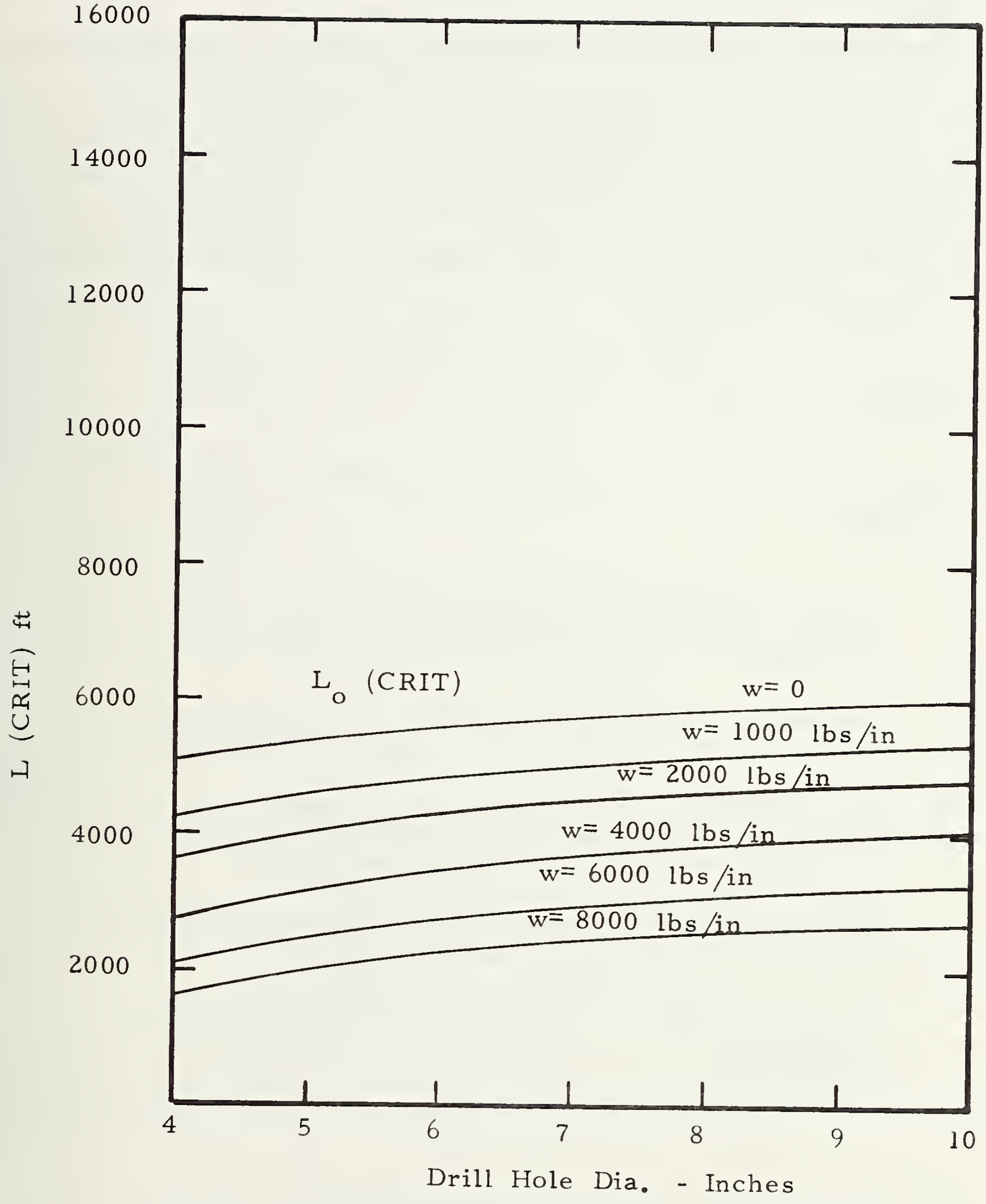


Figure B.6.c - Critical Length for Buckling vs. Hole Size f = .3

Thus, even though an average value of f = .1 might be achieved, individual movements of the drill string will be subject to wide variations of f.

The net result would be that the drill string would start locking up at critical depths far short of those indicated by the f = .1 curves. These lock-ups could probably be worked loose and the bit advanced at lower drilling weights. This could only be achieved at a considerable reduction of penetration rates and at the increased risk of "twist offs" or other failure modes dues to the stress impact of a sudden lock up.

Conclusions

If the range of friction coefficients assumed for this study are realistic:

- It seems doubtful if horizontal drilling by conventional means is feasible beyond about 5,000 feet in hard rock.
- Drilling in soft rock, or at light bit weights, could extend this range to perhaps 7,000 to 10,000 feet.
- It is doubtful if 15,000 feet can be reached at any realistic hole diameter, with a conventional drill rig, operating the drill string in compression.
- Lock-up conditions will greatly increase the probability of drill string failure in other modes.
- The full potential of horizontal drilling cannot be achieved as long as the drill string is operated in compression.

APPENDIX C
THE DUAL DOWN-HOLE THRUSTER

The force which a down-hole thruster must generate is equal to the frictional forces to be overcome plus the required weight on the bit. However, these two forces need to be independently applied. The frictional forces tend to be variable statistical quantities and will, in general, be nonuniform and not under the control of the driller. On the other hand the force applied to the bit should be precisely controllable. This would be especially true of diamond coring bits. Although exact data is not available, all qualitative information indicates that diamond bit life, and penetration rates could be greatly improved by careful control of bit forces and rpm.

C.1 Friction Forces

The friction forces can be expressed as:

$$F_f = .86\ D_h^{1.44}\ Lf \qquad \text{pounds} \qquad (C.1)$$

where:

F_f = The friction forces to be overcome - pounds
D_h = The hole diameter - inches
L = The hole length - feet
f = The coefficient of friction between the drill pipe and the drill hole.

Equation (C.1) assumes that the return flow is to be maintained at 150 feet per minute, and that the pressures are balanced for a cost optimum.

Alternatively, the friction forces could be calculated as:

$$F_f = 1.8\ D_o^{1.44}\ Lf \qquad (C.2)$$

where:

D_o is the outside diameter of the drill pipe.

Equation (C.2) assumes only that the drill pipe is the average of API standards.

The coefficient of friction can be expected to be in the range.

$$.05 < f < .3$$

The lower value of f might be achieved in certain formations with heavy lubricating muds and special additives. Higher values could be expected when drilling with a Dyna-Drill and nonrotating drill string.

Figure C.1 is a plot of the range of forces which could be expected from equation C.1 as a function of hole diameter.

C.2 Bit Forces

The forces on the bit can be expressed quite simply as:

$$F_b = KD_h$$

where :

F_b = the force on the bit

K = a constant characteristic of the bit, the rpm, and the formation. In general, it covers the range $500 < K < 8000$ pounds per inch.

This range of values is shown in Figure C.2.

Figures C.1 and C.2 illustrate a major problem of, not only a down-hole thrust device, but also of drilling to great lengths. The friction forces in any specific hole size can cover at any instant in time any of the values shown in Figure C.1. For example, combined friction and thrust forces in a 6-inch hole attempting to drill with a bit force of 12,000 pounds, could vary at random between 20 and 77 thousand pounds.

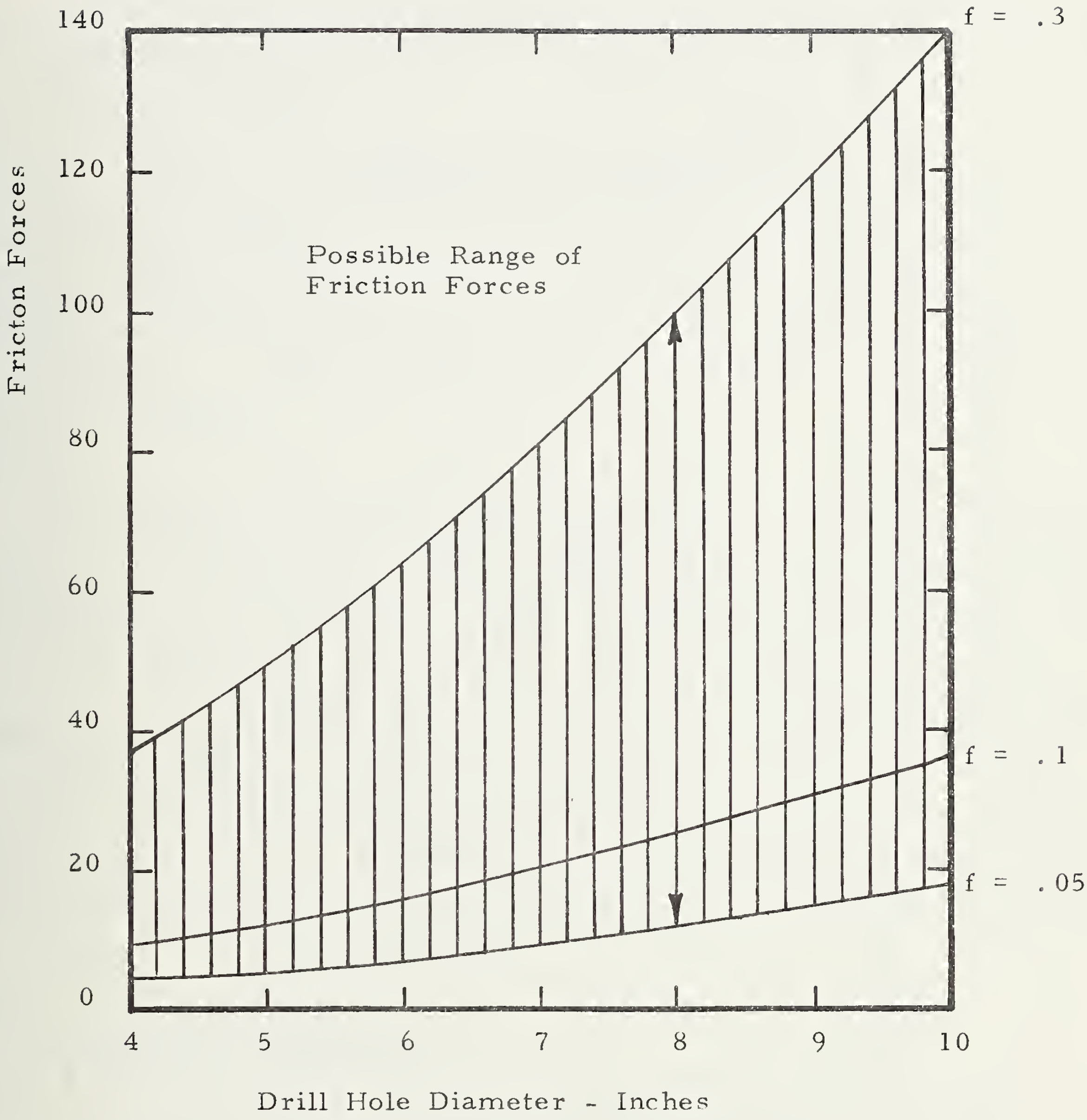


Figure C.1 - Range of Friction Forces Vs. Hole Diameter At L = 15,000 Ft.

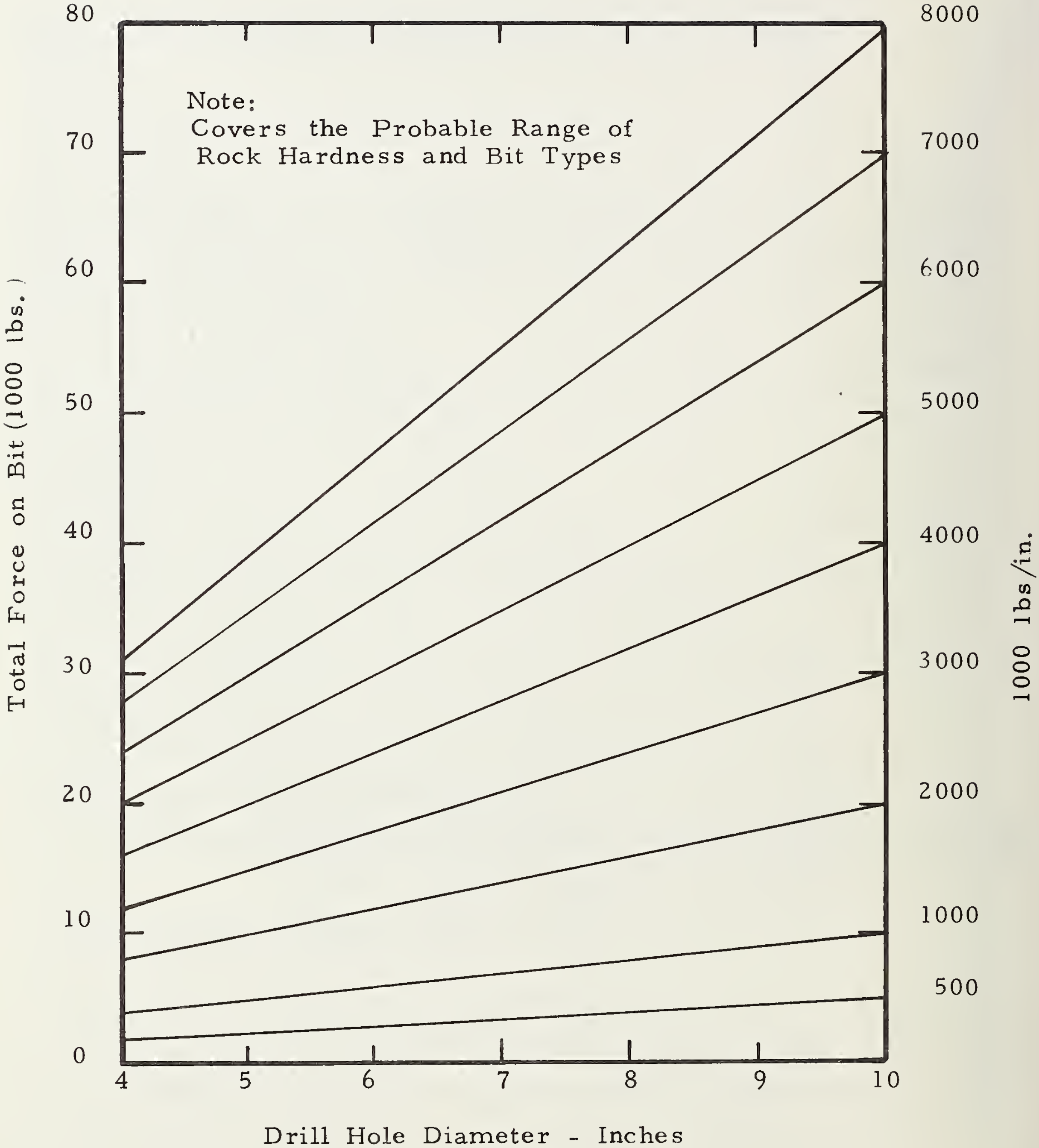


Figure C.2 - Force on Bit Vs. Hole Diameter

From a control standpoint, the required thrust on the bit can be considered as the signal, while the friction forces are noise. This indicates that the signal to noise ratio, S/N, can vary from + 35 Db to - 16 db.

Where:

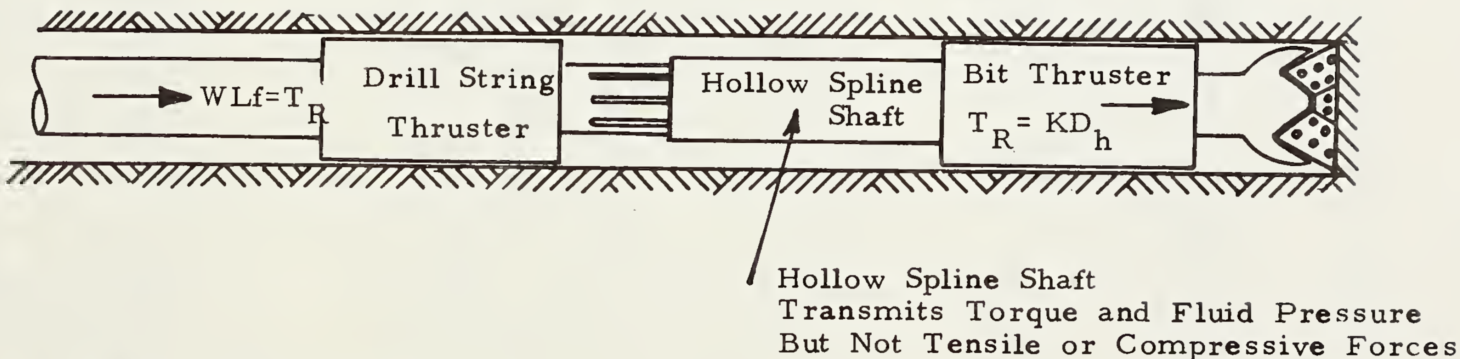
$$S/N = 20 \log \frac{F_B}{F_f} \quad \text{db}$$

It is axiomatic in control systems that even relatively crude control requires an S/N of at least + 10 db while precise control requires at least + 20 db and preferably + 30 db. Without the in-hole thruster, the problem would seem hopeless, even with the most optimistic assumptions on the value of f. With a single thruster, the situation could be improved but not significantly.

The concept of a dual thruster is presented in Figure C.3. It involves the use of two down-hole thrust units, interconnected, by a hollow splined shaft. This shaft can transmit the torsional rotation and the fluid flow and pressure of the drill string. It cannot transmit tensile or compressed forces parallel to the splines. The aft thruster, or drill string puller, is controlled only to the extent necessary to keep the spline shaft free to move, without being jammed at either end. Thus, it can move forward in jerks. As the friction load changes without affecting the actual force applied to the bit. The thruster which applies both penetration and steering forces to the bit can operate under precise remote control from the surface.

C.3 Multiple Unit Thrusters

Reference to Figures C.1 and C.2 will show that for any hole size there are potential requirements for wide ranges of thrust. It would, of course, be possible to make single thrust units capable of meeting the maximum requirement for the hole. However, this would not only create engineering problems, but would also make the unit a gross over-design for the majority of applications.



Key

T_R = Required Thrust - #

W = Drill String Weight - #/Ft.

L = Hole Length - Ft.

f = Coefficient of Friction

K = Constant, A Function of the Rock Strength and Bit

D_h = Diameter of Hole

Figure C.3 - Dual Down Hole Thruster

A preferable approach is to use the same concept as is used in vertical drilling. Here they have standard drill collars of fixed weights. As many drill collars as are necessary for the job are added to the drill string to get the desired weight on the bit. The thruster performs the same function as the drill collar. It can be assembled in the same manner.

The multiple thruster concept involves designing a single thrust unit adequate to meet the minimum thrust requirements of a specific borehole size. The requirements for any other configuration could be met by mounting a number of these units in tandem, and operating them in synchronization.

This approach has many practical advantages:

> The walls of the borehole must absorb the reaction forces of the bit, and the drill string. Multiple units spread this reaction force over a longer section of the borehole. With proper design, damage to the walls of the hole can be prevented.
>
> As a borehole deepens more units need be added only as required. This saves wear and tear on the equipment.
>
> All units are identical and interchangeable. This lowers the production costs, and the cost of spare and replacement units.
>
> The units are connected in series but operated in parallel. Thus a single control package can synchronize a large number of units. Individual control of individual units is not required.
>
> The single common control unit is probably the most expensive item. In addition to the hydraulic controls of the thruster, it contains: the survey and steering sensors, two way wireless telemetry, and electronic synchronization controls and batteries. This would be mounted with access to the center of the drill string so the entire unit could be recovered by a wireline overshot in the event the drill string became stuck. Thus the chances of losing this expensive item in the hole would be minimized.

C.4 Conceptual Design of a Thrust Unit

General

This paragraph will discuss the general conceptual design of a single thrust unit. Since detail design is beyond the scope of this study, only the critical parameters and structures necessary to establish the feasibility of the concept will be covered. There are in hole thrusters available, such as Drilco's Creepy Crawler, however, the details are proprietary, and as far as can be determined they are not suitable for operation at extended depth. The concept to be outlined here is based upon operation to 15,000 foot hole lengths.

Although the concept could work in any size drill hole, the illustrative calculations will be made for an eight inch hole. This is representative of the mid-point of the possible range of hole sizes. Other numerical assumptions will be made as required. Although practical values will be assumed, no real attempt will be made at engineering optimization. Thus, an optimized system should be capable of performance superior to the system discussed.

Derivation of General Performance Requirement

Reference to Figures C.1 and C.2 would indicate that an in-hole thrust unit capable of developing one thousand pounds of thrust per inch of hole diameter should have considerable utility. This would be applicable to soft rock and moderate hole lengths. Advance rates of up to 40 ft./ minute when tripping in or out of the hole would be desirable, as would drilling rates of up to 100 ft. per hour.

C.4.1 Power Requirements

The power requirements would be:

$$HP = \frac{VF}{33000} \text{ horsepower}$$

V = Velocity - feet/min.

F = Force - Pounds

F = $1,000\ D_h$ - Pounds

HP = 3.03×10^{-2} VDn horsepower

For D_h = 8

HP = 9.7, while tripping

HP = .404 while drilling

The unit is hydraulic powered, taking its power from the drilling fluid.

The large differential between power requirements while tripping and drilling is achieved by a wireline retrievable plug which is inserted prior to entering or coming out of the hole. Thus the entire power capacity of the mud pumps is diverted to the extraction of thrust at high pressure and low flow rate, with a correspondingly low pressure loss through the drill string.

The modest horsepower requirements to provide thrust while drilling are achieved through the incremental pressure drop through the bit, and other tools such as Dyna-Drill which may be on the drill string. If added pressure is needed it is achieved by replacing the plug used during transfer within the hole by a wireline retrievable* orifice, adjusted for the proper pressure drop and flow rates.

---

*This study assumes that precise control of thrust and steering is achieved through a wireless telemetry link to a battery operated control system, which itself is wireline recoverable. This assumption is based on other studies which indicate the desirability of a survey/steering system operated through a wireless telemetry system. Thus this form of control would already be available. An alternative approach would be for the force on the bit, and thus the drilling rate, to be controlled through the pressure of the drilling fluid, which in itself is controlled by the operator. In this case the wireless telemetry would not be needed. This concept has been examined in sufficient depth to establish its feasibility. However, it will not be pursued further at this time.

A review of techniques using hydraulic pressure from the drilling fluid indicates that pressure drops through the tools as high as 500 psi are acceptable to the drilling industry. This study will assume that 500 psi is available as a working pressure. The mechanism for obtaining this pressure will be discussed later. However, the pressure is applied to all units in parallel; thus, the pressure requirement is a total of 500 psi not 500 psi per unit.

There are two types of force required for a thrust unit. An axial force parallel to the drill string, and a radial locking force perpendicular to the drill string. Of the two, only the axial force performs any appreciable work. Thus it will be assumed that the total power requirement is absorbed in the generation of thrust.

Generation of Thrust

There are a number of ways thrust could be generated. The mechanism which makes the most efficient use of the cross sectional area of the borehole is the annular cylinder operating against a piston in the form of a cylindrical shell. Figure C.4 is an approximately half scale drawing of the essential features of a thrust cell. The O-rings shown serve the double duty of seals and absorption of asymmetric forces. They do not represent either the best or the most economical methods of achieving these functions. However, they conform more to standard practice and are thus used as an aid to conceptual visualization.

Although the unit is designed for a nominal 500 psi working pressure, an extremely large safety factor is required. The working pressure is derived from a pressure drop at a specified, balanced flow rate. Thus even a temporary blockage between the location of the intake and exhaust ports could cause a large pressure surge. A safety factor of 6 is assumed, with blowout plugs on a safety valve to take care of extremes. Thus the cell is stressed to take 3000 psi.

