EVALUATION OF DEEP ICE CORE DRILLING SYSTEMS

Roger E. Rinaldi (Consultant)

Bruce R. Koci and Jay M. Sonderup

Polar Ice Coring Office
University of Alaska Fairbanks
Fairbanks, Alaska 99775-1710

PICO
TR-90-1

November 1990

PICO is operated by the University of Alaska Fairbanks under contract to the National Science Foundation, Division of Polar Programs

ABSTRACT

National Science Foundation (NSF) Department of Polar Programs (DPP) has asked PICO to evaluate drilling systems capable of retrieving quality ice core to depths of 4,000 m.

Since there are many drill designs capable of accomplishing this task, a selection path is provided to choose basic drill type which in this case is mechanical. More detailed requirements of core quality, system cost, operating expense, weight and logistics considerations are examined for the final drill selection.

Two drills are considered, a cable suspended electromechanical system, and an oil field type of drill, the wireline system. Based on logistics, cost and ability to provide information on drilling parameters at the drill ice interface, a cable suspended electromechanical system is favored.

The wireline system, while worthy of consideration, currently does not supply core greater than 3.5 in diameter with an off the shelf drill. Increasing core size to 5.25 in requires redesign of the drill string and poses severe weight penalties. Communication with the drill head is difficult.

FOREWORD

The National Science Foundation, Division of Polar Programs (NSF) tasked the Polar Ice Coring Office (PICO), University of Nebraska, to develop and test "an instrumented, cable suspended electromechanical drill capable of retrieving ice core from a fluid-filled hole". The system was field-tested at the DYE-3 Dew Line facility in central Greenland during the 1988 field season.

On September 26, 1988, a technical Evaluation Panel, consisting of experienced ice core scientists and engineers convened at the University of Nebraska to evaluate the results of this test, to assess the current status of U.S. technical capability in ice coring, and to advise the NSF on the future course of deep ice drill development. The thoughts and recommendations of this panel were presented in the report "PICO Drill Test Report" and issued on November 4, 1988 by Polar Earth Science Program, Division of Polar Programs, National Science Foundation.

A recommendation of the report states: "Wireline Drill - it is not known whether a drill larger than 3.5-in core size is available, nor are the logistic requirements for such a system clear. In addition, chip separation may present a serious problem in a closed fluid system. Panel recommends that this alternative be more closely examined."

This report responds to the recommendation of the panel in comparison with other alternatives. It evaluates present deep coring systems to determine which one is preferable for deep ice coring operations. Particular attention is given to the wireline drill system to determine its capabilities for use in deep ice coring projects.

A TECHNICAL EVALUATION
OF
DEEP ICE CORE DRILLING SYSTEMS

TABLE OF CONTENTS

APPENDIX A. SIDEWALL CORING

APPENDIX B. CORING DIRTY ICE AND ROCK

PREFACE

The Polar Ice Coring Office was tasked to develop a deep ice coring capability in support of glaciological research world-wide. A cable suspended system which was under development by PICO for several years was chosen as the appropriate drilling method to obtain high quality ice cores. The National Science Foundation, Division of Polar Programs required additional information on alternative systems for acquiring high quality glacier ice cores. This report describes and compares three coring systems for application to the acquisition of ice cores.

John J. Kelley
Director

A TECHNICAL EVALUATION
OF
DEEP ICE CORE DRILLING SYSTEMS

I. INTRODUCTION

A. *Purpose of the Evaluation*

Over the past few decades, a number of coring techniques have been developed for coring both ice and rock. All of these systems perform the similar tasks of cutting/melting ice or rock, removing material from below the bit, and producing core. Although their functions are essentially the same, their physical designs, operational concepts and coring capabilities vary considerably. The purpose of this study is to define, evaluate, and compare these coring systems and recommend one which is best suited for deep ice coring. This report will respond to the recommendation by the National Science Foundation, that: Under Wireline Drill

> "It is not known whether a drill larger than 3.5 in core size is available, nor are the logistics requirements for such a system clear. In addition, chip separation may present a serious problem in a closed fluid system. Panel recommends that this system be more closely examined."

B. *Method of Evaluation*

When evaluating rock and ice coring systems, there is no single method capable of efficiently performing all of the coring operations desired and satisfying all the needs required by both the commercial and scientific communities. Thus, when one desires to obtain a coring system, the needs of the program must be determined and then different systems available can be evaluated against these needs. Operational requirements (depth, core diameter, ease of system operation, etc.), logistics (equipment weight, site location, fuel requirements, etc.) and cost (original equipment cost, labor, maintenance, fuel, etc.) are a few of the factors that must be considered.

When selecting a deep ice core drilling system, a similar evaluation should also be used. The ability to obtain quality core, system design, cost, and constraints posed by logistics problems, must be reviewed in detail.

In this report a series of coring system requirements will be stated and discussed. These requirements will then be used to evaluate/compare the various U.S. ice and rock coring systems available and determine that one which is best suited for deep ice coring. Particular attention will be given to both the commercial pipe-driven wireline core barrel system, and the PICO cable-suspended ice core drilling system.

II. SYSTEM DESIGN REQUIREMENTS

The primary purpose of deep ice coring is to obtain quality core of specific size and length so that the ice can be sectioned for appropriate scientific investigations.

The term "Quality Core" refers to core that is continuous in form and not shattered, flaked or otherwise damaged when removed from the core barrel. To obtain deep core of this nature, an understanding of the coring process and the ability to control it is necessary. The drilling system that supports this operation must have this control capability and must be reliable and cost effective.