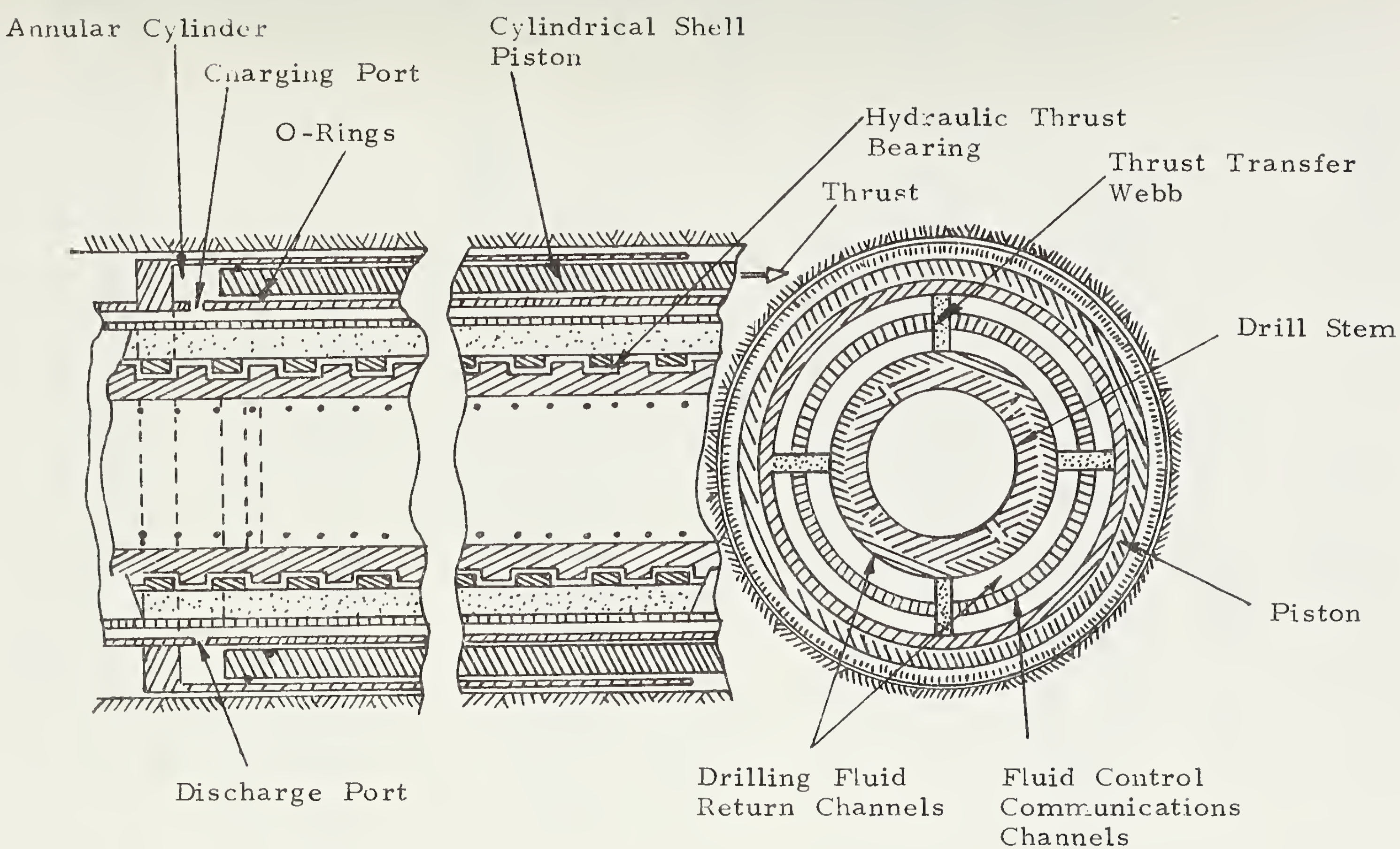


Figure C.4 - Conceptual Drawing of a Single Thrust Cell

Design Study of an 8 Inch Thrust Cell

An 8" thrust cell should deliver 8000 pounds of thrust at 500 psi. Thus:

$$A = \frac{F}{P} = \frac{8000}{500} = 16 \text{ in}^2$$

A .125 inch clearance is assumed between the cell and the hole. Thus D_{oo} = 7.75 in., the outside diameter of the cell. If a high strength steel is assumed:

Y = 150,000 psi, the yield strength

D_{io} = the inside diameter of the outer shell

sf = 6 the safety factor

P = 500 psi the working pressure

$$D_{ii} = D_{o1} \left(1 = \frac{Psf}{Y}\right) = 775 \quad \left(1 - \frac{500 \times 6}{150,000}\right) = 7.6''$$

Let:

D_{oi} = The outside diameter of the inner shell

D_{ii} = The inside diameter of the inner shell

$$D_{oi} = \left(D_{io}^{2} - \frac{4A}{\pi}\right)^{1/2} = \left[(7.6)^2 - \frac{4 \times 16}{\pi}\right]^{1/2} = 6.11 \text{ inches}$$

The effective ring thickness of the cylindrical piston is

$$\frac{7.6 - 6.11}{2} = .743, \text{ approximately } 3/4''$$

Unlike the outer shell which operates in hoop stress, the inner shell will fail by compressive collapse. There are a number of semi-empirical formulas to predict this failure mode. The most conservative formula is for failure in the elastic range.

$$D_{ii} = \frac{D_{oi}}{\left(\frac{(p_{sf})}{(E)}\right)^{1/3} + 1} = \frac{6.11}{\left(\frac{6 \times 500}{6 \times 10^7}\right)^{1/3} + 1} = 5.89 \text{ inches}$$

E = Youngs Modulus, 6×10^7 psi

Thus the inner shell is approximately 1/4 inch thick. Inside the inner shell are the fluid communications channels which transmit the control pressures through the system. Assume 1/4 inch spacing as shown in Figure C. 5, and a second inner shell, also stressed for compressive failure. (This is an ultra conservative assumption as it assumes that the inner thrust shell and the communications channels do not reinforce each other. Obviously, they do, and if clearances become critical the thickness could be reduced.)

The inner diameter of the thrust shell absorbs the hoop stress of the communications channel. This is already more than adequate. Thus the inner diameter of the fluid channel is:

$$D_{if} = \frac{D_{ii} - .5}{\left(\frac{(PSA)}{(E)}\right)^{1/3} + 1} \qquad \frac{5.89 - .5}{\left(\frac{6 \times 5.00}{6 \times 10^7}\right)^{1/3} + 1} = 5.2 \text{ inches}$$

Within this 5.2 inch diameter there is obviously ample room for both adequate two way fluid flow and a high strength drill pipe. This cell will generate its 8000 pounds of thrust with a reserve of 40,000 pounds before failure.

Generation of Locking Forces

The key to the operation of a down hole thrust device is that, colocated with each thrust cylinder, is a locking device to transfer the thrust reaction forces of the cylinder to the walls of the borehole.

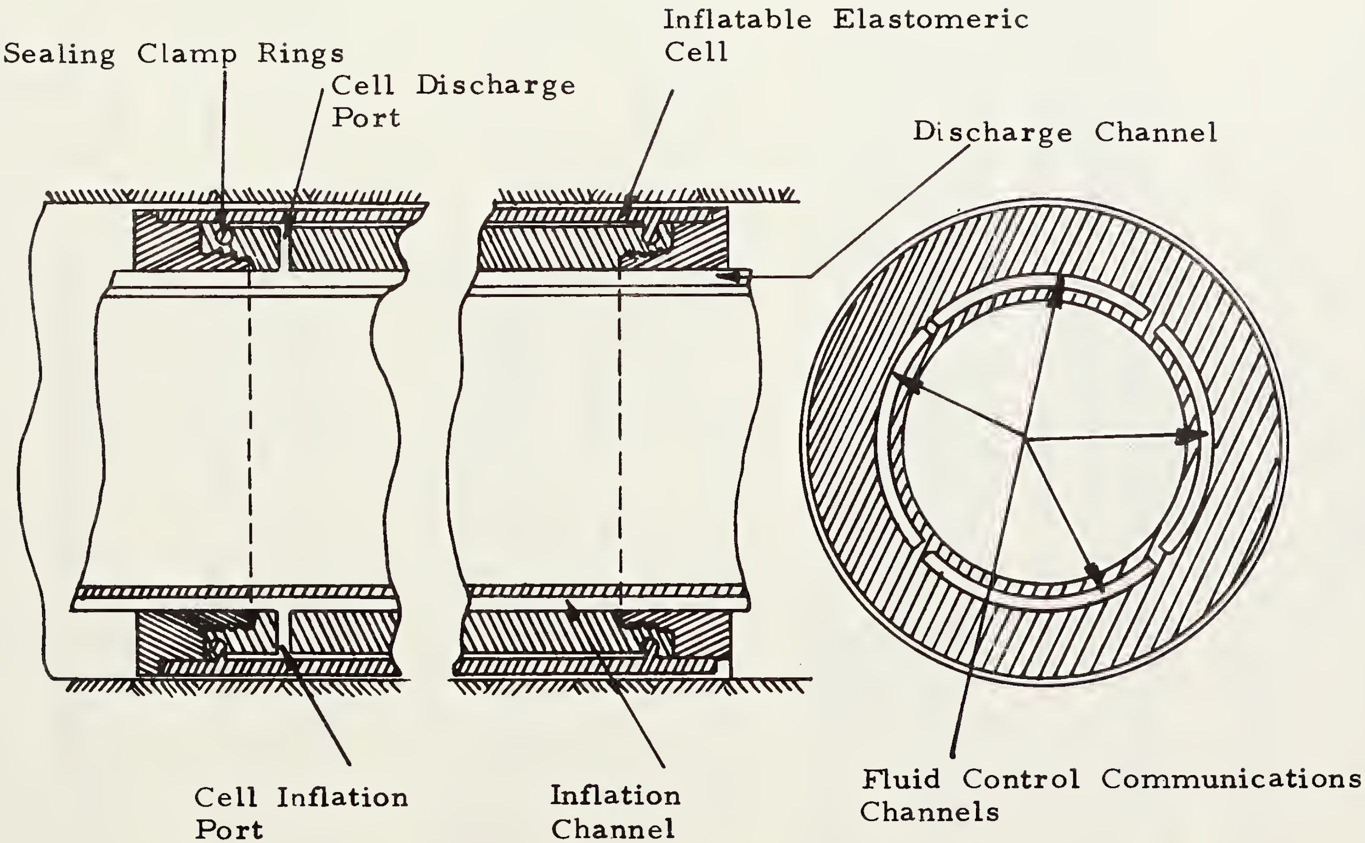


Figure C.5 - Conceptual Drawing of a Single Locking Cell

This is achieved by a locking cell if the device is hydraulic, or a brake shoe, if it is mechanical. Only the hydraulic system will be covered here. The force distributions of a locking cell are almost diametrically opposed to those of the thrust cell. The thrust cell, for reasons of economy of cross sectional area of the borehole, concentrates maximum force over a minimum area. Similar force concentration could destroy the walls of the borehole. The locking cell needs to distribute the reaction force over as large an area of the borehole wall as economically feasible. This generates a broad, soft footprint required in soft ground or gouge material. The economics of this functional difference between force units are favorable. There is a tremendous cost penalty for cross sectional area. There is little penalty for increased length in the borehole. Thus the broad footprint can be easily achieved. A more complete design study would have to balance probable compressive strength of the weakest section of the borehole against pressure, area, and flow rates through the fluid communications channels and valve orifices. This conceptual design study will arbitrarily assume that the cell operates at 20 psi.

Figure C. 5 is a conceptual drawing of a locking cell at approximately half scale. Essentially it is nothing but a sealed rubber sleeve which expands against the wall of the borehole. A polyether based urethane rubber of a durometer rating of 75 to 90 such as DuPont's L-100 or L-83 would be best. These rubbers have excellent abrasion resistance, a high tensile strength of about 4000 psi and are non-hydroscopic. The sleeve is sized to just have traveling clearance through the borehole. The actual volumetric expansion should be as small as practical. As a maximum, the clearance should be less than the thickness of the wall of the cell, so that the maximum cross sectional area parallel to the borehole axis is exposed to the shear load to be transferred. The thickness of the cell should be such that it can absorb the peak design thrust load without rupture.

Let:

F_p = Peak design force, 48000 pounds
S_t = Tensile strength of the rubber, 4000 pounds
D_r = The diameter of the hole, 8"
τ = The shell thickness

Then:

$$\tau = \frac{F_p}{2\pi D_r S_t} = .233 \text{ in.}$$

Thus a 1/4 inch shell should be adequate, and the 1/8 inch hole clearance assumed for the thrust cell would be satisfactory. The required force exerted on the wall of the borehole is:

$$F_B = \frac{F_D}{f}$$

where:

F_B = Force on the borehole wall
F_D = The design thrust force, 8000 pounds
f = The coefficient of friction of the locking cell against the wall of the borehole, assumed to be .75.
F_B = 10,700 pounds

Let:

L_C = The length of the cell
P_C = The applied locking pressure, 20 psi

$$L_C = \frac{F_B}{P_c \pi D_n} = 21.2 \text{ inches}$$

Thus a cell 24 inches long would be more than adequate to absorb the reaction force. Since both the thrust pressure, and the locking pressure are bled off of the pressure drop in the drill string, the locking force would increase proportionally to the thrust forces. Thus the cell would remain locked through any pressure surges.

The Single Thrust Unit

The individual cells comprising a thrust unit have been discussed to establish the feasibility of the design concept. A thrust unit consists of two thrust cells and two locking cells. The thrust cells work in phase opposition to each other. That is, while one cell is activated and expanding the other is deactivated and is being compressed by the expansion of the first. Each thrust cell operates in concert with a locking cell, in such a manner that it is locked to the wall of the borehole before it is allowed to expand. Thus the thrust movement of the thrust cell is always made with respect to the reference point in the borehole to which it is locked.

Figure C.6 is a drawing of the essential features of an operating single thrust unit. As shown, it is just completing its thrust cycle and is ready to start a recycle. The essential feature is that the aft thrust cylinder is coupled to the drill string by hydraulic thrust bearings, as is the forward locking cell. Thus the unit never changes its length. It produces thrust and motion by relative changes within its interior length and transfer of thrust points between the fore and aft bearings.

Hydraulic Control and Valving

There are two basic concepts for the synchronization and control of the thrust and recycle sequences in down hole thrusters.

- Each single thrust unit may have its own battery of solenoid operated valves. These operate in synchronization, controlled by a central electronic clock, common to all thrust units. The valves would switch high pressure fluid from the center of the drill string into the thrust and locking cells, then exhaust the fluid into the borehole.

- A central hydraulic control unit can be made common to all thrust units. It would be sized to handle the total, battery of thrust units needed for

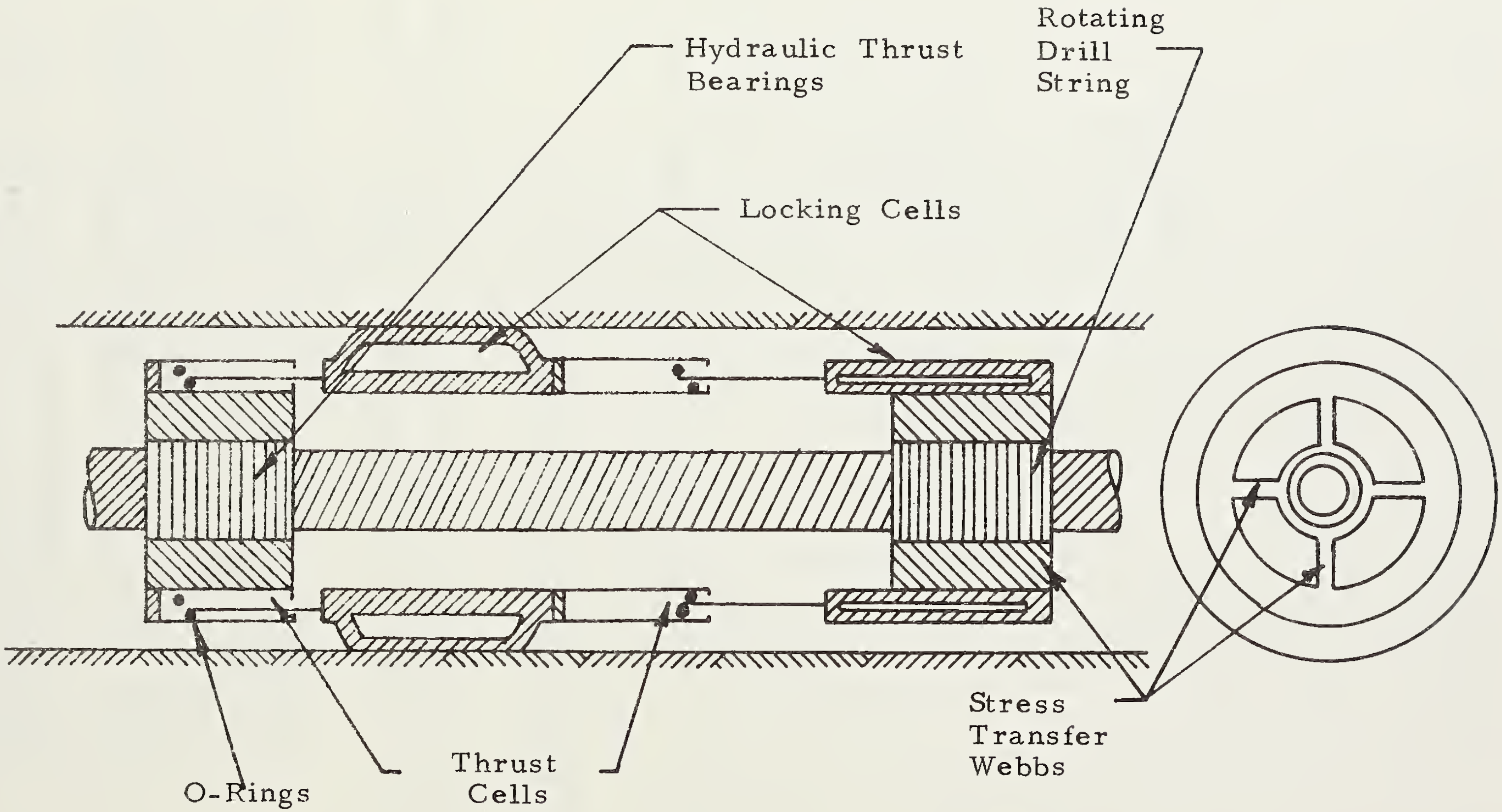


Figure C.6 - Single Thrust Unit for Rotary Drill

> the maximum thrust and drill string drags anticipated. All individual thrust units must be operated in synchronism. This is achieved by manifolding the controlled fluid flows down the fluid communication channels shown in Figures C.4 and C.5.

Each of these concepts has certain advantages and disadvantages. The second concept may be best in small diameter holes where the valving would have to be custom designed to fit the available space. It would have the advantage of higher reliability due to fewer operating parts, and probably lower eventual costs. It has one major disadvantage: The design of a system using a system such as this for long boreholes requires data which is not yet available from horizontal drilling such as friction coefficients. Thus it will not be considered further at this time. It should probably be considered as a second generation candidate.

The first candidate has the advantage of making each individual thrust unit a complete self-contained operating entity except for the synchronization common to all. Other advantages are:

> The concept can be proved at shallow depth with individual units.
>
> More units can be added as needed.
>
> Design is simplified.
>
> Commercially available valves can be used.
>
> Fluid flow problems are simplified.
>
> All units are identical.

Hydraulics Valving for Single Units

Using double acting, four way commercial solenoid valves, a thrust unit could be controlled with two valves and appropriate internal manifolding. Using simple off-on poppet valves a maximum of eight would be required. The actual valving would depend on a comprehensive search and evaluation of the commercial availability of valves of the proper characteristics and form factor.

This study will assume that eight valves are used. Because of their simpler operation they seem to be available in form factors more suitable for the tight packaging requirements of in-hole operation. Because each valve performs only a single function the internal fluid manifolding is greatly simplified. Typically, these valves in the pressure range required cost in the range of $15 to $25. It seems highly probable that the cost of added valves would be more than offset by reduced machining costs of special fluid manifolds.

Each thrust unit consists of identical pairs, each containing a locking cell and a thrust cell. Only the central signal sequences to the pairs will differ. Thus only the valving sequence to a half thrust cell need be discussed.

Figure C.7 is a pictorial schematic of the extremely simple hydraulic system required. An incremental pressure of 500 psi exists between the center of the drill string and the borehole. The magnitude of the pressure is set by a wireline retrievable orifice, which is matched to the flow rate and the pressure loss through the bit and other tools in the drill string. Hydraulic pressure is fed through holes in the sub containing the thrust unit, to a coupling manifold, which serves the purpose of a rotating slip ring. Actually the manifold and the hydraulic thrust bearings shown in Figures C.4 and C.6 would be a common unit.

The thrust unit is alternatively switched between the drill string pressure, for intake, and the borehole pressure for exhaust. The locking cell is switched to the drill string for intake, however its pressure is controlled by the pressure drop through the intake orifice and the bypass orifice as shown. It also is exhausted directly into the borehole. As shown, the system has only limited control of its thrust through control of the flow rate, and by changing the main control orifice. Precision thrust control is obtained by the electrical modulation of the on/off solenoid valves. This technique is effectively used in commercial hydraulic installations.

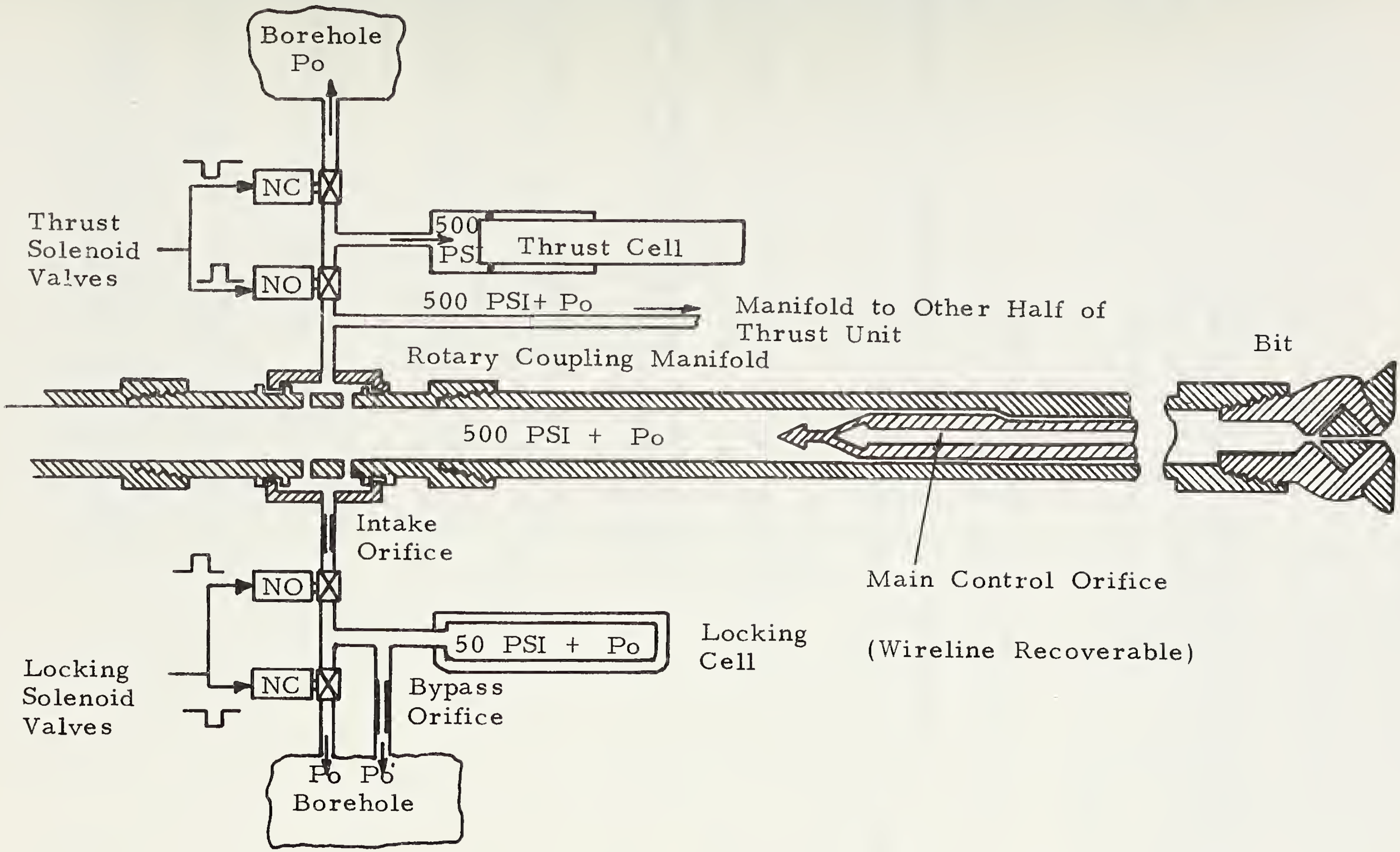


Figure C. 7 - Hydraulic Control System

System Considerations

Up to this point the discussion has concentrated on establishing the basic feasibility of the concept of making a down hole thruster around a combination of two types of cells. A locking cell, which is a well established borehole technique, and an angular thrusting cell, which seems optimal for providing force parallel to the drill string. In this section a few of the available techniques needed to weld it into a system will be discussed.

Functions of a Down-Hole Thruster

The functions which a down-hole thruster can implement to both enhance the capability and drastically reduce the costs of horizontal drilling include:

- Dragging the drill string into the hole which:

  * Keeps the drill string in tension and thereby reduces drill string failures and reduces fishing costs.

  * Allows the extension of hole length beyond the buckling length of the drill string.

  * Reduces torque requirements on the drill rig, and again allows lighter, less costly surface equipment.

- Separating the random friction forces of the interaction of the borehole with the drill string from the precision thrust forces required on the bit. This:

  * Reduces the danger of bit breakage and prolongs bit life.

  * Reduces the danger of overloading the bit, sticking it in the formation, which in turn will reduce torsional failures.

* Allows bits to be operated at their optimal torque/speed characteristics. This could be especially significant with diamond bits, where both penetration rates and bit life could be greatly improved.

Providing a transfer point for reaction torque and force to the borehole wall. It thus allows precision steering and guidance to be accomplished.

Survey, Control and Steering Considerations

The availability of the thruster, right behind the drill bit, opens the door to a complete spectrum of potential steering techniques. It is beyond the scope of this study to cover all of them, or to attempt to establish a preferred configuration. They range from the use of a Dyna-Drill on a bent sub, which will be treated as illustrative, to controlled whip stocks carried along for rotary drilling. Techniques for warping the drill string have been considered and look quite promising. In fact, the availability of the thruster holds promise of providing the same steering freedom, and transit time economies for rotary drilling that a Dyna-Drill and a kick sub such as Dyna-Flex provide for in-hole motor drilling.

A separate study indicated that a Dyna-Drill on a bent sub would become unstable, after a few thousand feet at most. Even with an in-hole steering tool, the range could only reasonably be extended a few thousand feet more. Beyond this range an in-hole thruster is needed to absorb the reaction torque which produces the instability. The magnitude of the stability problem can be seen by reference to Figure C. 8.

The thrust unit for the Dyna-Drill/bent sub drilling differs from that required for rotary drilling. The essential difference can be seen by comparing Figures C. 6 and C. 9. The hydraulic thrust bearings of the rotary unit allow it to generate thrust while the drill string is turning. These are replaced by an inner locking sleeve which serves as a clutch between the drill string and thrust unit. A locking cell is attached

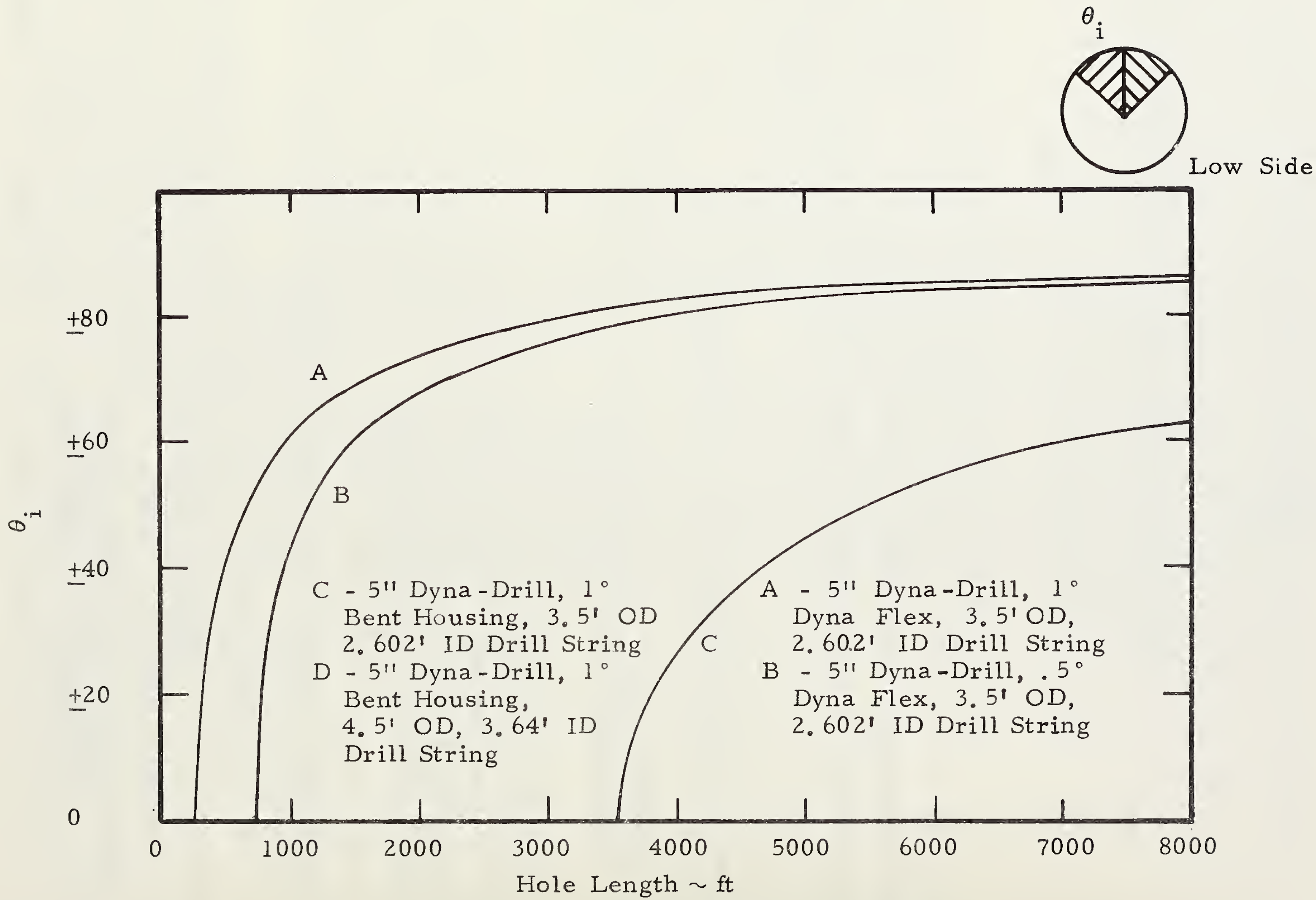


Figure C.8 - Instability Zone, θ_i for Various Dyna-Drill Hook-Ups (Dyna-Drill will not Stay within θ_i)

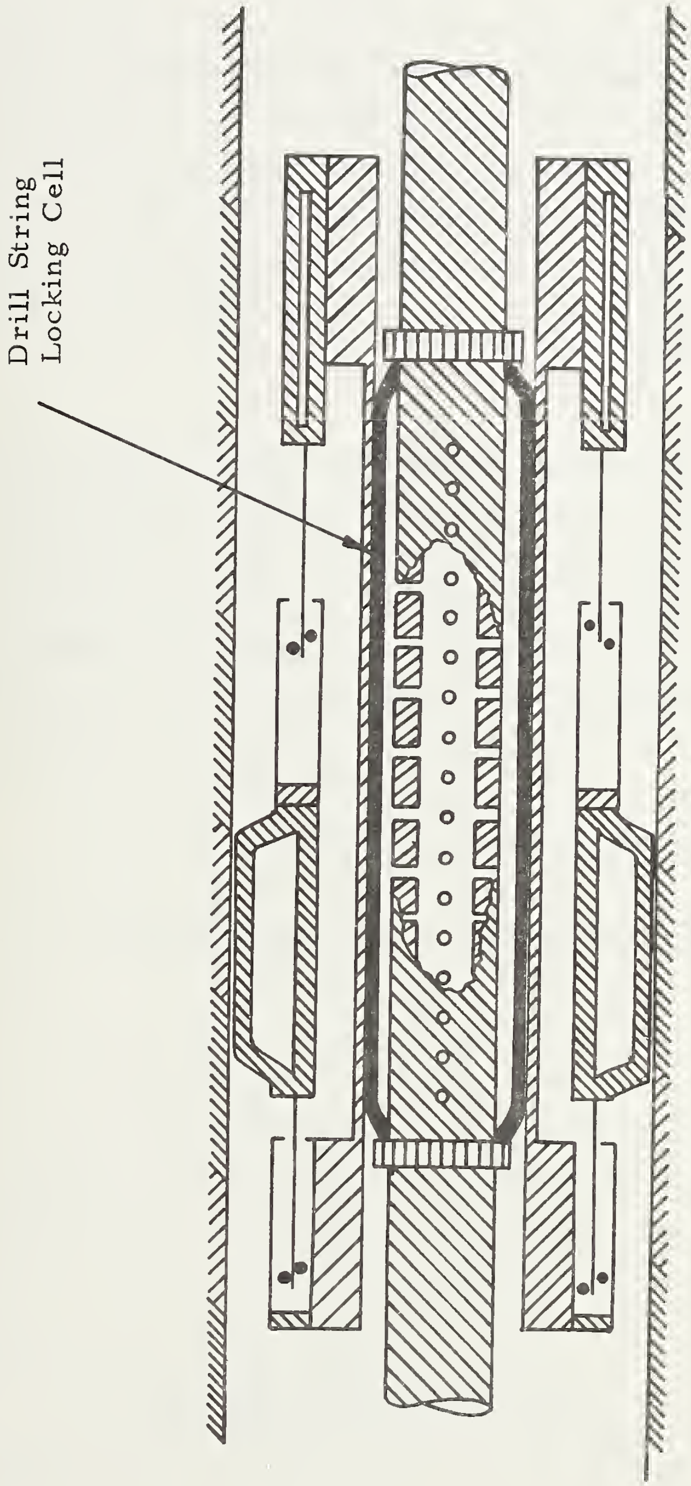


Figure C.9 - Single Thrust Unit for Down-Hole Motor to the drill string. The cell expands at even low hydraulic pressures and locks the drill string to the locking sleeve. Thus it causes the thrust unit to absorb the reaction torque of the drill motor.

Steering is accomplished by rotating the drill string to the proper azimuthal angle with the pumps deactivated. Under these conditions the inner locking cell is deflated and the drill string can be rotated. When the mud pumps are started, the cell expands and locks the drill string to the thruster before the pressure has built up to a point that the motor can generate torque. The reaction torque is thus absorbed by the thrust unit, and through it by the wall of the drill hole, and not by the torsional reaction of the drill string.

The steering could be as simple as rotating the drill string from the surface, as in present procedure. However, other studies have shown that drill string friction will make it extremely difficult to make a precise angular correction at hole lengths beyond a few thousand feet. Thus one version of the system to be discussed provides a procedure and mechanism for using the Dyna-Drill's own reaction torque to rotate the drill string to the proper azimuthal angle before locking it in that position. However, the discussion will be deferred till after treatment of the wireline recoverable package.

Survey, Guidance, and Control Package

The survey, guidance, and control package could be mounted directly behind the thruster as a semipermanent installation. It could also be designed into a wireline retrievable package and pumped down the center of the drill string. Both approaches have been used successfully. For several reasons it is believed the wireline tool would be preferable.

- It can be obtained from commercial sources with minimal development.

- Its operation is simpler to conceptually visualize.
- In the event of a stuck tool it can be recovered so that it will not be lost or damaged in fishing operations.

The tool is designed to perform several functions:

- It is a high angle gyroscopic survey instrument and as such it is available today on custom order.
- It is a high angle wireline steering tool.
- It is a power and synchronization source for the multiple unit thruster.

Figure C. 10 is a cross section of a wireline survey and control package. It shows the principle functions to be performed. Normal survey and steering tool functions are accomplished in the electronic package, which is mule-shoe aligned with the deflection plane of a kick sub such as Dyna-Flex. Not shown on the picture, but attached to the bottom of the mule-shoe cam would be the probe which governs the deflection angle of the Dyna-Flex.

The electrical power control signals are transferred through a transformer, with the secondary windings mounted on the drill string and the primary windings in the body of the probe. The control circuit is thus closed by electromagnetic flux whenever the mule-shoe is seated.

The function of the main pressure control orifice has already been discussed. Its size would be selected on the basis of the drill string diameter, hole diameter, and the pressure drops through the down stream tools such as Dyna-Drill, and Dyna-Flex. It is envisioned that it would be a screw-in sleeve similar to a carburetor jet.

Steering control would be as discussed previously except that, when drill string friction becomes too random for precision adjust-

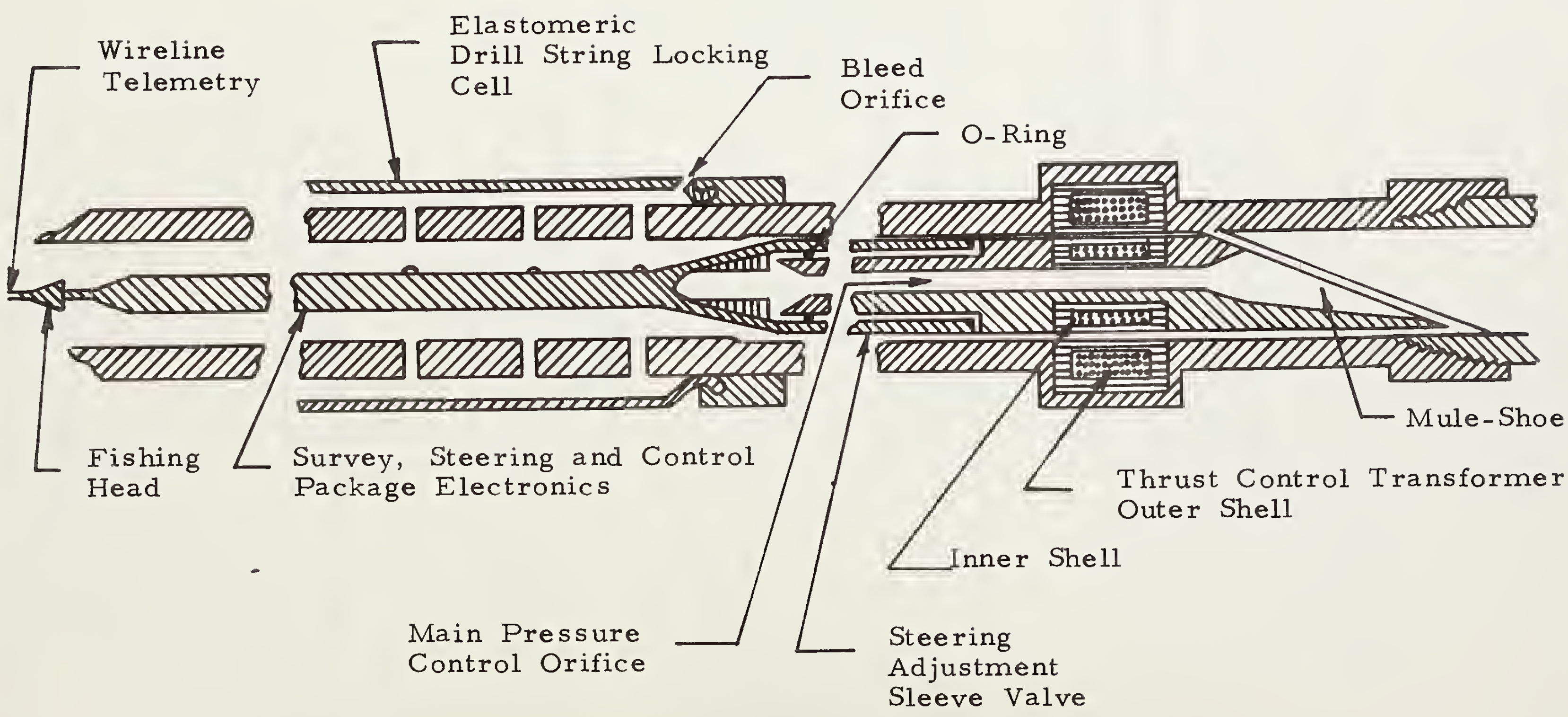


Figure C.10 - Wireline Survey and Control Package ment, the Steering Adjustment Sleeve Valve is used. Normal surface adjustments are made until the steering error correction angle is slightly positive (a counter clock-wise adjustment is needed). Then, with low pressure on the pumps, the tool is withdrawn approximately one foot. The pressure holds the lower section of the steering tool against the mule-shoe. However, the Steering Adjustment Sleeve Valve shown in Figure C.10, is drawn back, covering the ports to the locking sleeve. Any residual pressure in the locking sleeve bleeds off through a bleed orifice and the drill string is released and free to turn. Pump pressure is gradually increased, till the Dyna-Drill starts to generate reaction torque. This will twist the drill string counter clockwise. Pressure is controlled from the surface till the steering angle is correct. The steering tool is then released. The pressure carries the package and sleeve forward. The ports to the locking cell are reopened, and the drill is locked at the proper angle. Full drilling pressure and thrust are applied, and the correction is drilled. Force on the bit is controlled from weight cells measuring drill string stress. This is telemetered to the surface through the wireline. Modulation of the thruster is controlled from the surface to match the thrust to other drilling parameters.

Other Considerations

There are a number of additional factors which need to be borne in mind. Some will be presented briefly here.

- The drilling fluid will be abrasive. Dyna-Drill specifies that the particulate matter should be less than one percent. Field personnel state that a realistic minimum is more like five percent by weight. As discussed, the system is particularly sensitive to abrasion. This is recognized, however the techniques selected for discussion were chosen from the standpoint of conceptual clarity. There are a number of design techniques for handling abrasive slurries. These can be incorporated. The elastometric techniques is almost immune to abrasion, except at its valves. These are relatively inexpensive and can be designed for easy field replacement.

- In the event it was necessary to pull the unit from the hole while deactivated, the borehole walls could cause excessive wear on the locking cells, unless special design precautions are taken. Projecting replaceable wear pads or rings would be incorporated to provide low cost replaceable wear points.

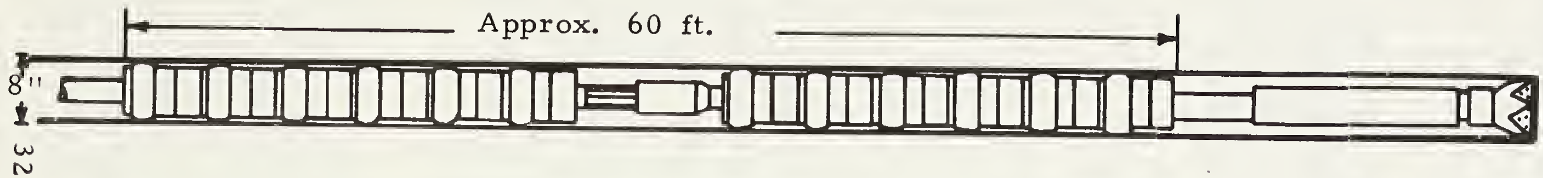
Complete System

Discussion -- Figure C.11 is a picture of a complete downhole thruster, capable of driving a precision guided 8 inch hole to depths in the order of 15,000 feet. It would generate a total thrust in excess of 100,000 pounds. It consists of two sections each composed of six single thrust units and each capable of generating average thrust of 50,000 pounds. Peak thrusts well in excess of these figures could safely be developed because of the safety factor of six used in its design. The aft section would automatically drag the drill string into the hole. It would be controlled so that the decoupling spline would present neither drag, nor thrust, to the forward unit. The forward unit would provide force to the bit in a precision controlled manner under the direction of the operator, and would advance the bit.

The unit shown incorporates the Dyna-Drill as its drilling system. It could just as easily be designed for standard rotary drilling, with the incorporation of the multiple core barrel guidance system discussed in another study. This system could provide a continuous, oriented core for the full length of the hole. Drilling costs would be far less than those for conventional drilling. In fact, the savings on a single hole would more than pay the development costs.

Alternative Concept

The system discussed above is presented for conceptual visualization of the thrust units as a system. Actually, the thrust units are modular building blocks of a system. The configuration shown in



Note:

Thrust per cell - 8000 pounds Working
24000 pounds with Safety Factor of 2.

Thrust Length - 6" per stroke

Figure C. 11 - 100, 000 Pound Thrust Down-Hole Thruster

Figure C.11 would have the same trouble propelling itself out of the hole that a conventional system will have in going into the hole. Coming out of the hole it places the drill string in compression. Beyond a critical length the string would buckle and jam. Of course, a surface unit could apply tension and the problem would be solved.

An alternative concept exploits the modular capability of the thrust units, by placing them where they are needed and only when they are needed. The configuration shown in Figure C.11 really consists of two functional units, one to pull drill string and one to apply thrust.

The number of thrust units in the aft thruster varies with the hole length and the actual friction encountered. They can best serve their function by being distributed along the drill string. Drilling would start with one thrust unit pulling drill string. The system would stay in this configuration until this single unit was working near its thrust capacity. At this time, a second thrust unit would be added to the drill string, at that point in the drill string. Each thrust unit would have its own sliding spline connections, and would be controlled by limit switches. Thus it would automatically work to keep itself isolated so that in the static condition neither compressive nor tensile forces would be transferred between sections. The thrust units would be reinforcing until that static condition was achieved. As additional thrust units were required they would be added to the drill string, at the point they were needed. The net result would be a distribution of thrust along the drill string, without a gross concentration at any one point.

The forward thrust unit in Figure C.11 provides weight on the drill bit. The amount of thrust required is a function of the rock type being drilled, and the bit being used to drill it. Each bit type is designed for a class of formation, or rock strength, and for a specific range of weights on the bit. Thus whenever a bit was changed, the required number of thrust units would be added to cover the range of design weights for that particular bit. Thus the bit would never be either over or under stressed.

The control concepts for this alternative would be slightly more sophisticated than those discussed. However they are all well within the state-of-the-art, and have already been field proven in a borehole environment.

APPENDIX D

TIME PENALTIES FOR SURVEY ACCURACY

D.1 Variables Involved

There are several prime variables in computing the penalties involved in meeting survey accuracy. The main parameter is the frequency of surveys, which defines the maximum allowable distance between surveys. This in turn reflects into time lost in inserting and removing the single shot survey instrument, and in pumping the instrument down the drill string, waiting a fixed time and then recovering it.

Guidance accuracy is specified in an allowable deviation from the projected path - in feet. In planning this allowance must be budgeted between steering errors, bias or calibration errors, and random errors.

As far as can be determined steering errors tend to be independent of hole length. Corrections are made at the bottom of the hole, on the basis of measurements also made at the bottom of the hole. Thus there are no direct functional reasons for them to increase with length. The ability to make these corrections will degrade, as the drill rod becomes more flexible with length, and friction builds up. However, once the correction angle is inserted and surveyed, there should be no functional distance relationship.