Commercial petroleum coring operations differ from scientific coring operations. Petroleum coring is confined to obtaining core from only specific geologic zones of interest. Ice coring, however, generally requires continuous core over the entire hole length. In this respect, ice coring more closely resembles mining coring operations which also require continuous core over the entire hole length.

This difference can be noted in equipment design. In the petroleum industry the primary objective of equipment design is the ability to drill and complete a quality hole in the most economic manner possible. Obtaining quality core is a secondary objective. Therefore, the equipment is designed to drill holes. Auxiliary components are added to the operating system when core is desired. Thus, the coring equipment is designed to fit into the drilling system.

Ice coring equipment is designed in the reverse sequence. Obtaining quality core is the primary objective. Speed, although important, is secondary to obtaining quality core. This comparison is noted by Gundestrup, Johnsen and Reeh[1] in their statement: "Production of perfect ice core is not easy due to varying pressure, temperature, crystal size and orientation. In order to handle this, the drill was considered and instrument designed to produce ice core and not just a tool to generate cuttings."[1] When designing an ice core drilling system, the ability to core is considered first. The design of all other

---

[1] N.S. Gundestrup, S. J. Johnsen, and N. Reeh; "ISTUK, A Deep Ice Core Drill System"; Ice Drilling Technology; Special Report 84-34; U.S. Army corps of Engineers, Cold Regions Research and Engineering Laboratory; December, 1984.

components is secondary and is done in a manner consistent with obtaining quality core.

Understanding the above stated design difference is fundamental to selecting an ice core drilling system. The difference can be noted in system operation, cost and logistical parameters.

To select or choose and ice coring system, a series of requirements must be met. These requirements are noted and described as follows.

A. *Bit/Ice Interface Control*

The primary function of the drilling and/or coring operation is the displacement of material from below the bit face so that the bit can penetrate the medium below it and produce a core. *Understanding and controlling the dynamics of the interaction between bit and medium is essential for efficient ice penetration and directly effects the obtaining of quality core.* All other operations are secondary when considering equipment design and system operation.

Interaction between the drill and the ice is complex. It takes into account weight on the bit, bit rotation per minute (RPM), torque, vibration, temperature, pressure, physical characteristics of the medium being drilled and other elements. Until recently, the importance of ice and bit interaction was not fully appreciated as noted by the limited amount of research and the lack of knowledge pertaining to it.

B. *Simplicity of Design*

Simplicity of design relates to the avoidance of use of unnecessarily complex mechanisms and materials. Non-complex designs are often more difficult to develop than complex designs.

C. *Light Weight Design*

Light weight design is primarily required because of the high cost of transporting the system to the various drilling sites. Equipment weight is also important when considering how to assemble components at the drilling site. Due to the lack of heavy equipment handling devices at the site, light weight components greatly reduce the problems involved. These design qualities may not be obtained easily for deep drilling devices.

D. *Low Fuel Consumption*

Fuel consumption is primarily a logistics problem and does not directly affect the obtaining of quality ice core. However, from a logistics standpoint the volume of fuel required, the direct cost of obtaining it, and the cost of transporting it are of concern. Thus, low energy consuming systems are desirable.

E. *Limited Crew Size*

Crew size primarily affects operation cost. This includes wages, overhead, transportation, insurance, shelter, food, and other costs involved in maintaining the crew. Crew size is also an indication of the degree of simplicity of operating the equipment.

F. *Ease of Maintenance*

Simplicity and reduction of maintenance are indications of simplicity of design. Both factors are directly related to operation cost. Often simplicity of maintenance is overlooked in system design. However, considering the environment in which the system must operate, all maintenance must be made as simple as possible.

G. *Ease of Operation*

Ease of operation refers to the simplicity of controlling and operating the system. Although the system may contain sophisticated controls, automated components, or other devices to enhance its ability, the operation of these components must be made as efficient as possible. This directly effects the type of crew required, reliability and cost.

H. *Safety*

Regardless of what system is used, safety is an important factor. Safety can be greatly enhanced by having highly reliable components, simplicity of system operation and ease of component repair. Safety must also be considered regarding fire, explosion, and toxicity.

I. *Core Size*

Investigators would like to have the largest core possible. Logistic considerations, however, limit this size. Current PICO core sizes are 5.2 in diameter for the deep core drill, 3 in for the hand-auger and 4 in diameter for the electromechanical drill.

J. *Penetration Into Dirty Ice and/or Rock*

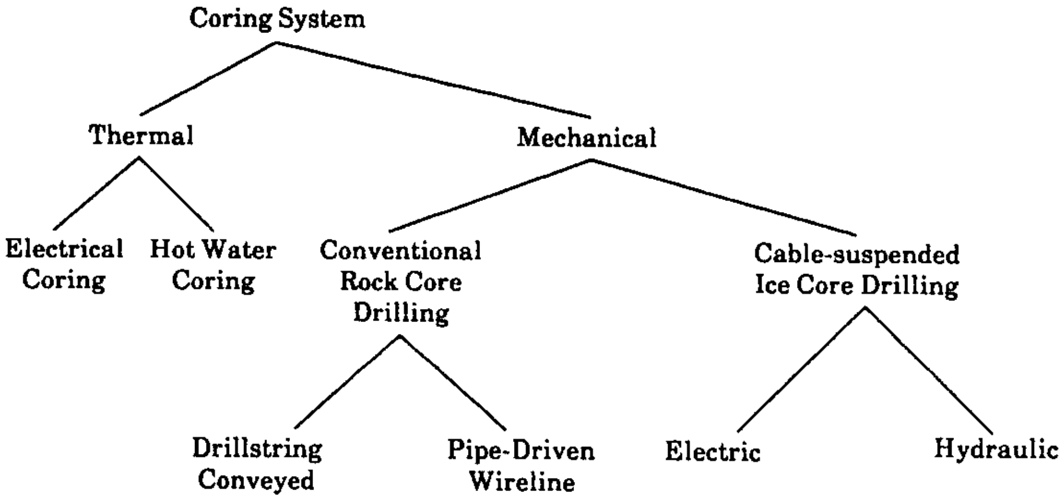
Penetration into dirty ice or rock is not a direct requirement of the system in question. However, it should be considered because in time the selected system will penetrate into areas where this capability will be required. If thought is given in the initial design to this capability, considerable cost might be saved in the future.