Calibration errors can be expected to increase linearly with length. However, with proper surface calibration, by surveying in the instrument against a benchmark, calibration errors can be made quite low. Random and reading errors will increase by the product of the incremental lengths between surveys and the square root of the number of points. Thus, conceptually at least they can be made as small as desired.

The total error at the end of the hole will be:

$$E_T = \sqrt{E_S^2 + (\frac{\pi}{180})^2 \quad (E_c^2 h^2 + E_r^2 I^2 N} \qquad \text{(D. 1)}$$

but: $N = \frac{L}{I}$

Thus: $$E_T = \sqrt{E_S^2 + (\frac{\pi}{180})^2 \quad (E_c^2 L^2 + E_r^2 \; LI)}$$

where:

E_t = Specified total allowable error, feet,

E_S + Steering error, feet,

E_c = Calibration error, degrees,

E_r = Random error, degrees,

L = Hole length, feet,

I = Survey interval, feet.

For fixed errors the survey increment will be:

$$I = \frac{(E_r^2 - E_S^2) \quad \underline{(180)}^2_{\pi} \quad - E_c^2 h^2}{E_r^2 \; L} \qquad \text{(D. 3)}$$

Volume II gives the time absorbed in survey as:

$$t = \text{Smts} + \frac{2L}{S_n V_s} \sum_{n-1}^{S_n} \qquad \text{(D. 4)}$$

but: $Sn = N = \frac{L}{I}$

and: $$\sum_1^n n = \frac{(N)(N+1)}{2} \cong \frac{N^2}{2}$$

Thus:

$$t = \frac{Lts}{I} + \frac{L^2}{V_s I} = \frac{L}{I} (t_s + \frac{L}{V_s}) \qquad \text{(D. 5)}$$

where:

t = total time chargable to survey, minutes

t_s = time lost in survey operations per survey, minutes

V_s = average transfer velocity per survey, feet/minutes

Combining (D.3) and (D.5) and multiplying by $(n\sigma)^2$ gives the total time at the $n\sigma$ confidence level required for survey.

$$t = \frac{(n \quad E_n)^2 L^2 \quad (t_s + \frac{L}{V_s})}{3283\ (E_r^2 - E_s^2) - E_c^2 L^2} \text{minutes} \tag{D.6}$$

or:

$$T = \frac{(n\, \sigma\, E_n)^2 \quad L^2 \quad (t_s + \frac{L}{V_s})}{60\ (3283 \left[E_t^2 - E_s^2\right] - E_c^2\ L^2)} \text{ hours} \tag{D.7}$$

If the three classes of error are known, then it is possible to compute the cost in hours to insure that the actual error is less than the specified error. However this is a probabilistic expression. If the known errors are specified by their standard deviation, (σ) values, then the value of E will also be the standard deviation. It can be expected that 68 percent of the time the resulting error will be less, and 32 percent of the time it will be more.

Example I

The best estimates of the state-of-the-art would give the following values:

$E_s = \pm\ 6$ ft.

E_c = .1 degree

E_r = 1 degree

V_s = 200 ft/min

t_b = 10 minutes

Actually, Equation (D.7) derives the total time on the basis of adjusting the interval length so that, with the use of the specified errors, the total error will just be equal to the total allowable Error, E_T. From an operational standpoint, this is unrealistic. Surveys are taken when new lengths of drill rod are added. However, it does define the limiting condition.

Figures D.1.a, b, and c show Equation (D.7) plotted for 1, 2, and 3σ confidence levels. Also shown on these figures, in dashed lines, are the cumulative survey times, from Equation (D.5), for various survey intervals. As long as the solid lines of Equation (D.7) are below the dashed lines, the error, E_T, will be less than the specified maximum value, if the surveys are taken at the listed intervals.

Figures D.1.a, b, and c also show the effect of varying the assumed calibration error. As long as this error is below .05 degrees it generates little impact on the system costs. However, allowing E_c to rise as high as .1 degree has tremendous impact, especially at the higher confidence levels.

These curves also show the danger of overspecified tolerances. At the 2σ (95 percent confidence) level and a .05 degree calibration error, a survey every 40 feet is satisfactory. This can be seen by reference to Figure D.1.b. If the required confidence level is raised to 3σ (99.7 percent), even a 20 foot survey interval is marginal.

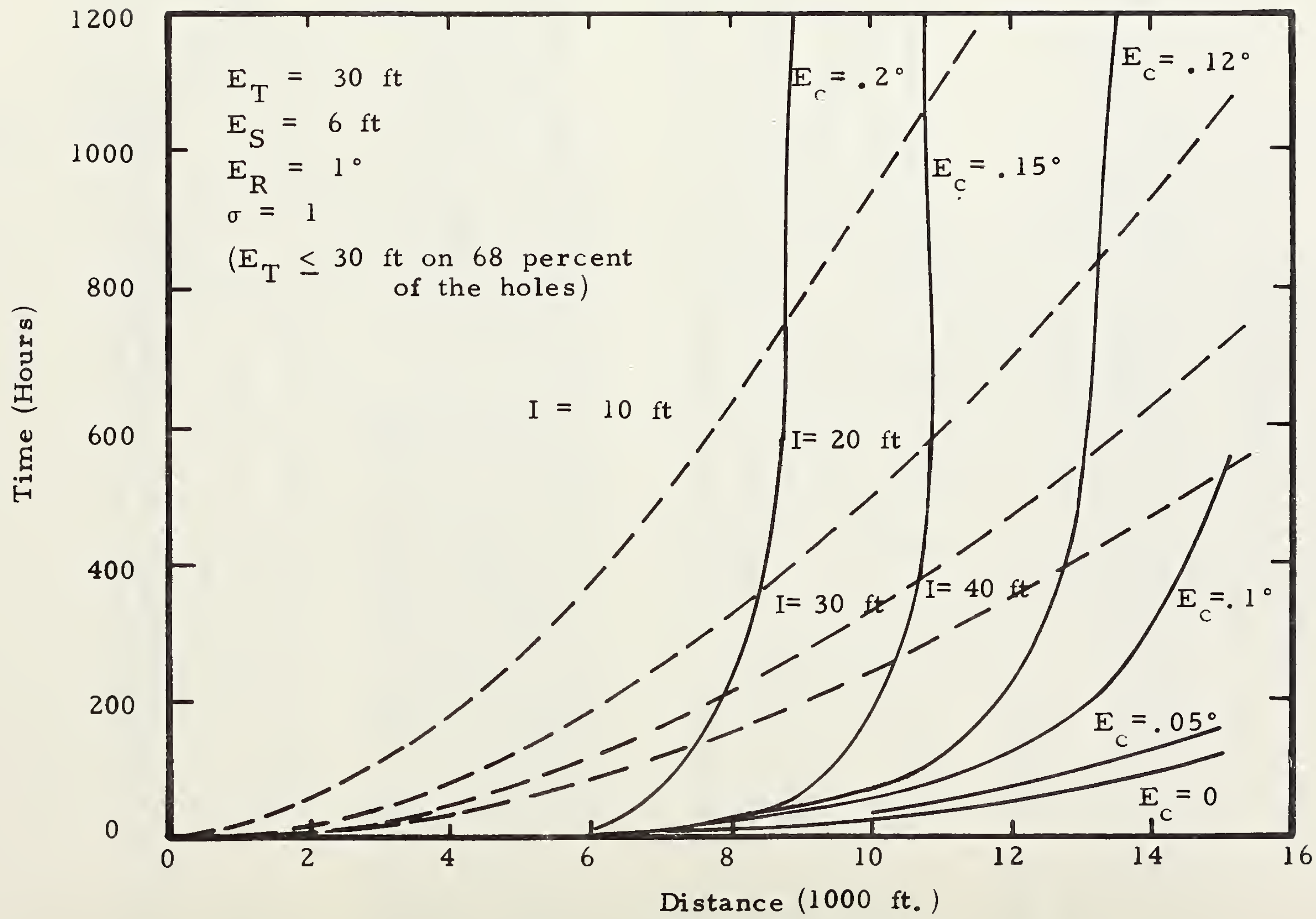


Figure D.1a - Cumulative Survey Hours to Achieve Specified Accuracy at 1 σ Confidence

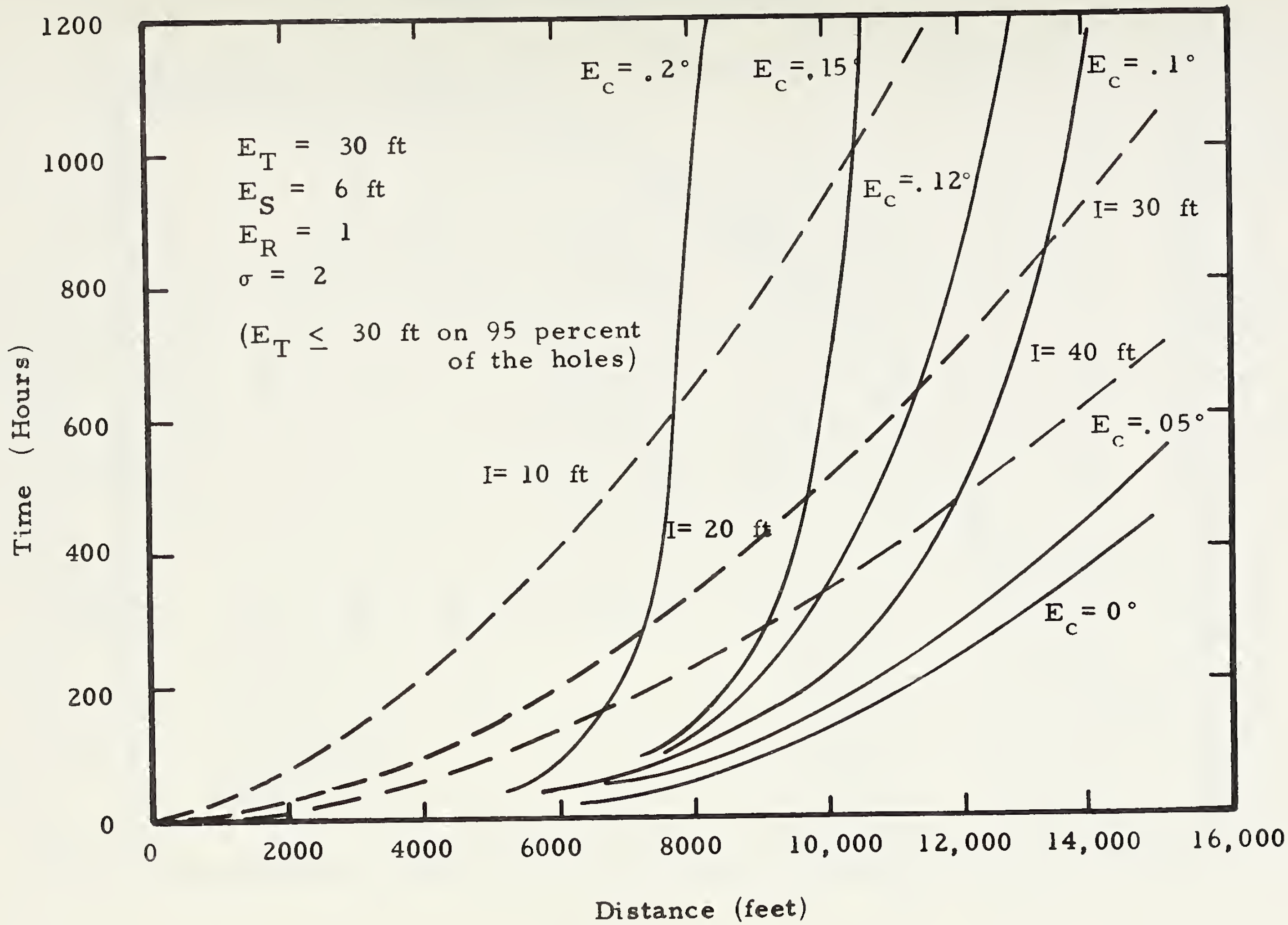


Figure D. 1b - Cumulative Survey Hours to Achieve Specified Accuracy at 2σ Confidence

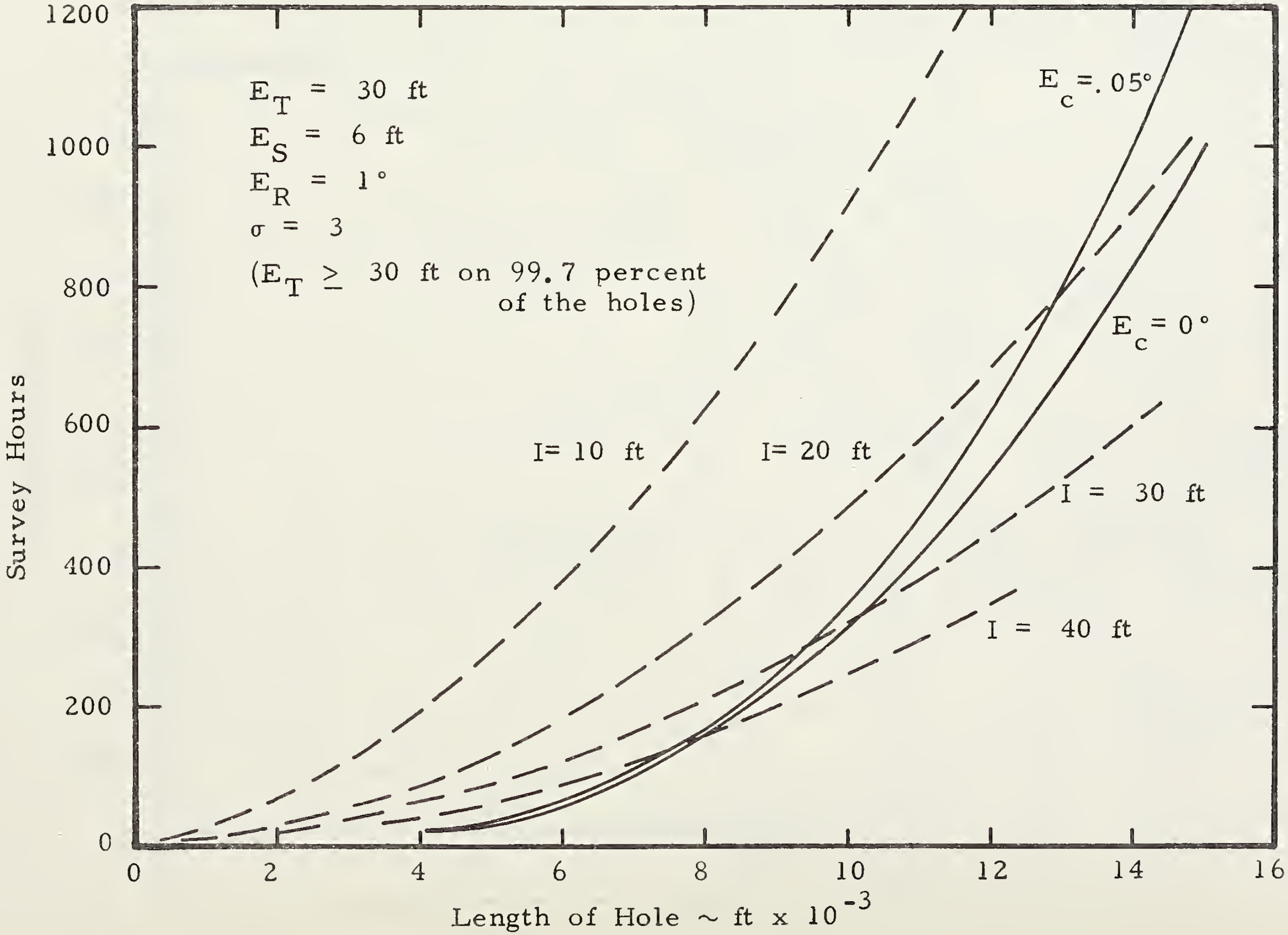


Figure D.1c - Cumulative Survey Hours to Achieve Specified Accuracy at 3σ Confidence

Figures D. 2. a, b, and c show the total time chargable to survey to be below a specified maximum error 95 percent (2) of the time. This error, E_M, is defined as:

$$E_M = \sqrt{E_t^2 - E_s^2}$$

This conversion is plotted in Figure D. 3.

These curves emphasize several factors:

- Horizontal holes have not yet been drilled to lengths where calibration has become a problem.

- As lengths increase calibration errors can become a significant cost factor by requiring excessively short survey intervals to remove as much of the random error as feasible.

- There is a critical length,

$$L = \frac{\sqrt{57.3 \quad E_t^2 - E_s^2}}{E_c}$$

beyond where the specification for E_T cannot be met.

D. 2 Specification of Allowable Calibration Error

D. 2. 1 Generalized Treatment of Error Formula

Equation (D. 7) is:

$$T = \frac{(n \sigma \quad E_r)^2 \quad (t_s^2 + \frac{L}{V_s})L^2}{60 \quad (\frac{180}{\pi})^2 \quad \left(E_t^2 - E_s^2\right) - E_c^2 L^2} \qquad \text{(D. 7)}$$

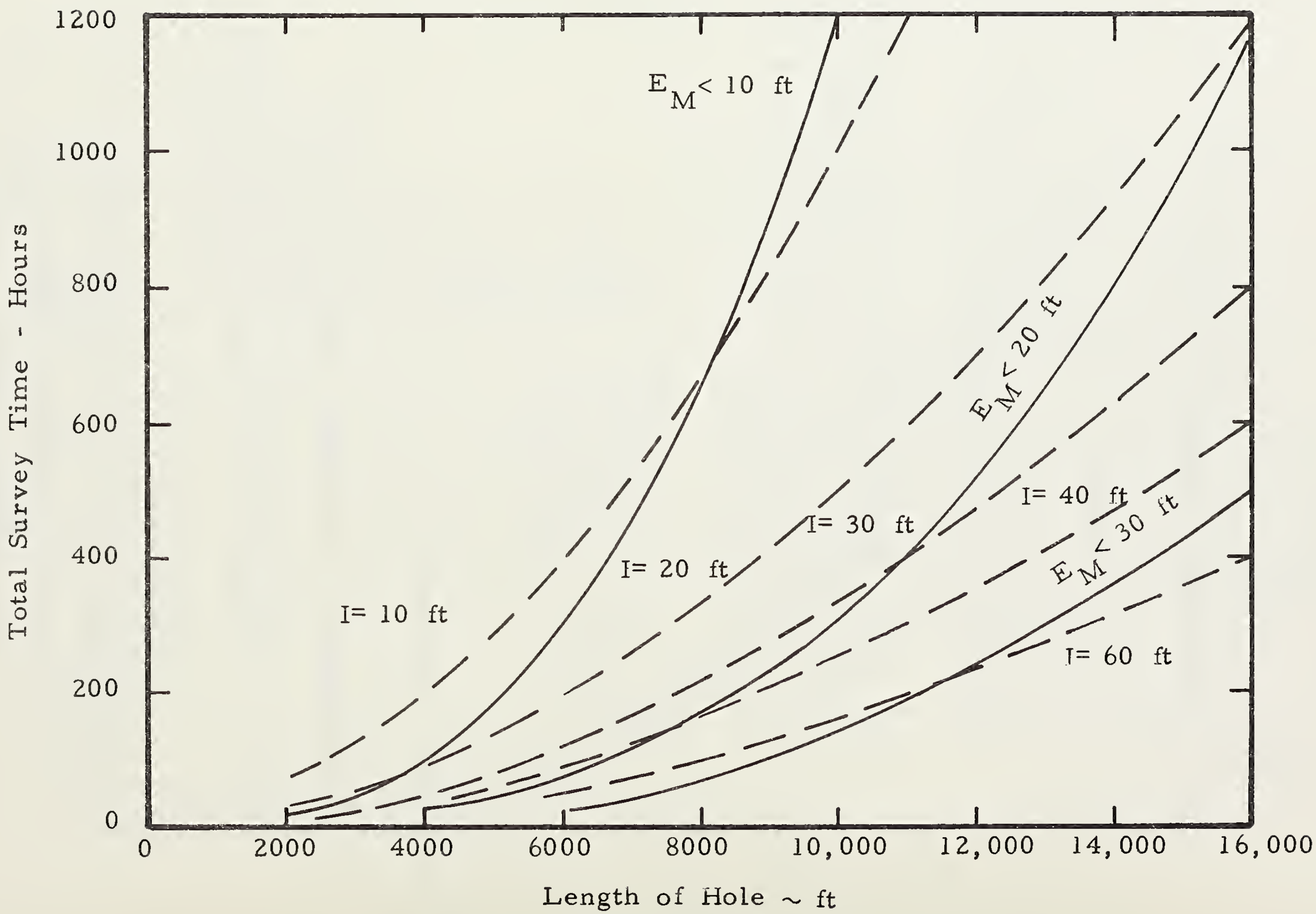


Figure D. 2a - Time Chargable to Survey for Specified Max Error Calibration Error = 0°

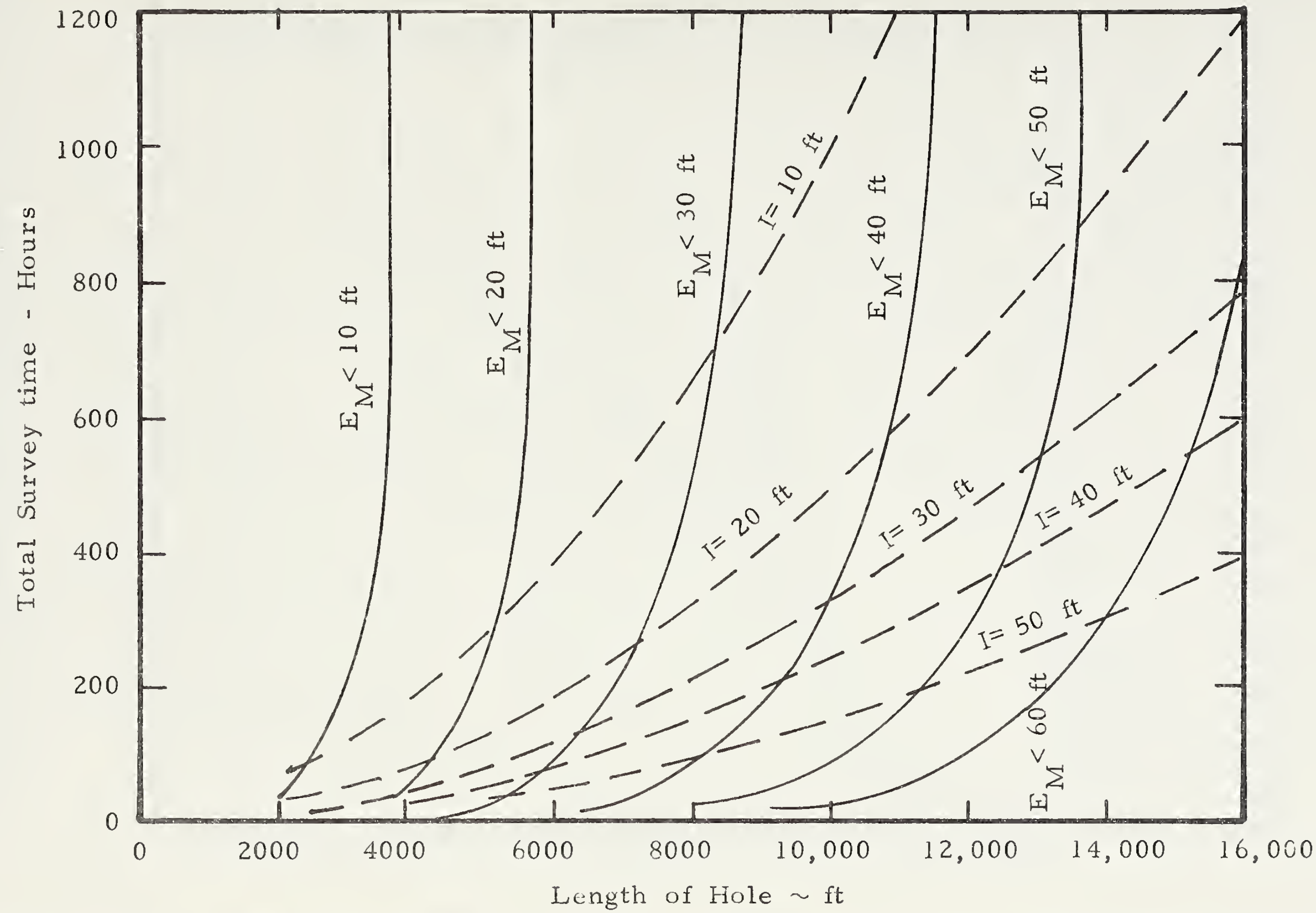


Figure D. 2b - Time Chargable to Survey for Specified Max Error Calibration Error = .2°

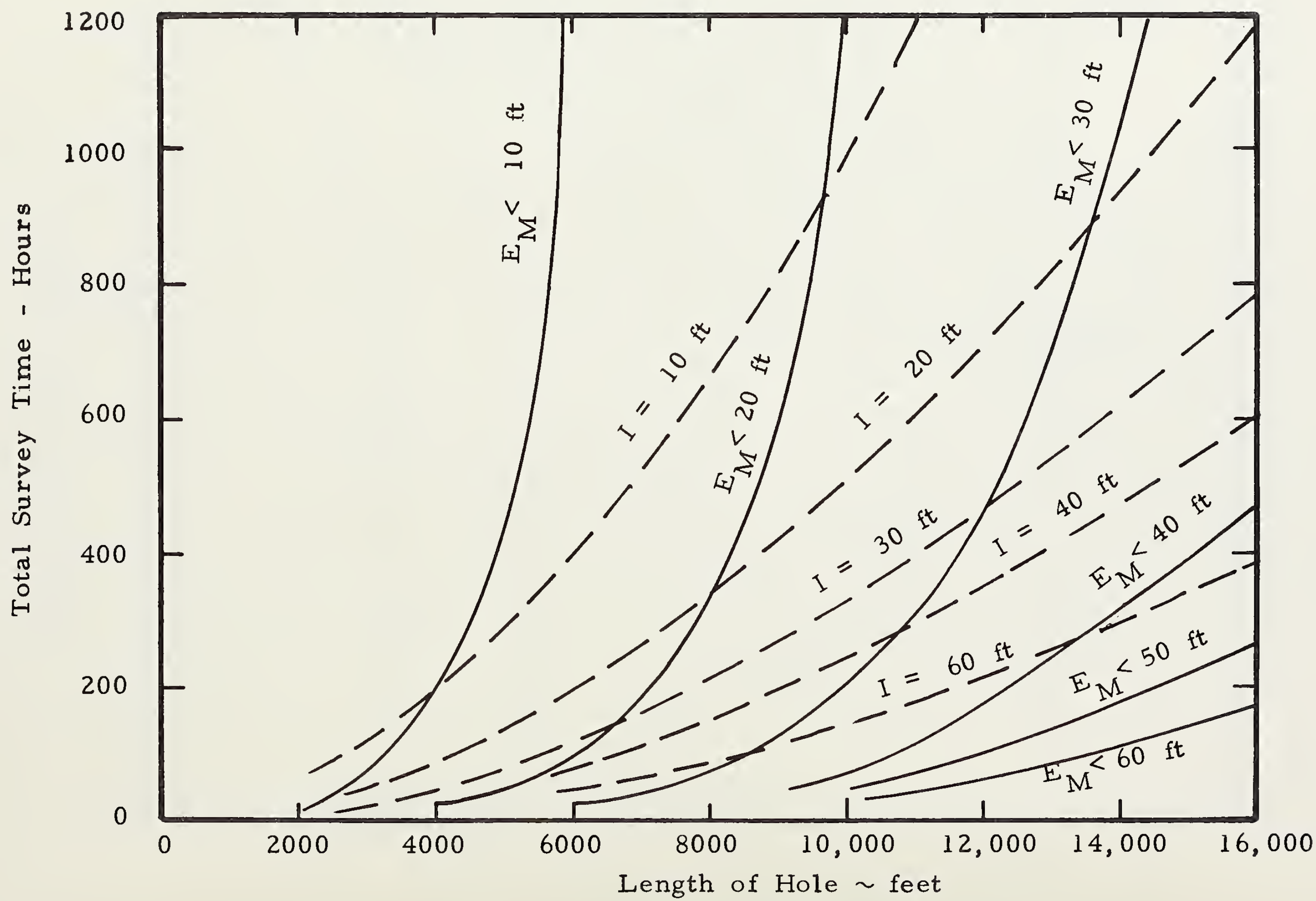


Figure D.2c - Time Chargable to Survey for Specified Max Error Calibration Error = .1°

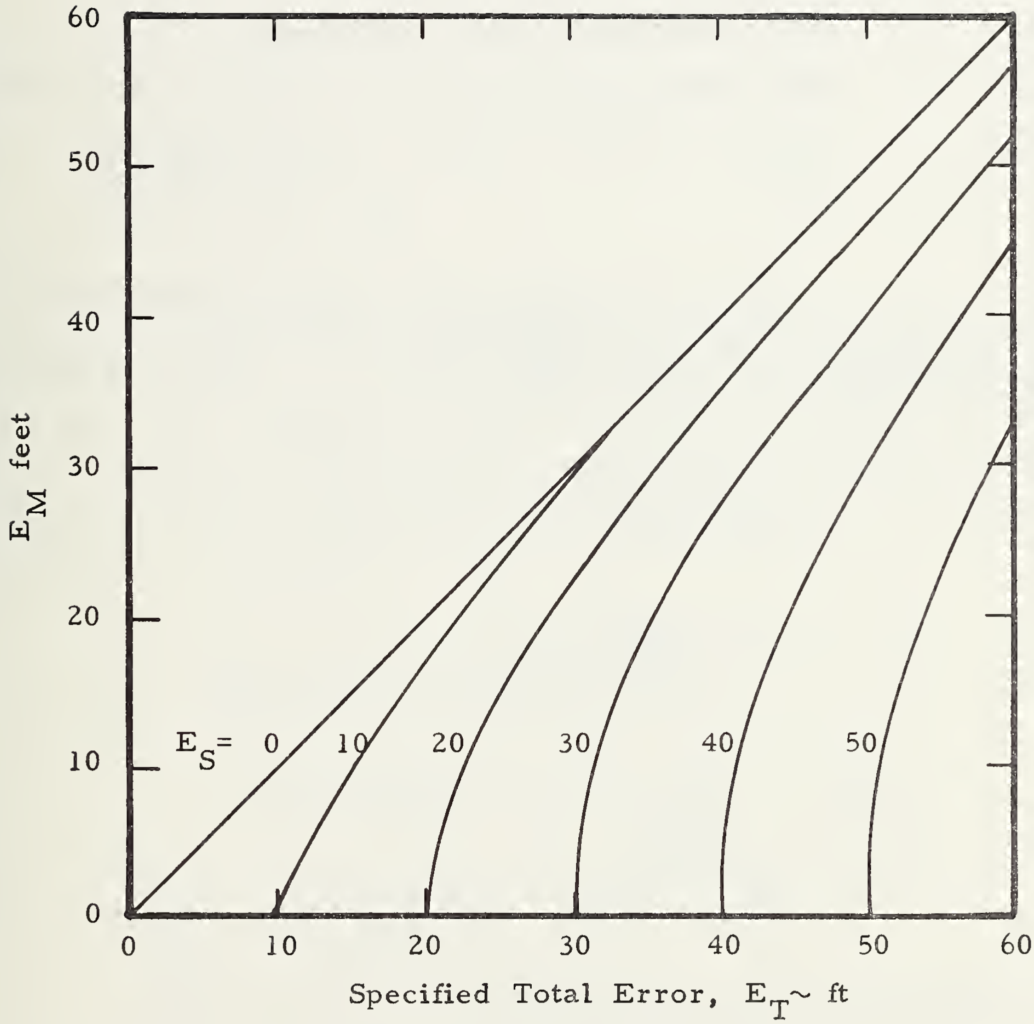


Figure D. 3 - Determination of E_M for Use in Figure 2

where:

T	=	Total time chargable to survey - hours
N	=	The specified confidence level in number of standard deviations
E_r	=	Standard deviation of reading error - degrees
E_T	=	Total maximum allowable error - feet
E_S	=	Steering error - feet
E_c	=	Calibration error - degrees
t_s	=	Time lost per survey - minutes
L	=	Hole length - feet
V_S	=	Average transfer velocity of survey package ft/min.

As L increases, L/V_S becomes greater than t_s and little error is introduced by assuming $t_s = 0$. Equation (D. 7) can then be manipulated into the form:

$$T = \frac{R_1^2 L^3}{60V_S (1-R_2^2 L^2)} \tag{D. 8}$$

Where:

$$R_1^2 = \frac{\left(\frac{n\pi E_n}{180}\right)^2}{(E_t^2 - E_s^2)} \tag{D. 9}$$

$$R_2^2 = \frac{\left(\frac{\pi E_c}{180}\right)^2}{(E_r^2 - E_s^2)}$$

Thus the values of R are error ratios.

for: $R_2 L^2 << 1$

$$T \cong \frac{R_2^{\,2} L^3}{60\ V_S}$$

and as $R_2 L^2 \rightarrow 1,\quad T\ \infty$

Let $(E_T^{\,2} - E_S^{\,2}) = E_M^{\,2}$

then: $R_2 = \frac{\pi}{180}\ (\frac{E_c}{E_n})$

Figure D. 4 shows a plot of the time factor contribution of normalized calibration error, V_S, the error itself.

i. e., $\frac{1}{1-R_2^{\,2}\ L^2}\ \ Vs\ \ R_2 L$

It can be seen that up to the point of $R_2 L = .5$ the contribution is small. The calibration error penalty increases rapidly beyond that. The conversion factor, $\pi/180$ simply converts E_c from degrees to radians. Thus the error contribution of the calibration error in radians times the length should be less than half the maximum allowed error, or:

$$\frac{\pi}{180} E_c L \leqslant .5 \sqrt{E_t^{\,2} - E_s^{\,2}}$$

$$E_c \text{ in degrees} \leqslant 28.65 \sqrt{E_t^{\,2} - E_s^{\,2}}$$

for: $L = 15{,}000$ feet

$E_r = 30$ feet

$E_s = 0$

$E_c \leqslant$ $(.0573^{o} = 1$ mile radian)

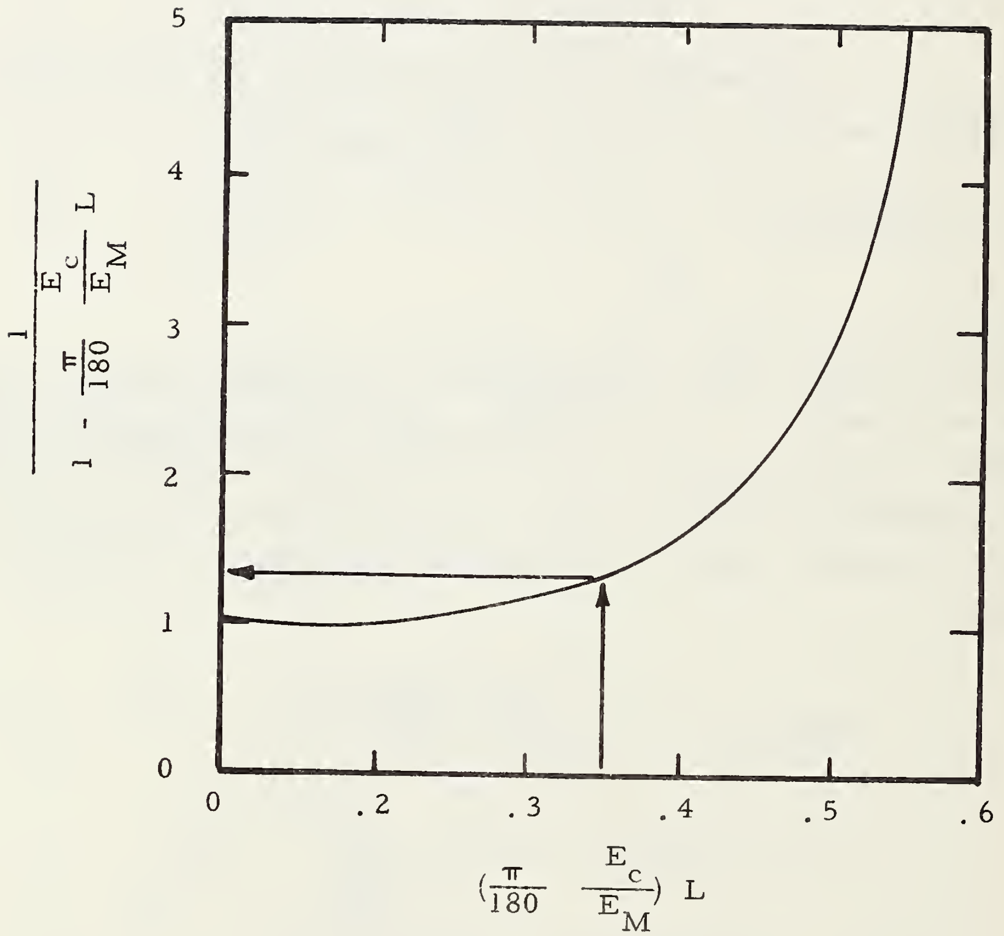


Figure D.4 - The Effect of Normalized Calibration Error vs. Length

D.2.2 Demonstrability of Calibration Accuracy

A major deficiency of the current single shot/ multishot equipment is their rather large

In order to demonstrate or prove a calibration accuracy of better than one mil, (.0573°) with a random reading error of one degree an exhorbitant number of samples must be taken.

$$E_c \leq .0573^\circ \text{ within 2 } \quad \text{(95 percent) confidence}$$

$$E_c \leq \frac{2E_r}{n}$$

$$n \leq \frac{4\,(E_r)^2}{(E_c)^2} = 4\left(\frac{1}{.0573}\right)^2 = 1218$$

Thus, readings from over 1200 pictures would be required to establish the calibration accuracy to this degree. We are left with the inherent biases of the manufacturing process undefined unless a series of tests such as this are run.

D.3 Conclusions

Theoretically existing equipment will meet the requirement to hold the error under thirty feet in 15,000 feet.

However, when the total picture is analyzed, the performance will be marginal, and the cost penalties high. Beyond 5,000 to 7,000 feet, a better less costly approach is needed.

Task B and C efforts should concentrate on this problem. Either an in-hole survey/steering tool, with wireless telemetry or possibly a gyroscopic corebarrel guidance system hold promise. They both attack the Time Equation (C.7) to eliminate the major time costs, and they are both amenable to rapid and accurate calibrations with high accuracy.

APPENDIX E

SURVEY TECHNIQUES IN SUPPORT OF CONTINUOUS CORING

E. 1. Introduction

The ability to take continuous, oriented and interpretable core would seem to be almost invaluable for an exploratory horizontal drilling system. We have examined the problem of taking such core and it seems that technically feasible and economical systems, which will meet all the requirements of this program, and take continuous core can be achieved.

This study examines two basic approaches to the taking of continuous core, and have selected one for further investigation at greater depth. The two candidates considered are, the use of a dual drill string with core being recovered through the center string by reverse flow, and the use of two core-barrels where one core-barrel is being retrieved while the other continues to collect core. Although the study briefly discusses the reverse flow technique, the two core-barrel technique seems to hold the most promise for economically meeting the systems requirements, and is treated in greater depth.

E. 2. Reverse Flow Core Recovery

The reverse flow core recovery technique is already on the market and seemed initially to hold a great deal of potential for core recovery in long horizontal boreholes. In this technique two drill strings are used, one inside the other. The inner type can be considered as a core-barrel with its length equal to that of the hole. As the system drills in the conventional manner core enters the inner pipe where a core-breaker breaks it off at convenient lengths and it is carried to the surface by the pressure of the drilling fluid at the bit. This approach presents the conceptual simplicity for complete core recovery without the use of core-barrels. However it creates many undefined and unsolved problems, and generates a serious system impact in the area of survey and guidance. We see no mechanism for marking the orientation of the core as it is taken. It is highly doubtful if, after being washed for almost 3 miles down the center of a rotating drill string, the various pieces of broken or shattered core would retain their orientation, one piece with respect to the next. Certainly there would be little hope of recovering, retaining and identifying any gouge material which originally existed between any two adjacent pieces of core.

In addition to the obvious increase in complexity of the problems of drill pipe handling on the surface, as the drill string is either inserted or withdrawn, this approach presented serious problems in survey and guidance for the rest of the system. Historically the center of the drill string is used to transfer both single-shot and multi-shot survey and orientation equipment between the surface and the bottom of the hole. We see no mechanism to use conventional survey techniques in conjunction with this type of core recovery. The economics of first having to empty the center drill pipe of core in transit or to remove it every time a survey instrument has to be run down the hole, would soon become prohibitive.

The survey and guidance problem could be solved by the use of a down-hole survey and orientation package. The data could be brought to the surface by a wireless telemetry system. A system such as this was developed for the Bureau of Mines for its horizontal methane drainage drilling program. This system could be mounted in nonmagnetic drill collars directly behind the drill bit. It would require some major redesign effort to package this system to fit into the annular space surrounding the center core recovery drill string. The system would be subject to all the indeterminacies and errors inherent in a purely magnetic survey system. However these could be overcome by periodically pumping the residual core out of the central drill pipe and running gyroscopic surveys. An acceptable alternative would be to run gyroscopic surveys whenever the drill string was cleaned for removal to make a direction change or to replace a worn bit. Although the concept which we have described is technically feasible we believe that from an over-all standpoint it suffers when compared to more standard wireline core-barrel recovery techniques.

E.3. Concurrent Drilling and Survey

A separate study addressed to the use of high angle gyroscopic survey/steering tools indicated that this technique held considerable promise in reducing the time chargeable to survey and orientation. However this study addressed itself to the use of the tool in conjunction with a down-hole hydraulic motor, such a Dyna-Drill. A question naturally arises. Could similar savings be accrued with a guidance package attached to a core-barrel in wireline coring?

The drill string does not rotate when using a Dyna-Drill. Wireline coring is a rotary drilling technique, thus the drill string must continue to rotate while the tool is pumped down and recovered, if maximum time savings are to accrue. There is a question whether a nonrotating cable inside a rotating drill string is feasible. A simple calculation would indicate that the actual twisting torques developed over even 15,000 feet do not seem excessive.

Let

W_W = the weight of cable in pounds per foot
r = the radius of the cable in feet
L = the length in feet
f = the coefficient of friction

$$T = WLrf$$

The cable will be well lubricated with water and be under tension due to the water pressure on the tool. The coefficient of friction for water lubricated smooth surfaces in the order of .05 to .1 for a 3/8 inch cable W = .2 pounds per foot.

$$T = \frac{.2 \times 15,000 \times 3 \times .05}{12 \times 16} = 2.34 \text{ foot pounds}$$

Thus for the range of probable frictions the torsional component would be in the order of two to five foot-pounds. Although data on the torsional limits of logging cables is not available it would seem that five foot pounds is not excessive for a 3/8 inch cable.

Although the feasibility of operating the cable in a rotating drill string needs added verification, the concept seems sufficiently feasible to warrant further investigation.

E.4. Core-Barrel Guidance System

The overall concept presented involves the use of two core-barrels. While an empty core-barrel is in place being filled by normal drilling procedure, the full one, is being retrieved by a solenoid actuated over-shot attached to a gyroscopic survey and orientation package on a wire-line through the center of the drill string.

Although discussed as a single unified system, the attachment of the core-barrel to the guidance system, and the use of two core-barrels simultaneously, are actually distinct and independent concepts. The single core-barrel guidance approach will be discussed first. It will then be shown how, with modest additional development, this concept can be expanded to provide continuous core with minimal interruption of the drilling process.

E.4.1 Single Core-Barrel Guidance Package

Figure E.1. is a conceptual sketch of a core-barrel guidance system. Because of disproportionate ratios of lengths to

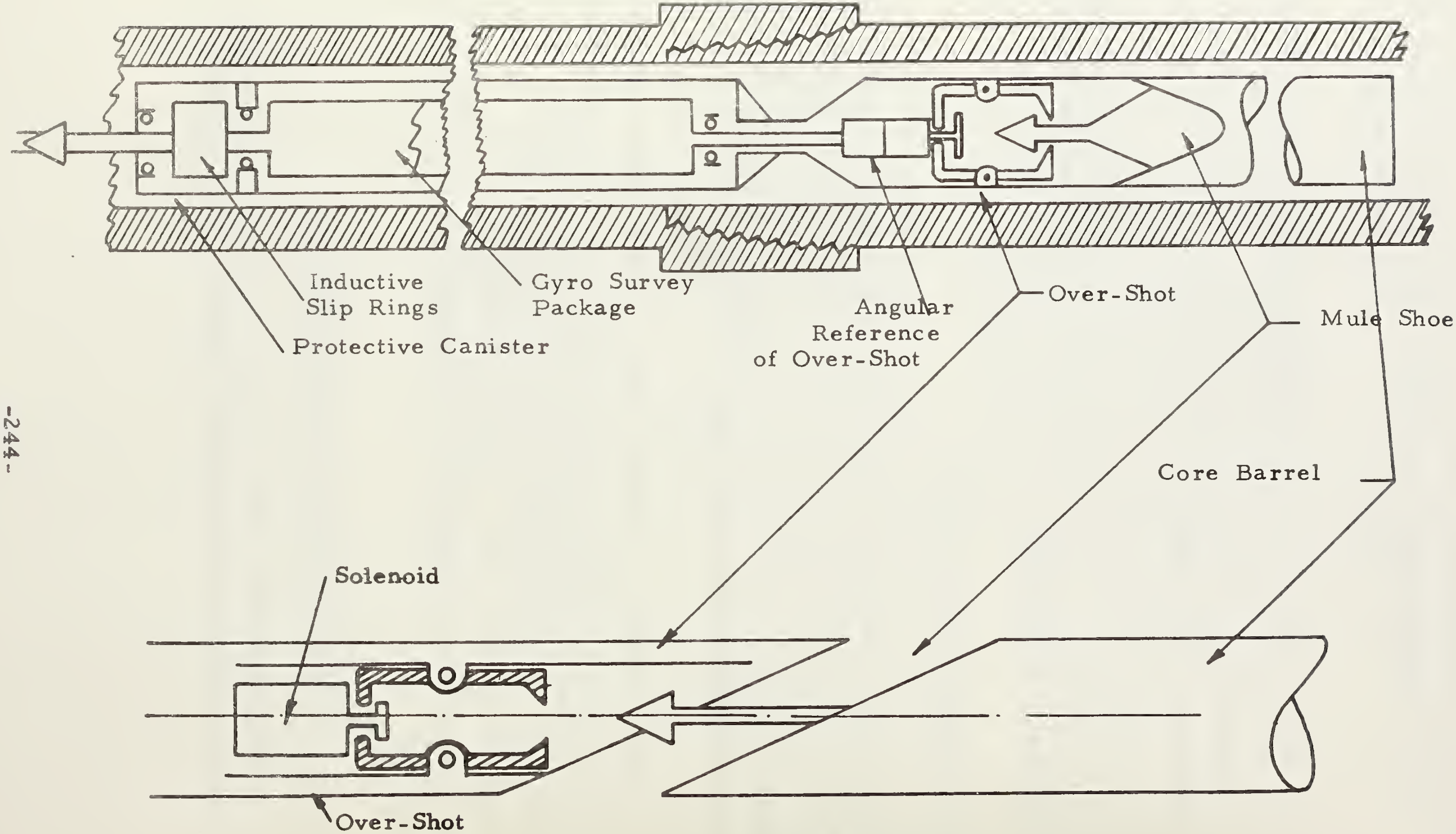


Figure E.1 - Basic Core-Barrel/Survey Package diameters little attention has been made to draw it to scale. The basic guidance package is a slim hole gyroscopic survey and orientation system of the type which can be obtained commercially today on custom order. The gyroscopes in this system are gimbel mounted. Thus the case can assume any azmuthal orientation about the axis of the package without affecting the accuracy of the readings. However this package is designed to be transferred down non-rotating drill strings. The present concept involves pumping the package down the drill string while drilling is in operation. Since it is questionable whether a basic package could be continually rotated about its axis and still retain the high degree of survey accuracy required, the basic package is shown as being bearing-mounted in a thin walled protective canister which is free to rotate with the drill string. The interior package can be pendulously mounted so that the rotation of the drill string need not transfer to the gimble mounts of the gyroscopes. The wire line to which the package is attached would also be subjected to the drill string rotation, however this will result in a torsional twist of the cable rather than a continuous rotation. To insure isolation the cable connects to the inner package through a set of inductive slip rings. Thus the package remains as nearly isolated as possible. Below the guidance canister is a solenoid actuated over-shot. The over-shot is mounted to the canister which contains the feed-through of an angular transducer to the inner gyro reference package. Thus angular reference of the over-shot with respect to the gyro horizon is always known. The core-barrel which attaches to the over-shot with a mule-shot alignment cam, can be remotely engaged or disengaged from the surface. Near the front of the core-barrel are shown a series of small diamond scribing broaches. These will make the orientation of the core as it is taken. In turn the core-barrel is aligned with the mule-shoe which can only be picked up at one orientation of the over-shot. Thus a reading taken of the orientation of the over-shot just before the core-barrel is retrieved will define the orientation of the core in the core-barrel. Although not shown in the drawing, the core-barrel has inner and outer sleeves. The outer rotates with the drill string while the inner is attached to the mule-shoe and is kept from rotating by the core.