It should be noted that the above criteria (A through J) represent factors to be considered in the design of ice coring devices. Most of the factors are general in nature, but they directly relate to cost, reliability, safety and the general success of an operation.

III. SELECTION OF SYSTEM TO BE EVALUATED

A. *Coring System Categories*

All ice coring systems can be classified into one of two broad categories: thermal or mechanical. These categories can be further subdivided as noted in Figure 1.



CORING SYSTEM CATEGORIES
Figure 1.

A brief review of each category will be made to determine if other systems, in addition to the wireline and PICO systems, should also be included in this analysis.

1. Thermal Systems

Thermal electric coring systems use coring heads that have heating elements circularly embedded in them. When power is applied to the head, the elements heat up and create a means for melting ice. In operation the heated coring head is lowered onto the ice, thereby melting a circular ring in it. As the operation continues, the heated head is slowly lowered into the melted ring, the melted ring penetrates deeper into the ice, and the non-melted interior of the ring (the ice core) moves into the core chamber of the system.

In operation this system produces water, and is power consuming as illustrated in Table 1. The presence of liquid water in a hole that is below freezing can result in the sticking of the coring system. heat from the coring element may also thermally fracture the core. In addition, the system cannot penetrate dirty ice. Balanced against these negative aspects is the fact that this system tends to core straight holes and works well in temperate ice.

TABLE 1. Specific energy requirements for drilling systems.

CHARACTERISTICS	SYSTEM		
	ELECTRO THERMAL	HOT WATER	MECHANICAL
SPECIFIC ENERGY MN/M^2	590 - 680	590 - 680	1.9 - 4.8

Hot water drilling has proven itself as a drilling technique able to reach depths in excess of 1,000 m. In this system, hot water (175° to 200°F) is pumped down the hole and out of the bottom of the drill head, thereby melting the ice in front of it and making a hole. The cooled water is then sucked back into the drilling system and pumped to the surface. At the surface it is reheated and circulated back to the drill head.

Since large quantities of heat are available at the nozzle, high specific energy (energy required to remove a measured volume of ice) requirements are overcome (Table 1) and drill rates in excess of 100 m/h have been experienced. Total drilling time, however, must take into account core retrieval, maintenance, etc. With hose insulation, depths of 3000$^+$m may be possible. Although discussed, a system of this type has not been developed with coring capability. Currently a hybrid thermal mechanical system is being considered.[2]

---

[2] Discussion with Bruce Koci, Polar Ice Coring Office, University of Alaska, Fairbanks, Alaska, 1989.

MECHANICAL AND THERMAL DRILLING SYSTEMS CHARACTERISTICS[3]

1. Conventional mechanical, rock core drilling systems (drillstring-conveyed and pipe-driven wireline) (wireline refers to a drilling system that is pipe driven and uses a cable suspended messenger to retrieve the core and core barrel) have been used successfully for years by the petroleum and mining industries. In both industries rock coring tools are used in conjunction with rotary drilling systems. If used properly, holes far in excess of 3000 m can be drilled and cored in soft or hard rock. Over all system weight and the inability to develop a closed loop telemetry system between surface controls and the drill head are penalties encountered. The latter is essential for obtaining quality core.

Cable-suspended downhole ice core drilling systems have been used to successfully penetrate ice sheets and obtain samples of subice material. Recent advances in cutter geometry and core catching devices have reduced power consumption and winch design requirements. The use of Kevlar (a high-strength aramid fiber) reinforced cables could further reduce system weight and power requirements. Two types of cable-suspended systems, electric and hydraulic, must be considered.

Electrically driven systems are powered by a downhole electric motor that receives power from a surface diesel-generator set. These systems are light weight, and have the ability to monitor progress while drilling. The main disadvantage is the high percentage of drill weight located high above the cutting head. As a result, the drill can wander off vertical at a faster rate than thermal or pipe suspended systems.

---

[3] Malcom Mellor, and Paul V. Sellmann; "General considerations for Drill System Design"; *Ice Core Drilling*; Proceedings of a Symposium; University of Nebraska Press; Lincoln, Nebraska; August, 1974.

Hydraulically driven systems are similar to electrically driven systems except that hydraulic power from the surface is used to drive the downhole hydraulic motor. The transfer of this power creates difficult design problems regarding the suspension cable and makes this system impractical.

B. *Selection of Systems to be Evaluated*

The requirements of core size, depth to be drilled, potential for conversion to drilling into dirty ice and/or rock, and overall system control, eliminate thermal systems from consideration because of the inherent problems noted; e.g., inability to core dirty ice and high specific energy requirements. In time, thermal systems may be developed to a point where they could compete with mechanical systems but as yet they cannot meet the general requirements stated.

Mechanical systems, however, have proven their ability to drill/core rock to depths of 32,000 ft or more. There is no question as to their ability to core ice and to penetrate the dirty ice or rock below it. In addition, under certain conditions, it is possible to develop a closed loop telemetry system for control of the bit/ice interface operation and to develop the technology for controlling it.

Considering the above, three coring systems will be discussed:

- Drillstring-Conveyed Core Barrel
- Pipe-Driven Wireline Core Barrel
- Cable-Suspended Ice Core Drilling

IV. DEFINITION OF SELECTED ICE CORE DRILLING SYSTEMS

A. *Drillstring-Conveyed Core Barrel*

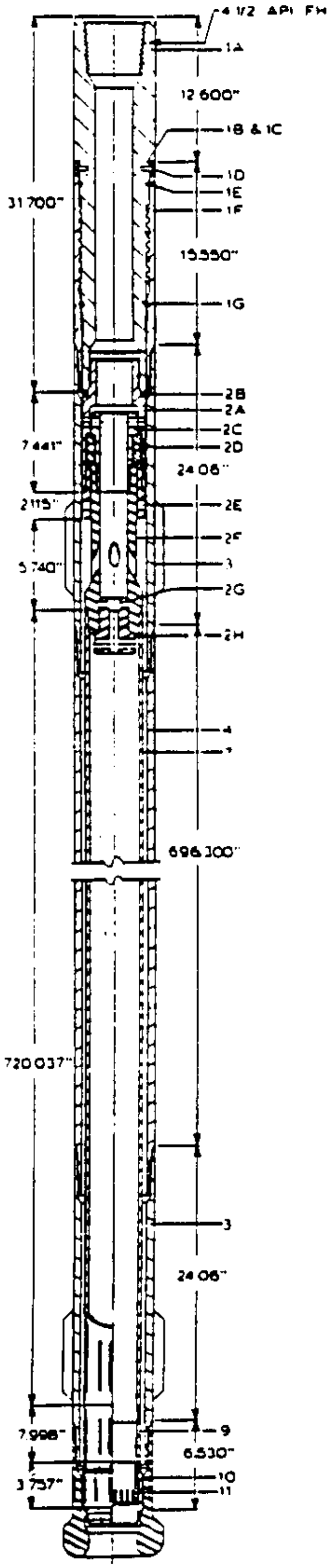
This system is used primarily in the oil and gas industry because the number of cores required is usually small and generally drilled in soft, sedimentary formations. The system consists of a core bit and coring assembly attached to the end of a rotating drillstring. The core bit has a large kerf (core bit face) (Figure 2) that provides a relatively large clearance between the drillstring and the bore of the well.

During coring operations, after the core has been cut, the entire drillstring and its integral core barrel is pulled (tripped) out of the well. The core is then removed form the core barrel after which the empty core barrel and the entire drillstring is lowered (tripped) back into the hole. Pulling/lowering speed rates averages approximately .8 hrs per 1,000 ft of hole for holes less than 10,000 ft in depth.[4]

A typical oil field drilling system (rig) capable of utilizing this type of equipment is noted in Figure 3. This system is a Cooper LTO-055 manufactured in Tulsa, Oklahoma. although the drilling rig shown is truck-mounted, a skid-mounted version can be easily developed for ice coring operations. Table 2 states specifications of the rig, the fluid system, the drill pipe and core barrel assembly, system weights and crew size. Even though this rig, when drilling in rock and using 4$^1/_2$ inch diameter drillstring, is rated only to 8,000 ft using 3$^1/_2$ inch diameter drill pipe because of the lower torsional stresses and vibration induced into the pipe. Comparative information is noted for 3$^1/_2$ inch and 5$^1/_4$ inch diameter core systems.

---

[4] J. A. Short, *Drilling andCasing Operations*, Penn Well Publishing Company, Tulsa, Oklahoma, 1982, pg. 255.



Part Name:

1. Safety Joint Assembly
   - A. Safety Joint Pin
   - B. Spring
   - C. Plunger
   - D. Friction Ring
   - E. "O" Ring
   - F. Safety Joint Box
   - G. "O" Ring

2. Bearing Assembly (complete)
   - A. Bearing Housing
   - B. Shim Set
   - C. Bearing Retainer
   - D. Bearing Set
   - E. Bearing Stop
   - F. Flow Tube
   - G. Ball-Relief Valve
   - H. Seat-Relief Valve

3. Outer Barrel Coupling (stabilized)
   - A. Spiral HM
   - B. Spiral TCI

4. Outer Barrel (30 ft)
5. Thread Protector (not shown)
6. Thread Protector (not shown)
7. Inner Barrel (30 ft)
8. Thread Protector (not shown)
9. Inner Barrel Sub
10. Core Catcher Sub
11. Core Catcher

Specifications:

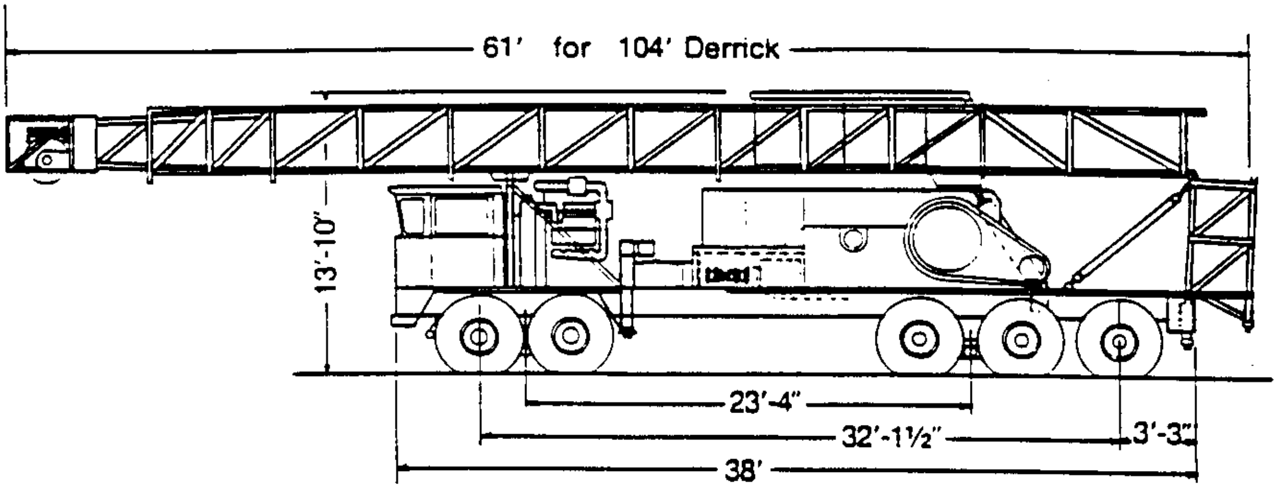
Core Length	- 60 ft
Core Diameter	- $3^{1}/_{2}$ in
Outer Barrel O.D.	- $5^{3}/_{4}$ in
Bit O.D.	- 6 to $8^{1}/_{2}$ in

Reference:

Diamant Boart

Figure 2.

Drillstring Conveyed Core Barrel
(Petroleum Industry)



Weight Truck Mounted	-92,000 lbs
Weight Skid Mounted	-80,000 lbs
Drilling Capacity	-8,000 ft
Workover Capacity	-14,000 ft
Well Servicing Capacity	-18,000 ft

NOTE: ONLY SKID MOUNTED VERSION WILL BE CONSIDERED IN THIS STUDY.

Reference: Cooper Manufacturing Corporation, Tulsa, Oklahoma

Figure 3.

Cooper LTO-550
8,000 Foot Drilling Rig
Dimensions

Table 2.

10,000 FOOT DRILL STRING CONVEYED, CORE BARREL SYSTEM SPECIFICATIONS
(COOPER LTO-550)[1]

Drill Rig

Drill Pipe Stand - 60 ft
Mast Load Capacity - 235,000 lbs
Mast Racking Capacity ($3\frac{1}{2}$ in Drill Pipe) - 11,400 ft
Engine - Detroit Diesel 12V71-N

Fluid System

- Using $3\frac{1}{2}$ in Drill Pipe and $7\frac{7}{8}$ in Diameter Core Bit (3.50 in Diameter Core)

Fluid Required, Hole Empty - 253.0 gal/100 ft
Fluid Required, Drill Pipe in Hole - 234.2 gal/100 ft
Total Fluid Required to Drill 10,000 ft Hole[2] - 38,000 gal

- Using $4\frac{1}{2}$ in Drill Pipe and $9\frac{7}{8}$ in Diameter Core Bit (5.25 in Diameter Core)

Fluid Required, Hole Empty - 397.9 gal/100 ft
Fluid Required, Drill Pipe in Hole - 375.0 gal/100 ft
Total Fluid Required to Drill 10,000 ft Hole[1] - 59,700 gal

Drill Pipe and Core Barrel Assembly

Core Diameter (in)	3.50	5.25
Hole Diameter (in)	7.87	9.87
Bit Kerf Width (in)	—	—
Drill Pipe O.D. (in)	3.50	4.50
Drill Pipe Wt. (lbs/ft)	13.30	16.60
Max. Pipe Pull (lbs)	272,000	331,000
System Depth Capacity (ft)	10,000	10,000

Drilling System Weight

	3.50 in Core	5.25 in Core
Rig (Skid Mounted)	80,000	80,000
Drill String (10,000 ft)	133,000	166,000
Mud Pump	45,000	45,000
Mud System	10,000	15,000
Drlg Fluid (Diesel, s.g. .85)(10,000 ft. Hole)	270,000	423,700
Fuel[3]	—	—
Misc. Equipment (Generators, Fuel Tanks, etc.)	100,000	100,000
Est. Total weight:	638,000 lbs	829,000 lbs

Crew Size

12 hr/day Operation - 4
24 hr/day Operation - 9

Note:
1 - Reference: Cooper Manufacturing Corporation, Tulsa, Oklahoma.
2 - Total fluid required based on empty hole volume plus 50% overage.
3 - Fuel consumption not calculated because number of pipe trips (large consumption of energy) and wireline trips difficult to define.

The main differences between the two systems is the size of the hole required, the volume of drilling fluid needed and the weight of the drillstring. The larger the core, the larger hole diameter required (Table 3) and the greater drilling fluid volume needed. Neither of these two characteristics can be reduced to any significant extent. However, as noted by Hansen[5], fiberglass-reinforced epoxy pipe can be substituted for the steel drill pipe and thereby reduce the weight of the drillstring by approximately 50%. This weight reduction in turn could allow reduction of the mast weight; thus a lighter rig could possibly be used.

With regard to operation, during normal drilling operations approximately 10-40% of rig operating time[6] is involved with tripping the pipe in and out of the hole. This is particularly true during coring operations and will significantly increase if shorter core barrels are used (i.e., 20 ft as opposed to 60 or 90 ft core barrels). This will also result in higher fuel consumption rates.