In operation with a single core-barrel the over-shot would not be needed. The guidance package would be attached to the core-barrel each time an empty core-barrel was pumped down the drill string, it would be removed with the full core-barrel. While being pumped down and retrieved, it can conduct a continuous survey of the hole. Alternatively, its drift rate could be measured from the surface and while the core-barrel was filling at the bottom. The drift rate could be measured again at the bottom for an additional calibration. This would give an added measure of accuracy to the system. The amount of data required to be processed for this operation would be such that it would be almost mandatory that the surface instrumentation include either a minicomputer or some form of advanced microprocessor. However, the complexity of the surface instrumentation would be no worse than the processing equipment currently used for in-hole steering tools. Even without the second core-barrel, this system would provide considerable cost advantage, but the transfer and survey operations could not take place while the drilling was continuing. Thus, in projecting the cost of the system, only the hours chargeable to survey need not be considered as separate time items.

E.4.2 Two Core-Barrel System

The addition of a second core-barrel to be used in conjunction with the core-barrel guidance system is conceptually simple. By this approach it is possible to retrieve a full core-barrel and replace it with an empty one so that drilling can continue during the process of core-barrel retrieval. This is accomplished by use of a pair of transfer tubes located down hole close to the drill bit. These tubes operate just like a railroad side track and switching system which allows a train going in one direction to be switched to the side so that one going in the opposite direction can pass. The operation of this technique is shown in the sequence of pictures in Figures E.2.a through E.2.f, which are intended to be essentially self-explanatory. The discussion of the

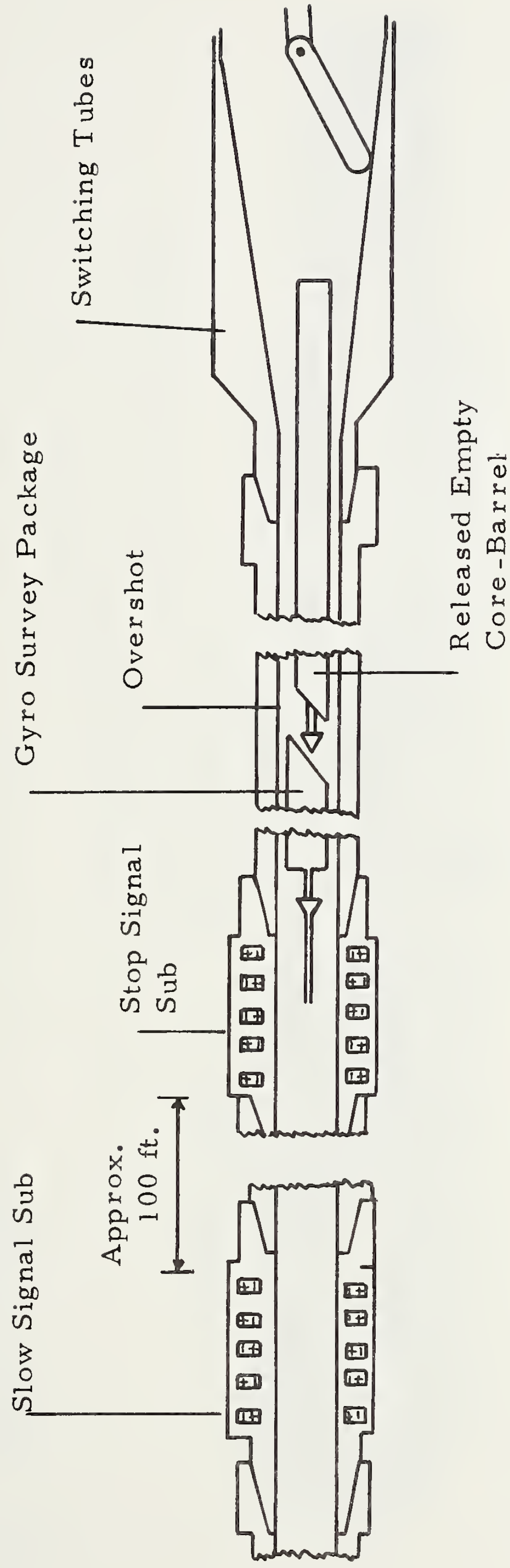
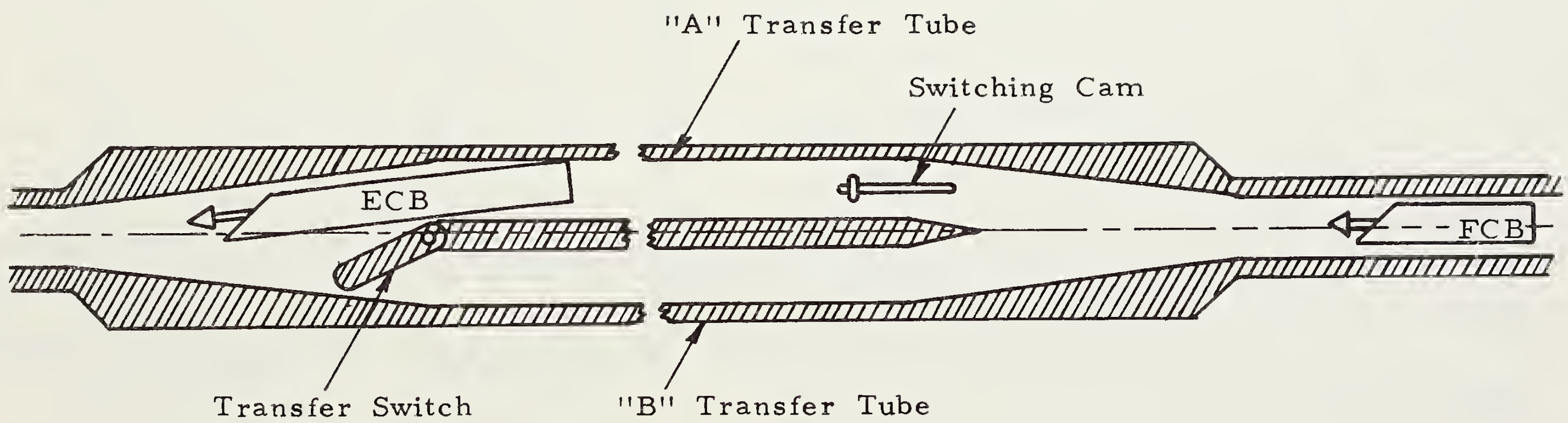


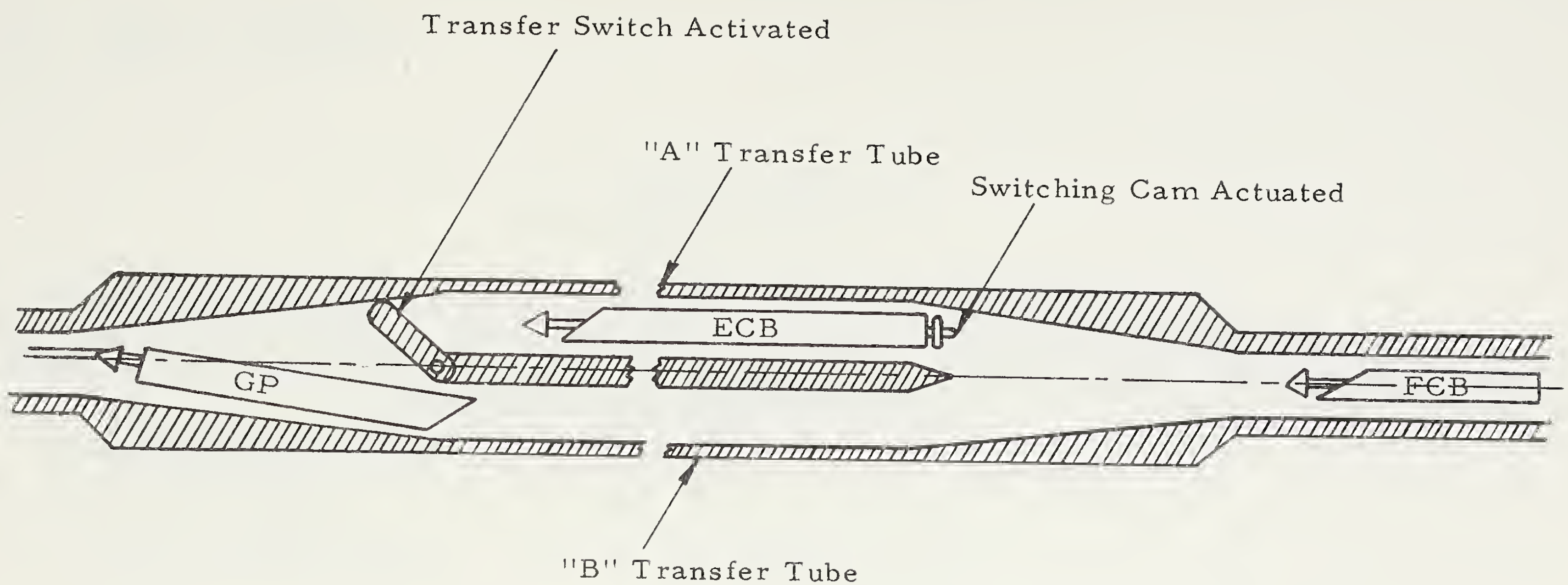
Figure E.2.a - Start of Switching Process



Key:

GP - Guidance Package
ECB - Empty Core-Barrel
FCB - Full Core-Barrel

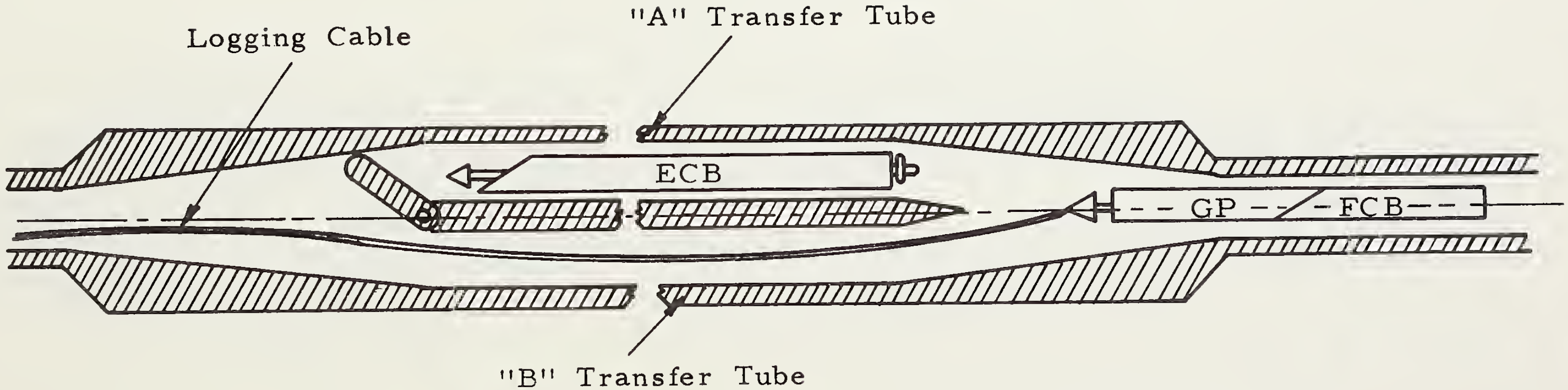
Figure E.2.b - Empty Core Barrel Entering Tube "A"



Key:

GP - Guidance Package
ECB - Empty Core-Barrel
FCB - Full Core-Barrel

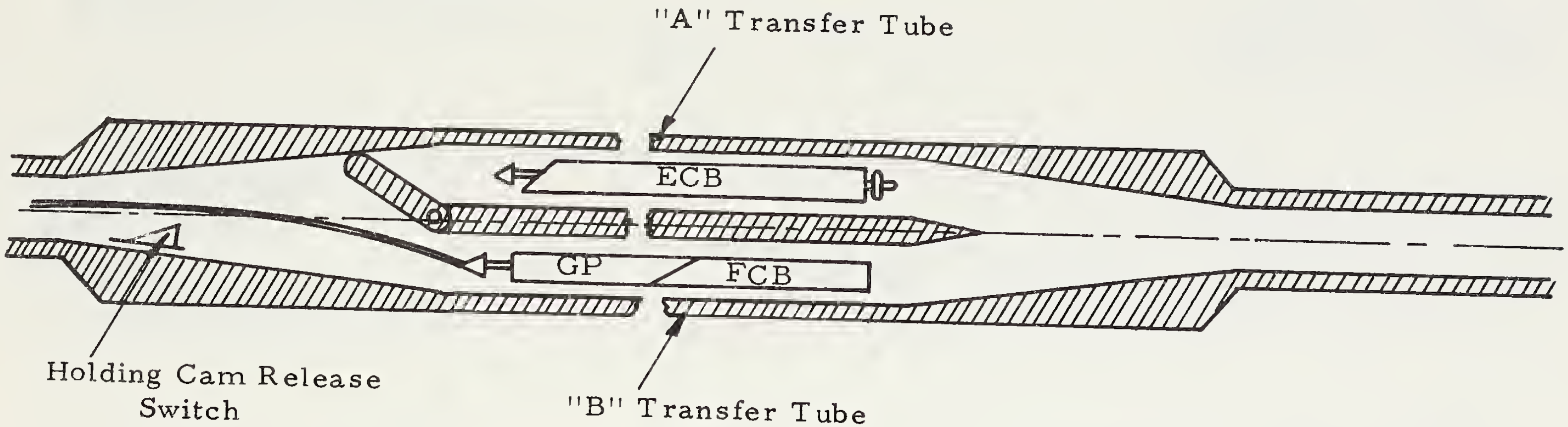
Figure E.2c - Guidance Package Entering Bypass Transfer Tube "B"



Key:

GP - Guidance Package
ECB - Empty Core-Barrel
FCB - Full Core-Barrel

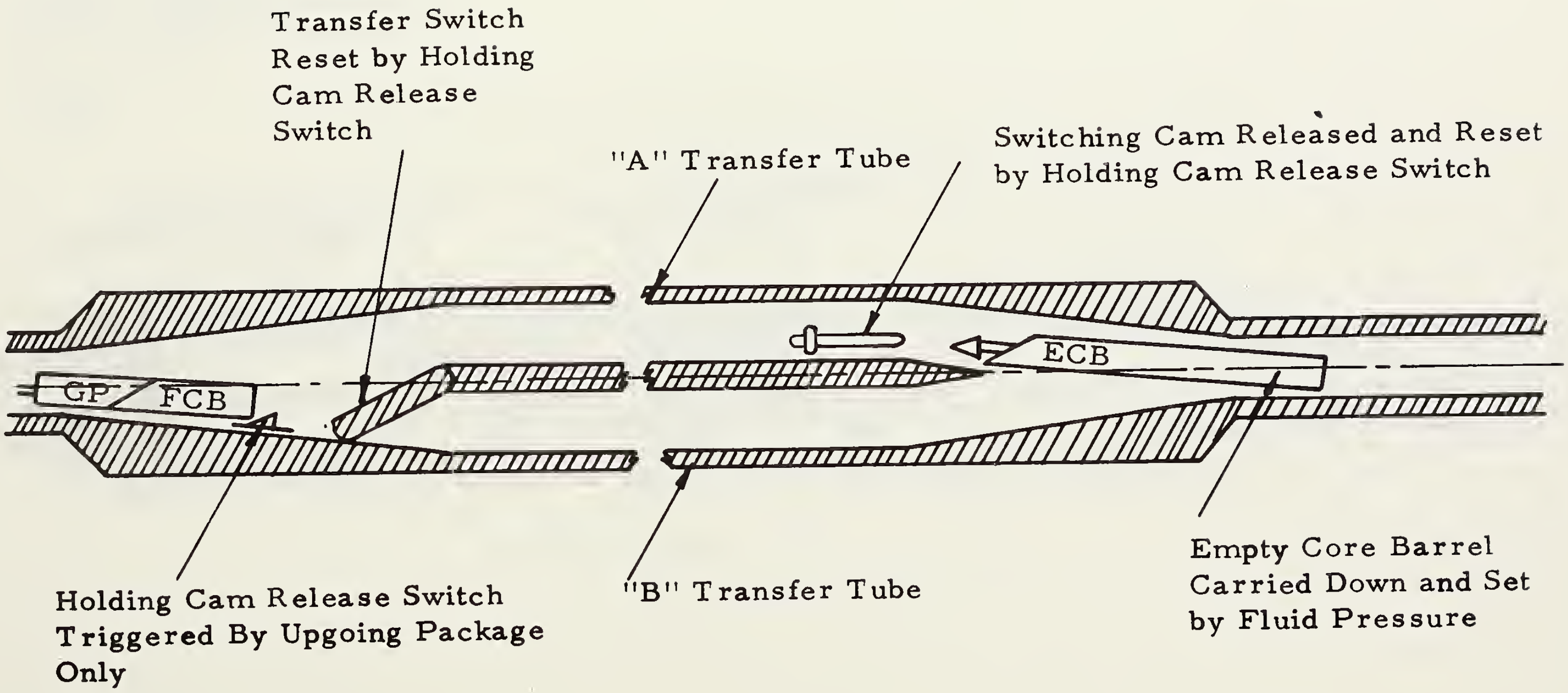
Figure E. 2d - Guidance Package Attached to Full Core Barrel.



Key:

GP - Guidance Package
ECB - Empty Core-Barrel
FCB - Full Core-Barrel

Figure E. 2e - Removal of Full Core Barrel



Key:

GP - Guidance Package
ECB - Empty Core-Barrel
FCB - Full Core-Barrel

Figure E. 2f - Completion of Core Barrel Transfer

sequence starts with a core-barrel in place being filled and an empty core-barrel in transit down the drill string, being transferred at fluid velocity. In order to insure minimum transit time, as well as adequate chip removal from the hole, fluid velocity in the drill string is moderately high. It should range in the order of 350 feet per minute. At this velocity, there is a considerable head of water behind the core-barrel guidance package, thus when it is stopped the deceleration action must take place over an appreciable distance. The velocity head of the water must be given time to convert itself into an added pressure head to maintain its flow rate through the annulus between the guidance package and the wall of the drill string. The down-hole portion of this system starts in the sequence with an advance warning sub inserted in the drill string several hundred feet above the point where the package must be brought to an initial stop. This sub is shown as containing a set of permanent magnets spaced along its axis to provide a space-coded, unique signal. These magnets activate a set of correspondingly spaced magnetic reeds in the guidance package to provide a slow down signal to the operator. The package decelerates until it passes a second coded sub which signals that it is at the proper location for the package to stop. The empty core-barrel is released, and carried forward by fluid pressure into the switching tubes. This sequence is shown in Figure E.2.a. Figure E.2.b shows the general structure of the switching tubes and the logic cam that controls the switching action. Here again, the pictures are distorted to show concept rather than engineering design, with the vertical scale being magnified almost 100 times with respect to the horizontal. The core-barrel switching section consists of two transfer tubes each slightly greater than 2 inches in diameter. The upstream entry to these tubes is controlled by a transfer switch which directs the fluid flow into either one tube or the other. In normal operation, the flow is directed into the transfer tube labeled "A" on the diagram, an empty core-barrel being carried down-stream by fluid pressure thus enters this tube. In tube A, the empty core-barrel is brought to rest and held by a switching and core-barrel holding cam. The pressure of the empty core-barrel on this cam causes the transfer switch behind it to switch to transfer tube B. Thus, when the guidance package and wireline are released to come down-stream, they will bypass the empty core-barrel through this second transfer tube. This action is shown in Figure E.2.c.

Figure E.2.d shows the guidance package having passed completely through the switching section and attaching itself to the full core-barrel by standard wireline retrieval techniques. In Figure E.2.e, the guidance package and full core-barrel are being withdrawn, once again through transfer tube B and bypassing the empty core-barrel in transfer tube A.

Figure E.2.f shows the completion of the transfer cycle as the full core-barrel emerges from the second transfer tube activating a holding cam release switch. This is a mechanical ratchet type switch which is sensitive only to motion of the package as it moves upstream. The action releases the empty core-barrel which is carried down-stream by fluid pressure and seats itself in the proper position to receive additional core. It is locked in place by fluid pressure. As the empty core-barrel emerges from transfer tube A, it releases the holding cam which moves upward under spring load, resetting both itself and the transfer switch so that the cycle can repeat.