B. *Pipe-Driven Wireline Core Barrel*

In the mining industry, long intervals of continuous core in hard and often fractured rock is usually required. Because of the extensive trip time required if drillstring-conveyed core barrels are used and the lack of need for large diameter cores, wireline coring systems are used. This system differs from the drillstring-conveyed core barrel system in that the core barrel is independent of the drillstring and can be retrieved by attaching a wireline to it and pulling it to the surface through the center of the drillstring. This requires the diameter of the core barrel and its internal core to be less than the internal diameter of the drillstring. Thus, pipe-driven, wireline cores are smaller in diameter as compared to drillstring-conveyed cores (Table 3). Normally, the mining industry uses a narrow kerf bit (Figure 4) as compared to the large kerf bits used by the oil and gas industry. The cutting surface of the bit may consist of a diamond impregnated material that

---

[5] B. Lyle Hansen; "An Overview of Ie Drilling Technology", Ice Drilling Technology; Special Report 84-34; U.S. Army Corps of Engineers, Cod Regions Research and Engineering laboratory; December, 1984.

[6] J. A. Shor pg. 257.

allows long bit life. In addition, higher RPM and lower weight on bit are required to drill the hole as compared to the large kerf bit used by the oil and gas industry.

During coring operations, after the core has been cut, the core barrel is released from the drillstring and pulled to the surface with the attached wireline. The core is then removed from the core barrel and the empty core barrel is lowered back to its position at the bottom of the drillstring.

Table 3.

CONVENTIONAL ROCK CORE DRILLING
CORE SYSTEM DIMENSIONS

Core Diam. (in)	Hole Diam. (in)	Core Barrel O.D. (in)	Core Barrel Length (ft)
Drill String Conveyed Core Barrel Assembly[1]			
2.00	3 13/16 - 4 3/4	3 5/8	30/60/90
2.50	4 3/4 - 6 1/8	4 1/2	30/60/90
3.50	6 1/8 - 7 7/8	5 3/4	30/60/90
3.50	7 7/8 - 9 7/8	6 1/4	30/60/90
4.00	7 7/8 - 9 7/8	6 3/4	30/60/90
4.25	7 7/8 - 9 7/8	6 7/8	30/60/90
5.25	9 7/8 - 17 1/2	8	30/60/90
Pipe Driven Wireline Coring System[2]			
1.71	3	2 7/8	5/10/15/20
2.50	4	2 7/8	5/10/15/20
3.34	5 1/4		5/10/15/20

Reference: (1) Dowdco Coring Services, Midland, Texas
(2) Longyear Company, Salt Lake City, Utah

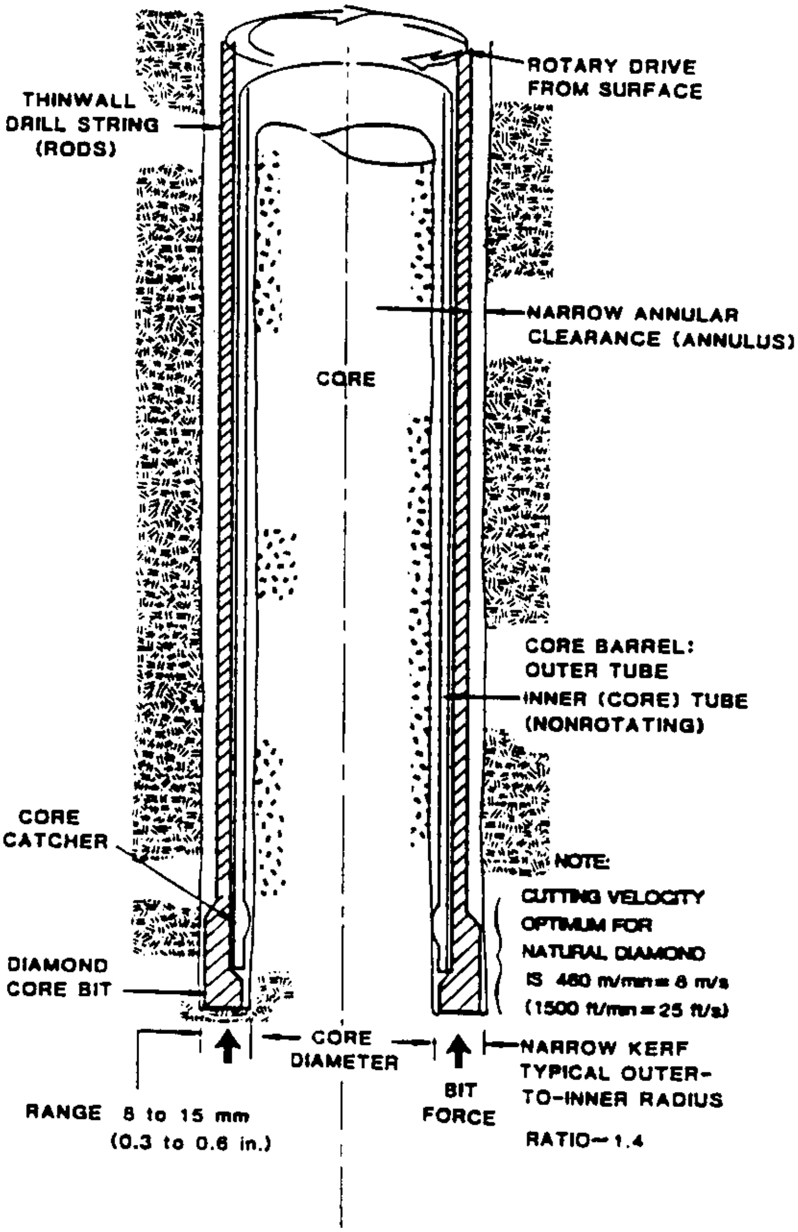


Figure 4.