The description of the two core-barrel transfer process has been presented from a mechanical aspect purely as an aid to visualization. Actually, it is a logical sequence of operations which could be initiated and controlled by any one of a number of design techniques. The entire operation could be electrical, it could be hydraulic, through the use of some form of fluid logic, or it could be mechanical as discussed. In addition, there are a number of ancillary operations which must take place during the transfer cycle. Figure E.3 presents the operation from the standpoint of a logic flow and control diagram. The entire process is simple and straightforward. It could, and probably should, be automated to a great extent. The diagram of Figure E.3 shows how the process could be automated through simple off-on controls and signals transmitted to the

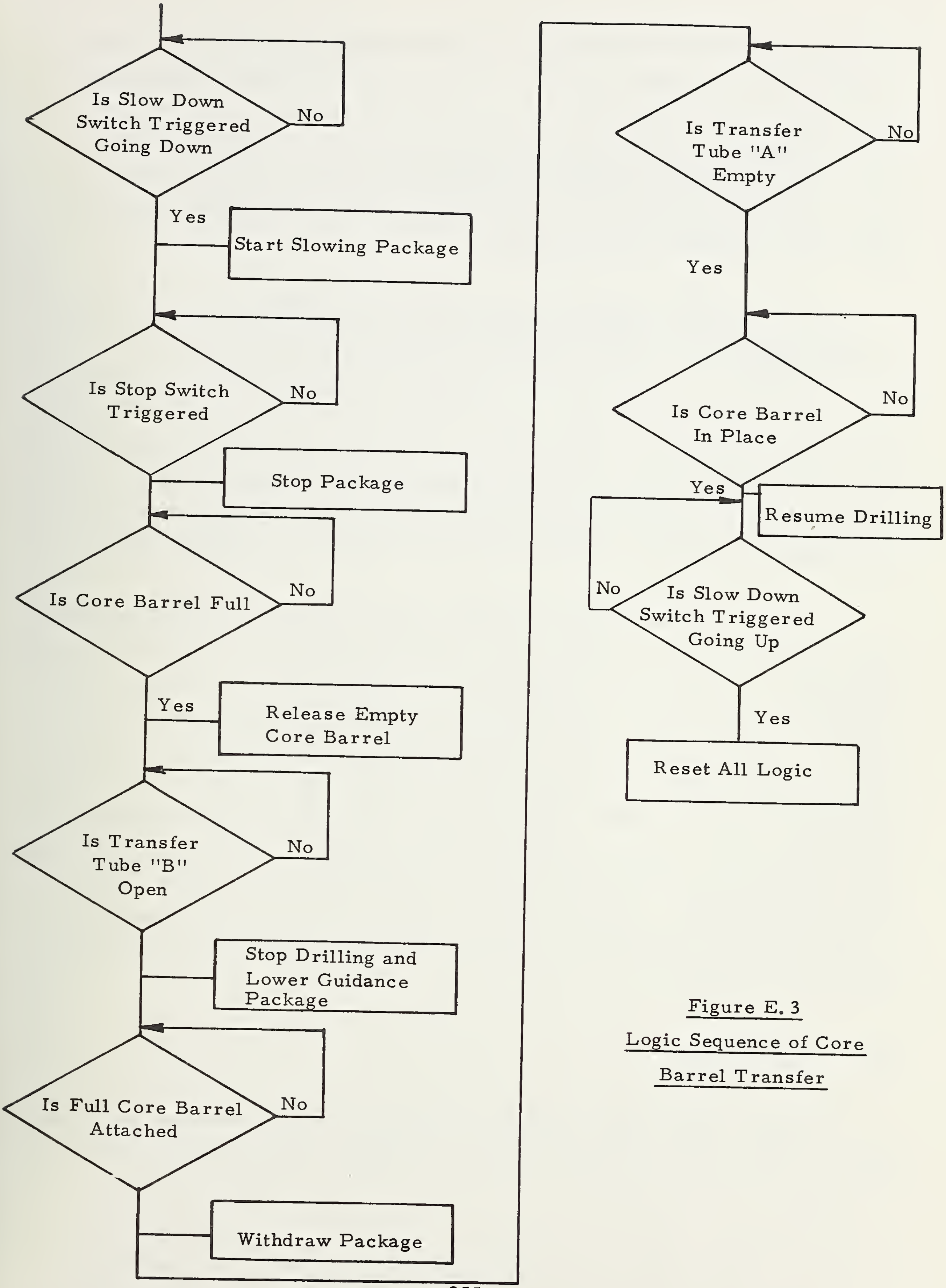


Figure E. 3

Logic Sequence of Core Barrel Transfer

surface. The need for automation becomes apparent when one realizes that this is a repetitive sequence, involving considerable forces, and transfer at relatively high speeds. Even a momentary lapse of attention on the part of a driller could create considerable damage. When one considers the many other factors which the driller has on his mind throughout this entire process, it would seem that highly reliable automation with fail-safe features should be incorporated.

The value of this approach can best be seen by extrapolating drilling times to the 15,000-foot limit. In addition to the 1900 hours chargeable to survey and orientation which would be saved, there is an additional approximately 1900 hours saved in wireline core retrieval time over a pure wireline system. Alternatively, when compared against a baseline system taking intermittent core every time there is a direction change, there is a net saving of almost 4900 hours. This results in a net savings of approximately $840,000 per hole in a 15,000-foot hole.

Although this technique seems to be extremely attractive on the basis of first analysis, there is an additional factor which must be considered. A round trip completed once every 20 feet of drilling for 15,000 feet results in a total distance traveled of approximately 4,260 miles. A 10-foot core-barrel would result in 8,500 miles of travel up and down the center of the drill string. The impact of this amount of travel on cable wear and stress as well as the wear on the equipment itself needs to be evaluated on a cost and reliability standpoint. This would be a consideration on wireline coring, and would not be unique to this particular technique. However, the fact that to achieve cost savings, transfer velocities must be as high as possible could add to the stress and wear problems.

E.5 Conclusions

There seems to be a number of factors to be considered in taking core in long horizontal holes. Of the techniques available, the attachment of a high angle gyroscopic survey tool to the back of a core-barrel seems to be the most attractive.

> The most immediate and surest payoff is in reducing survey time, and improving survey accuracy. This can be accomplished whether or not it is feasible to operate the wireline with the drill string turning. Thus, it is essentially a zero risk development.
>
> At slightly higher risk is the operation of the core-barrel guidance system, while drilling continues. This can be achieved by use of two core-barrels simultaneously. One core-barrel would always be in place while the other was in transit.

Thus core retrieval times do not have to be charged as separate drilling costs till the round trip times for the replacement barrel exceed the time required to drill one core-barrel length. This would achieve major cost savings.

APPENDIX F

APPLICABILITY OF DYNA-DRILL FOR CORRECTION OF DEEP HOLES

F. At present there are just two methods of steering a drill string:

- Whipstocking, which, beyond relatively shallow depths, becomes prohibitively expensive due to the numerous round trips required.

- Correction with a downhole motor such as Dyna-Drill, using a bent sub.

If coring is not required, the use of a Dyna-Drill with a kick sub such as Dyna-Flex seems especially attractive. Straight hole drilling is accomplished with the sub deactivated. Corrections are accomplished by turning the sub to the correct angle and activating it.

This concept becomes even more attractive if a high angle steering tool is available. The only major limitation to this concept rests in the question of the ability to control the Dyna-Drill at long hole depths. There is considerable qualitative information to indicate that Dyna-Drill becomes increasingly difficult to control as the hole deepens. The general feeling is that the availability of a high angle steering tool will help to alleviate this problem.

This study addresses the problem of Dyna-Drill stability from a quantitative standpoint. Unquestionable, the availability of a real time survey tool will extend the usable range of the Dyna-Drill. However, it is questionable just how much extension of range is possible.

Although existing holes do not support the concept, there is little doubt that steering accuracy will deteriorate as the hole length increases. This study also incorporates the concept of degradation of accuracy due to uncertainty of frictional and torsional forces on the control of the bent sub angle.

F. 1 Stability Considerations in Bent Sub Drilling

F. 1. 1 Inherent Instability

In general, the trend for directional control is to the use of a down-hole hydraulic motor on a bent sub. However, here new torsional conditions come into play. Figure F. 1 shows a simplified coordinate system for these forces.

The reaction torque of the motor causes the drill string to twist from the static angular setting of the bent sub. To this will be added an additional torque. This is caused by the weight of the motor acting through a lever arm of the displacement due to the bent sub angle perpendicular to the center line of the drill string which produces a moment arm. The eccentric force of the motor weight times the moment arm produces a torque which can be either to the left or right depending on the orientation. In operation, the drill string will twist until all torsional forces are in equilibrium.

Let:

T	=	The reaction torque of the motor.
W	=	The weight of the down-hole motor.
θ_S	=	The static azimuthal angle of the plant containing the axis of the hole, and the drill motor (drill motor off).
θd	=	The dynamic angle at equilibrium (drill motor on and drilling).
Ψ	=	The fixed angle of the bent sub.
ℓ	=	The distance from the bent sub to the c. g. of the motor.
L	=	The effective length of the drill rod twisted by the reaction torque.
K	=	The torsional spring constant of the drill string.

The system will be in equilibrium when torques sum to zero. Then:

Ψ = Bent Subangle

θ_s = Static Azimuthal Setting

θ_d = Dynamic Azimuthal Angle due to Drill String Twist

ℓ = Length from Sub to Drill CG

L = Effective Length of Drill String Twisted by Reaction Torque

K = Torsional Spring Constant of Drill Rod

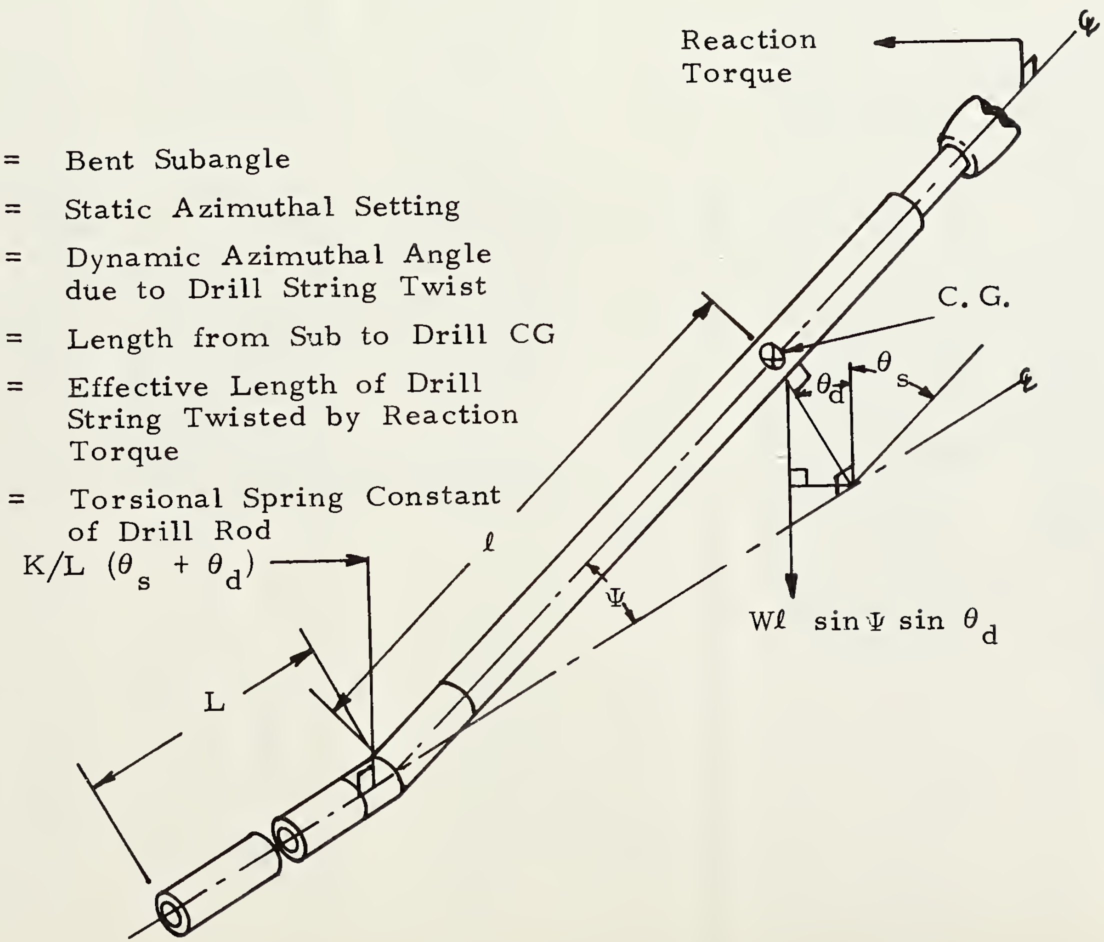


Figure F.1 - Torque Analysis Coordinates

$$T - W\ell \sin \Psi \ \sin \theta_d - (K/L)(\theta_s - \theta_d) = 0 \qquad (F.1)$$

Let M = $W\ell$ sin , the moment arm of the motor/bent sub combination.

Equation (F.1) is rearranged to give:

$$T - (K/L)\theta_s = M \sin \theta_d - (K/L)\theta_d \qquad (F.2)$$

The terms on the left are under the control of the operator. The desired deflection angle is the dependent variable to be controlled. It would seem that for the generation of any desired deflection angle a combination of reaction torque and input angle could be produced. Static equilibrium can be achieved. However, dynamic equilibrium cannot always be obtained.

Let C = the control forces, $T - (K/L)\theta_s$. Then:

$$C = M\sin \theta_d - K/L\ \theta_d \text{ and}$$

$$\frac{\partial C}{\partial \theta_d} = M\cos \theta_d - K/L \qquad (F.3)$$

In order for the system to hole an angle while drilling (be dynamically stable), the right hand side of Equation F.3 must be negative. Figure F.2 shows two plots of the stability conditions. As long as the torsional rigidity, K/L, is greater than the torsional moment, the system will be stable. However, as L increases, dynamic instability will occur.

This discussion is very important from the standpoint of extrapolating the art of controlled directional horizontal drilling to greater and greater lengths.

The moment arm of the bent sub motor combination should be as low as possible, and the drill rod should have the maximum torsional rigidity. Even under these conditions there will eventually be a point where the length of the hole makes the term K/L less than the moment arm of the bent sub motor combination. When this occurs the hole cannot be made to climb and hole angle without some lateral deflection. The situation will continue to degrade until the drill will not climb at any deflection angle.

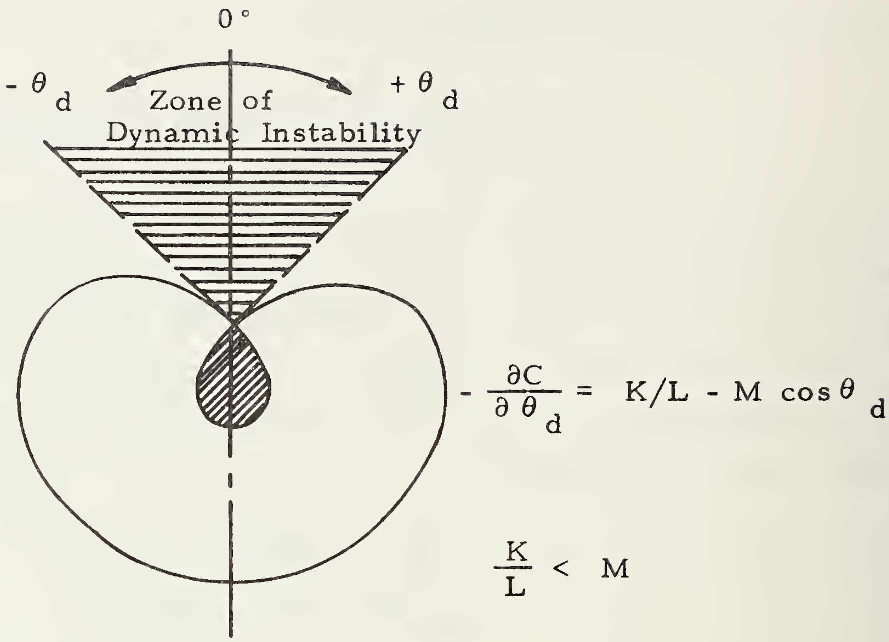


Figure F. 2a - Zone of Dynamic Instability

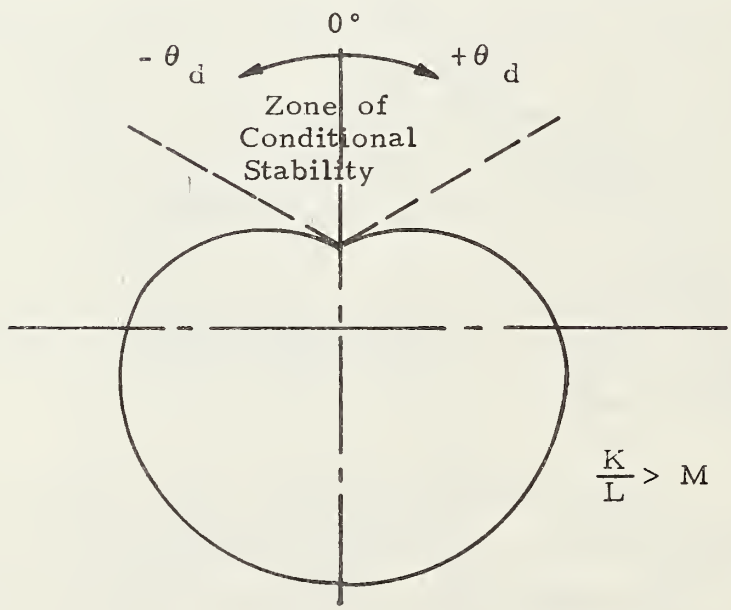


Figure F. 2b - Conditions for Dynamic Stability

In the conditions of Figure F.2.a, the drill bit can be made to enter the shaded area. However, it will not hold. It will drill on through and drop down the other side. In the conditions shown in Figure F.2.b, the drill will hold angle by itself; however, near the vertical it will be poorly damped and tend to wander.

These conditions will limit the length of hole under the conditions of available steering equipment. There are methods by which the hole can be stabilized: however, this will require development of equipment which is not now commercially available.

This analysis has been presented rather concisely but still in moderate mathematical form. It is included as a possible explanation to certain control problems observed by Rommel and Ash[13] in attempting to build vertical angle and lateral deflection simultaneously.

The following two paragraphs are quoted verbatim as an indication of these effects. They can be expected to increase as holes get longer.

> "The Dyna-Drill was the most effective deflecting tool tested. With this tool, hole direction was easiest to deviate to the right or down, and most difficult to deviate up and to the left. When oriented due left or due right, the Dyna-Drill dropped rapidly, due to the high revolutions per minute and the low thrust on the bit. To hold existing vertical angle and at the same time turn the hole laterally, the Dyna-Drill had to be oriented left or right and up to minimize drop off.
>
> The limited testing done on this problem indicated the equilibrium angle required to hold vertical angle was between 40° and 60° left or right of top center.
>
> Although the Dyna-Drill with BQ bent-sub was effective in turning the hole in all directions, the most effective Dyna-Drill assembly was the Dyna-Drill with bent housing. The AW-size bent sub was not effective. This may have been due to the high degree of flexibility of the AW-Rod." (13)

These comments are completely in agreement with the analysis. This aspect is stressed as it is believed that as holes become longer and longer, control of the rotational angle of the bent sub from the surface will become more and more difficult. At some hole depth the frictional build-up along the horizontal rod will become so great that it will become difficult if not impossible to transmit accurate rotational controls from the surface.

The condition of inherent instability in drilling with a borehole motor on a bent sub has been identified. The stability requirement is:

$$M \cos\theta \geqslant K/L \tag{F.4}$$

where:

M	=	the moment of the bent sub/motor/ bit about the axis of the borehole.
θ	=	the angle of the plane containing the bent sub combination and the borehole axis, measured with respect to the vertical.
K	=	the inherent torsional rigidity of the drill string.
L	=	the length of the drill string.

From (F.4) it can be seen that the system will always be stable for principal values of θ for:

$$-90^{\circ} > \theta > +90^{\circ}$$

and that instability will begin at $\theta = 0$ for $M \leqslant K/L$. Thus $M = K/L$ can be taken as the point of incipient instability.

For any drill string configuration, the length at which bent sub instability will begin will be:

$$L = \frac{K}{M} \tag{F.5}$$

For a hollow shaft:

$$K = \frac{\pi G}{32} \left(D_o^4 - D_i^4\right) \tag{F. 6}$$

$$M = \frac{W L_t}{2} \operatorname{Sin} \Psi \tag{F. 7}$$

where:

G

G	=	the torsional modulus of the pipe shell taken to be 12×10^6 psi.
D_o	=	outer diameter of the drill string - ins.
D_i	=	inner diameter of the drill string - ins.
W	=	weight of the tool.
L_t	=	length of the tool.
Ψ	=	the bent sub angle.

For this study we will assume the following:

(1) The bent sub is a Dyna-Flex.

(2) The down-hole motor is a Dyna-Drill.

(3) That the weight and length of both Dyna-Flex and Dyna-Drill vary as continuous functions of hole size. (This assumption is obviously in error, but it enables the analysis to handle them as continuous variables. The assumption will not change any of the conclusions of the study).

(4) The flexpoint of Dyna-Flex is one-third of the way back on the tool. This seems reasonable from the picture of the tool.

(5) Weights are uniformly distributed.

(6) The bit and matching subs add 18 inches to the tool configuration at the same weight per foot as the tool.

An empirical fit for all available Dyna-Drill and Dyna-Flex data indicates that:

where:

D_h = diameter of the hole in inches. This gives:

$$Le = \frac{\pi G}{32} \frac{(D_o^4 - D_i^4)}{4320 \; D_n^2 \; (12) \; \text{Sin} \; \Psi} \quad \text{feet} \qquad (F. 8)$$

$$= \frac{22.7 \; (D_o^4 - D_i^4)}{D_n^2 \; \text{Sin} \; \Psi}$$

Other studies have found the following empirical relationships to hold:

$$D_o \cong .6 \; D_h$$

$$D_i \cong .425 \; D_h^{1.11}$$

Inserting these in (F. 8) fibes:

$$L_c = \frac{.75 \; D_h^2 \quad (4 - D_n^{.44})}{\text{Sin} \; \Psi} \quad \text{feet} \qquad (F. 9)$$

L_c is the critical length beyond which the system will be dynamically unstable. By itself this instability is not serious, provided there is a feedback control channel available. The instability will be slow, the drill simply will not hold a high climbing angle without continuous external correction. The problem is analogous to that of trying to balance a tower without guy wires, or control a rocket in flight. As long as corrections can be applied more rapidly than the hole deviates, the situation can be controlled.

Figure F.3 is a plot of equation (F.9) for bent sub angles to 2° over the range of hole diameters of interest. It can be seen that beyond a few thousand feet the Dyna-Drill will have to have a relatively continuous real-time feedback of its angular orientation down-hole. The implication of this portion of this study is that as follows:

If a bent sub/Dyna-Drill is to be used for hole corrections beyond a few thousand feet, an in-hole high angle steering tool which will provide real-time data is needed. In order to deviate the hole upwards, it will be necessary to turn the bent sub to a climbing angle and to hold it at that angle by continuous corrections as the hole is drilled. This can only be accomplished with real-time data, provided by some type of in-hole survey tool.

F.1.2 Closed Loop Control Considerations

There are several factors to consider in the closed loop control of the Dyna-Drill:

- Reaction torque of the motor will twist the drill string counter clockwise. This must be countered by a corrective angle of rotation from the surface.

- From the surface the drill string can only be rotated clockwise, otherwise it will unscrew at the joints thus no counter clockwise torque can be applied.

- Reaction torque can be controlled by thrust on the bit. It will change as the bit drills off the applied thrust.

From these factors, it can be seen that control of the deflection angle can only be achieved by balancing the initial angle inserted from the surface against the reaction torque, controlled by the thrust on the bit.

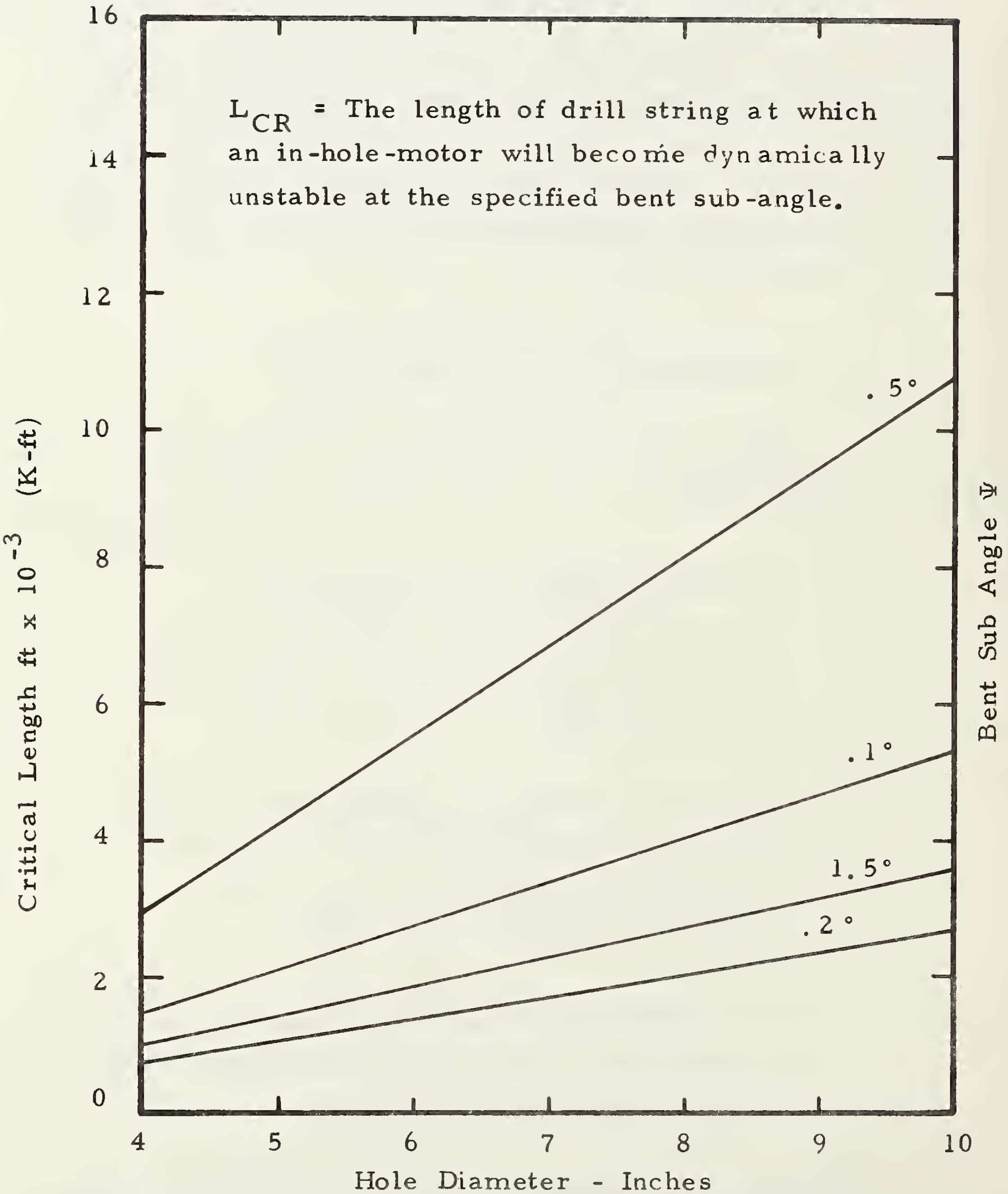


Figure F.3 - Drilling Instability Critical Length vs. Hole Diameter

Fortunately, Dyna-Drill inherently provides information on the reaction torque as controlled by thrust. The use in pressure of the drilling fluid is a direct measure of this torque.

Unfortunately, there is no corresponding measure of the countering torque applied through the drill string. Existing steering tools, even if modified for high angle drilling, can measure only the orientation angle.

Especially in the case of an inherently unstable situation, corrections made on angle alone can only guarantee a crooked hole. The hole must deviate before the even need for a correction can be sensed. As the hole gets longer the angles involved, i. e., the angle applied from the surface and that induced by reaction torque, assume the roles of quasi random variables.

The reaction torque generated by the drill must be absorbed by a twist of the drill string. The twist of the drill string is countered by the frictional forces acting on the drill string in the hole, and eventually by the counter torque applied from the surface. The equilibrium state:

$$\sum T = 0$$

must hold.

The same argument holds for the corrective torque applied from the surface.

The frictional component along the hole must be considered as a true random variable. Not only its magnitude but its effective point of application within the hole will change almost at random with changes in either reaction torque, or correctional angle. We will make the following assumptions:

- The coefficient of friction can assume any value between .05 and .2 with a median value of .1.

- There is no correlation between the coefficient of friction from one corrective steering adjustment to the next.

Under these assumptions we will examine the randomness of the angle generated by reaction torque, and that of the surface inserted correction.

For a hollow circular shaft:

$$\Theta = \frac{32TL}{\pi (D_o^4 - D_i^4) G} \quad \text{radiams} \qquad \text{(F.10)}$$

or

$$\Theta = \frac{4.49 \times 10^{-5} \; TL}{D_o^4 - D_i^4} \quad \text{degrees}$$

where:

T	=	torque in inch-pounds
L	=	length in inches
D_o	=	outer diameter - inches
D_i	=	inner diameter - inches
G	=	13×10^6 psi, the torsional modulus of steel.

Torque can be expressed in terms of weight in pounds per foot, the outside diameter of the drill string, and the hole length.

$$T = \frac{WLD_o f}{2} \quad \text{inches pounds} \qquad \text{(F. 11)}$$

where:

W	=	weight of drill string in pounds/foot
D_o	=	outside diameter of the drill string inches
L	=	hole length in feet
f	=	coefficient of friction, a random variable such that .05

Figure F.4 is a plot of all API standard drill string weights over the range of interest. A reasonable average expression would be:

$$W = 1.8\ D_o^{\ 1.44} \quad \#/\mathrm{ft}$$

Using the expression:

and converting L in equation (F. 10) to feet, enables equation (F. 10) and (F. 11) to be combined into:

$$\Theta = \frac{4.25\ L^2\ f}{4D_n^{\ 1.56} - D_n^{\ 2}} \tag{F. 12}$$

Figure F. 5 is a plot of the median uncertainty for $f = .1$ covering the extremes of hole sizes of 4 and 10 inches.

F. 1. 3 Uncertainty Angle Due to Reaction Torque

The angle due to reaction torque will be subjected to the same type of uncertainty. This would be the angle which the operator would be attempting to match from the surface. Figure F. 6 is a plot of the available Dyna-Drill torques over the range of recommended hole sizes. It can be seen that this data is fitted quite well by the continuous curve:

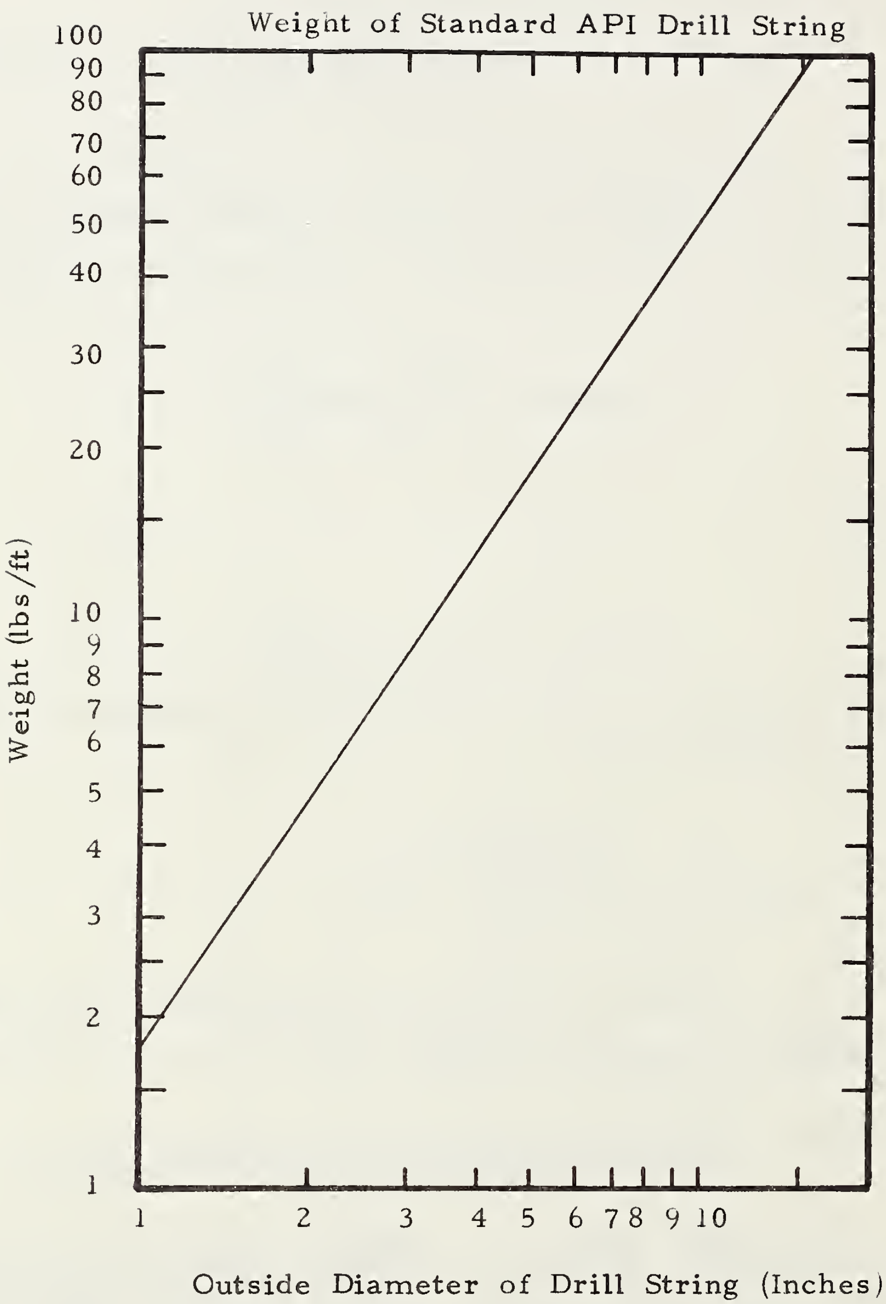


Figure F.4 - Weight of Standard API Drill String

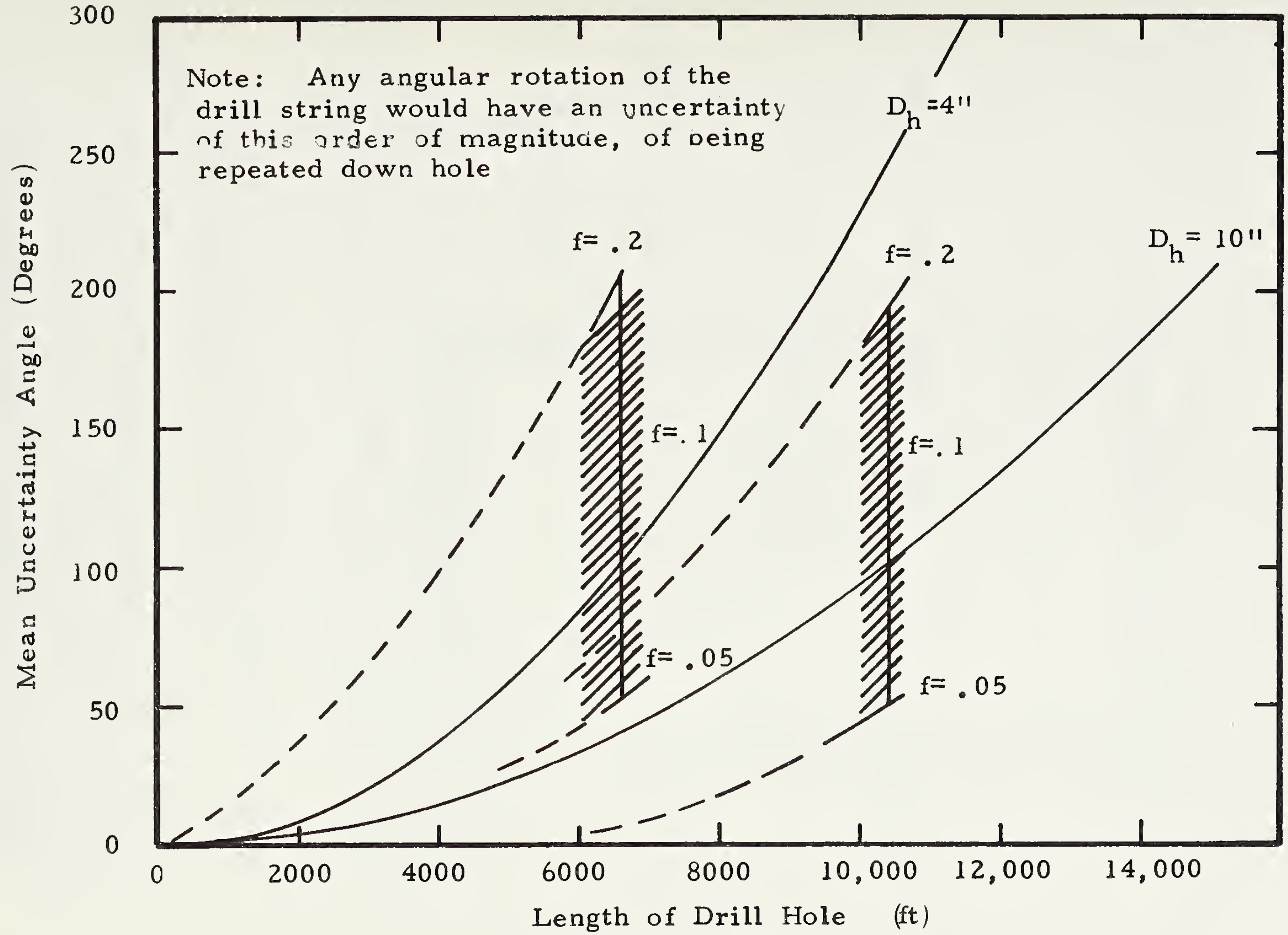


Figure F.5 - Uncertainty of Input Angle vs. Hole Length - for Possible Ranges of f, the Coefficient of Friction

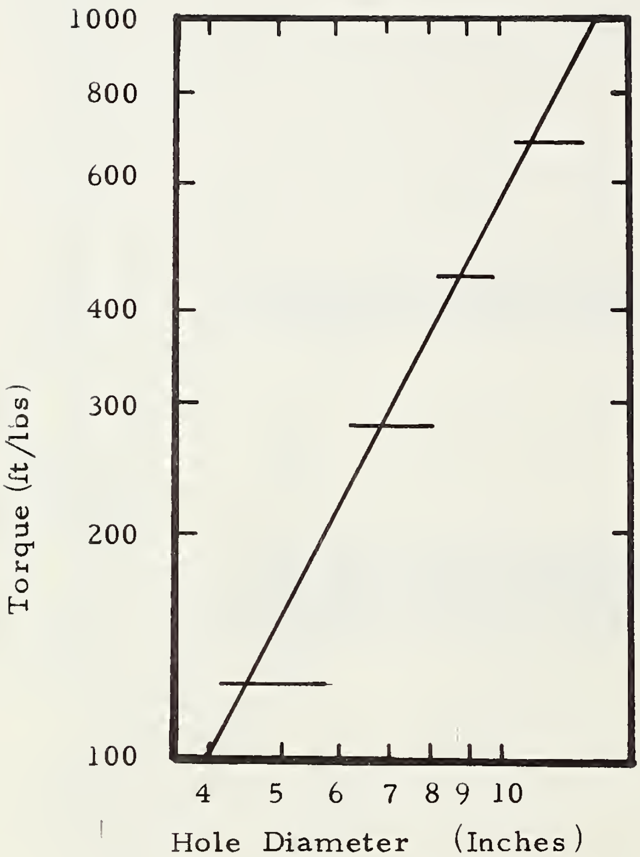


Figure F.6 - Dyna-Drill Torque vs. Hole Size

$$T = 75\ D_n^{\ 2} \text{ in-pounds}$$

The equation for the torsional angle is:

$$\theta_o = \frac{32TL}{\pi(D_o^4 - D_i^4)G} \quad \text{radians} \tag{F.13}$$

which, when converted by our standard emperical formulas to drill hole size, degrees, and conversion units, becomes:

$$\theta_o = \frac{1240\ L}{D_n^2\ (L - D_h^{.44})} \quad \text{degrees} \tag{F. 14}$$

Since θ_o varies in a linear manner with L, it can best be expressed as a ratio:

$$\theta_o = \frac{1240}{D_h^2\ (4 - D_h^{.44})} \quad 0/1000 \text{ ft} \tag{F. 15}$$

This is shown in Figure F. 7.

F. 2 Discussion

It does not seem reasonable to carry the analysis beyond this point. The control of the Dyna-Drill for steering corrections is subject to the behavior of two random variables, involving the frictional and bending effects of the drill string in the bore hole.

- There is the indeterminancy of the correctional angle inserted.
- There is the indeterminancy of the torque itself due to the inability to apply a smooth continuous thrusting force as the drill "drills off" the face of the hole.

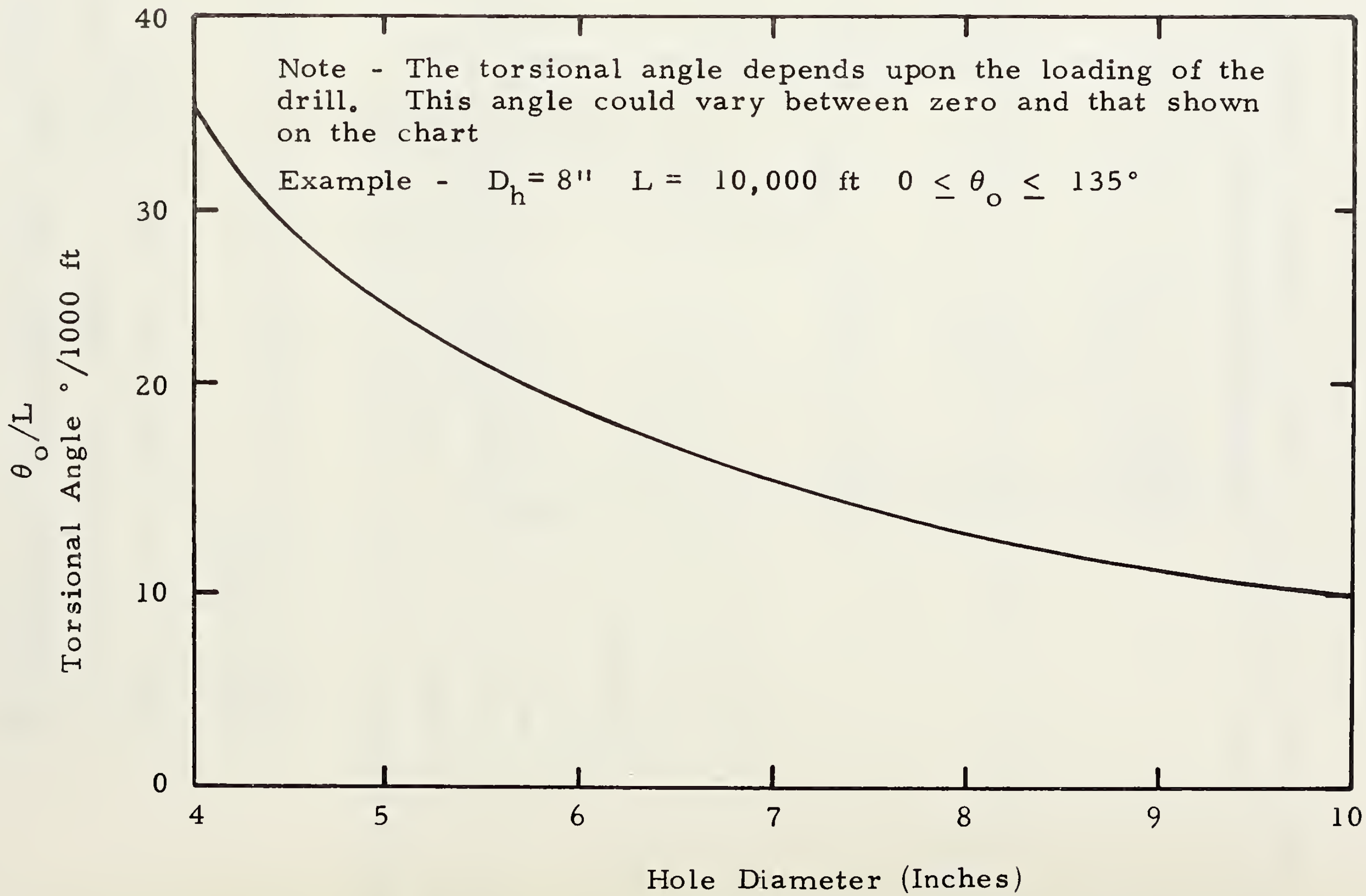


Figure F.7 - Maximum Dyna-Drill String Reaction Torque Angle in Degrees/1000 ft vs. Hole Size

It would be possible to set this situation up as a dynamic simulation on a computer and use mote carlo techniques to determine the statistical interaction of these variables. However, the results of such a simulation could be no better than the adequacy of the statistical distributions assumed. This data is almost completely lacking.

It is believed that better results could be obtained by the application of engineering judgement. Techniques should be developed which will minimize these effects regardless of the statistics. Thus it would seem that the developments discussed in the following paragraph would be in order.

F.3 Recommended Developmental Approach

The developments are presented in a priority order based upon the premise that longer and longer holes will be drilled. The length of the hole will really govern the priority.

F.4 High Angle Wire Line Steering Tool

At the start of this study it was anticipated that a high angle wire line steering tool would greatly extend the useful depth to which a Dyna-Drill could function. The analysis does indicate considerable pay off, the limited transfer velocities, 500 ft/min average, coupled with the need to continuously monitor the Dyna-Drill for direction changes at hole lengths beyond a few thousand feet, make this approach less attractive than was anticipated. This is not to say it is not of value.

If the high angle wire line steering tool is coupled with a gyroscopic survey capability, it will fill an immediate need. It will probably enable the utility of an in-hole motor steering device to the hole lengths in the order of 3,000 to 5,000 feet. This will depend upon the hole diameter. Beyond these distances it will be necessary to measure and control the torque applied to the bent sub. This will require in-hole instrumentation.

Since the transit times of the wire line tool will be getting appreciable at these depths, an in-hole survey/steering tool relying on telemetry will be getting more cost effective anyway. A natural transition occurs with the addition of torque sensors so that the inclusion of telemetry would seem logical.

F. 5 Telemetry Steering Tool

As the hole length gets longer it is believed that it will be impossible to control the in-hole motor/bent sub orientation and stability by angle alone. It will, in addition to having the correct angular orientation, be necessary to match applied torque to reaction torque of the motor. This implies instrumentation on the drill string in the form of torque and force sensors. The increased transit times and handling problems of a wire line steering tool will be becoming appreciable at these same hole depths. Thus it would seem logical to incorporate a magnetic survey capability with a telemetry and sensing package. The wire line tool would then be used only for periodic surveys to calibrate the magnetic survey package against the higher accuracy gyroscopic instrument. It is believed that the incorporation of the telemetry/survey/force and torque sensor package would extend the drilling capability of the down-hole motor to perhaps five to seven thousand feet.

F. 6 In-Hole Anchor/Thrust Device

As the hole deepens the growth of the statistical indeterminancies will be such that the system will become uncontrollable. It will be necessary to provide a firm anchor near the bit to absorb reaction torque and thrust. When these variables can be controlled from such an operating point near the bit, the indeterminancy will vanish. From a purely control and steering aspect, there should be no further limits upon the use of in-hole motor/bent sub combinations.

F.7 Conclusion

It should be noted that these three developments which are recommended are not given as alternative approaches. The telemetry system will need the gyroscopic survey capability of the wire line system. The in-hole thruster will need both the previous systems. Thus the three provide a systematic orderly program to extend the range at which in-hole motors can be used to make steering corrections in long horizontal holes.

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FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

* The complete 7-volume official statement of the FCP is available from the National Technical Information Service (NTIS), Springfield, Virginia 22161 (Order No. PB 242057, price $45 postpaid). Single copies of the introductory volume are obtainable without charge from Program Analysis (HRD-2), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements which affect the quality of the human environment. The ultimate goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge of materials properties and technology to fully utilize available naturally occurring materials, to develop extender or substitute materials for materials in short supply, and to devise procedures for converting industrial and other wastes into useful highway products. These activities are all directed toward the common goals of lowering the cost of highway construction and extending the period of maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural designs, fabrication processes, and construction techniques, to provide safe, efficient highways at reasonable cost.

6. Prototype Development and Implementation of Research

This category is concerned with developing and transferring research and technology into practice, or, as it has been commonly identified, "technology transfer."

7. Improved Technology for Highway Maintenance

Maintenance R&D objectives include the development and application of new technology to improve management, to augment the utilization of resources, and to increase operational efficiency and safety in the maintenance of highway facilities.

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R&D