Pipe Driven Wireline Core Barrel
Narrow-Kerf, Diamond Impregnated Coring Configuration
(Mining Industry)

A typical mining industry rig of this type is the Longyear HD-600, manufactured by the Longyear Company, Salt Lake City, Utah. A drawing of a skid-mounted version is noted in Figure 5. Specifications of the rig and its operating characteristics are noted in Table 4. Although specifications are given for a 3.345-inch diameter core system, the HD-600 is only capable of operating this system to depths of 7,500 ft because of the lifting capacity of the mast.

One means for coring to 10,000 ft with a 3.345-inch core barrel would be to use a heavier oil field rig, and a CHD 134 drill pipe and core barrel system with a narrow kerf bit. This type of rig or the use of a stronger mast utilized on a HD-600 would resolve this problem.

C. *Cable-Suspended Ice Core Drilling*

Cable-Suspended ice core drilling systems have been built and utilized by various scientific ice coring groups for a number of years. These systems have drilled to approximately 6,000-ft depths with 10 and 20-ft core barrels and have obtained excellent 4.0 in diameter core.

The development of the PICO deep ice coring system capable of obtaining 5.25-in diameter core, is an extension and modification of existing designs. Conceptual drawings for a system of this capability are noted in Figure 6. Specifications for this drill and its operating characteristics are noted in Table 5.[1,5]

The downhole drilling/coring unit (Figure 7) is approximately 87 ft long. It operates on the principal of shaving a ring of ice, thereby producing core. the ice shavings are transported upward into the unit by a series of spiral ways around the core barrel which is driven by the system drive shaft. Shavings and fluids are then deposited in chambers where the fluid is allowed to drain through well screens back into the well. The shavings are stored in these chambers for transportation to the surface. Power for the unit is derived from an electric motor which drives a

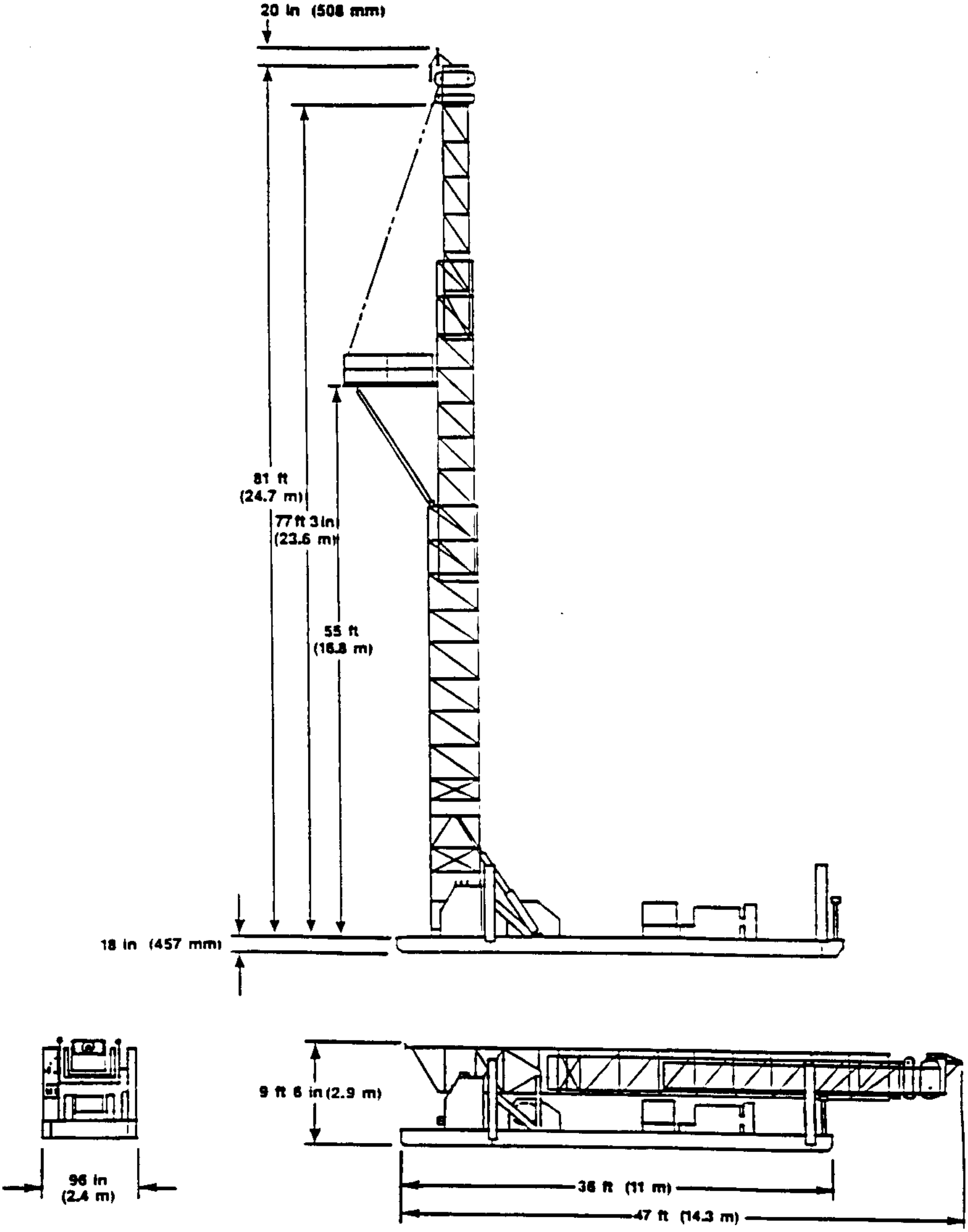


Figure 5.
Reference: Longyear Company, Salt Lake City, Utah
Longyear HD-600
10,000 Foot Wireline Coring Rig
Dimensions

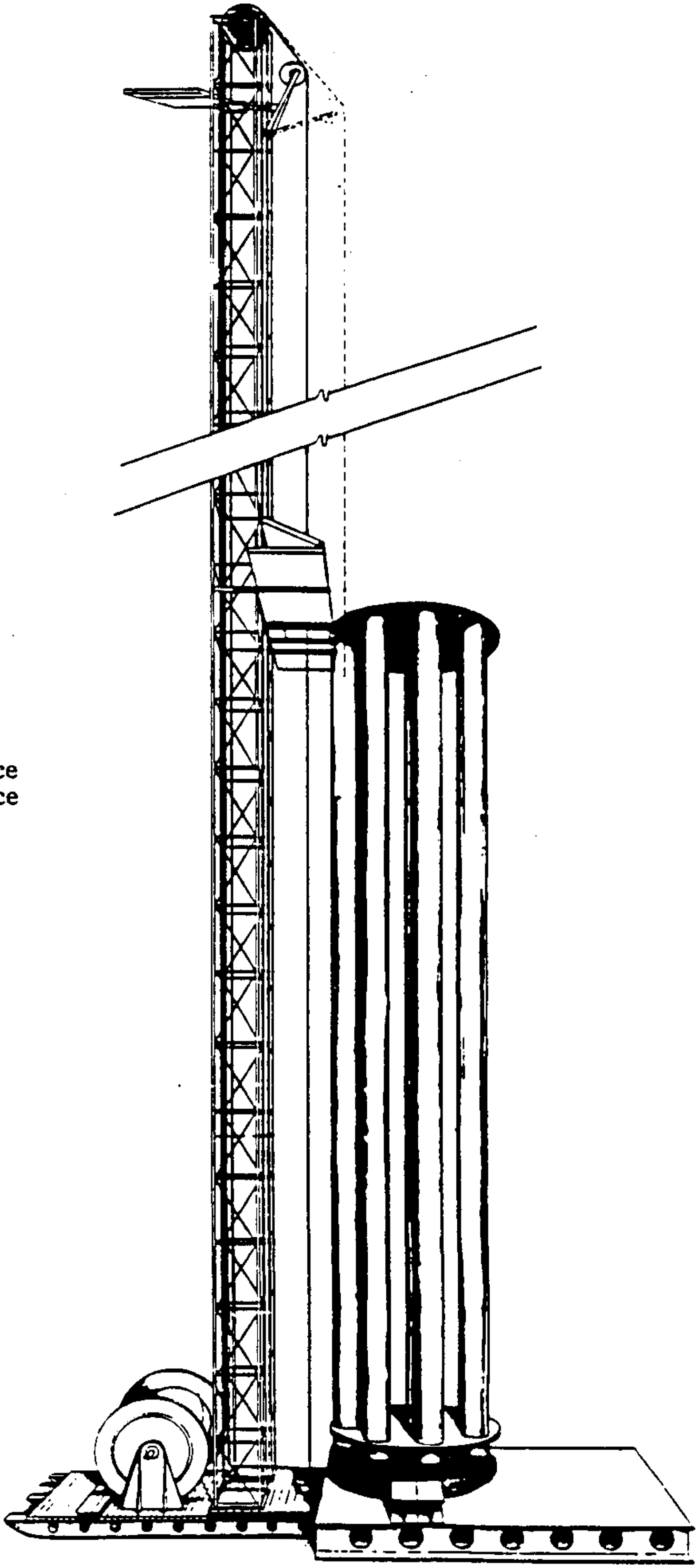


Figure 6. Cable Suspended Ice Core Drilling System, Polar Ice Coring Office

Table 5.

10,000 FOOT, CABLE SUSPENDED, DEEP ICE CORE DRILLING SYSTEM SPECIFICATIONS
(PICO)

Fluid System

- Using Cable and 7.00 in Diameter Core Bit (5.25 in Diameter Core)

Fluid Required, Hole Empty	- 200 gal/100 ft
Total Fluid Required to Drill 10,000 ft Hole	- 30,000 gal[1]

Cable and Core Barrel Assembly

Core Diameter (in)	5.25
Hole Diameter (in)	7.125
Bit (Cutter) Width (in)	.81
Cable Diameter (in)[2]	0.80
Cable Weight. (lbs/100 ft)[2]	27
Cable Pull (lbs)	20,000
System Depth Capacity (ft)	14,000

Drilling System Weight

Rig (Carousel, Mast, Base, Winch, Engine)	- 25,000
Downhole Drilling/coring Unit (2 required)	- 4,000
Cable (10,000 ft)	- 4,000
Fluid System	5,000
Drilling Fluid (BUOAC) (10,000 ft. Hole)	- 225,900
Fuel[3]	—
Misc. Equipment (Generators, Fuel Tanks, etc.)	- 20,000
Est. Total weight:	288,000 lbs

Crew Size

8 hr/day Operation - 4

Note:
1 - Total fluid required based on empty hole volume plus 50% overage.
2 - .800 diameter Kevlar cable with 4 instrument wires and 10 #18 power conductors. Weight of 14,000 ft is 3,900 lb.
3 - Fuel consumption not calculated because a rig of this depth has never been built.

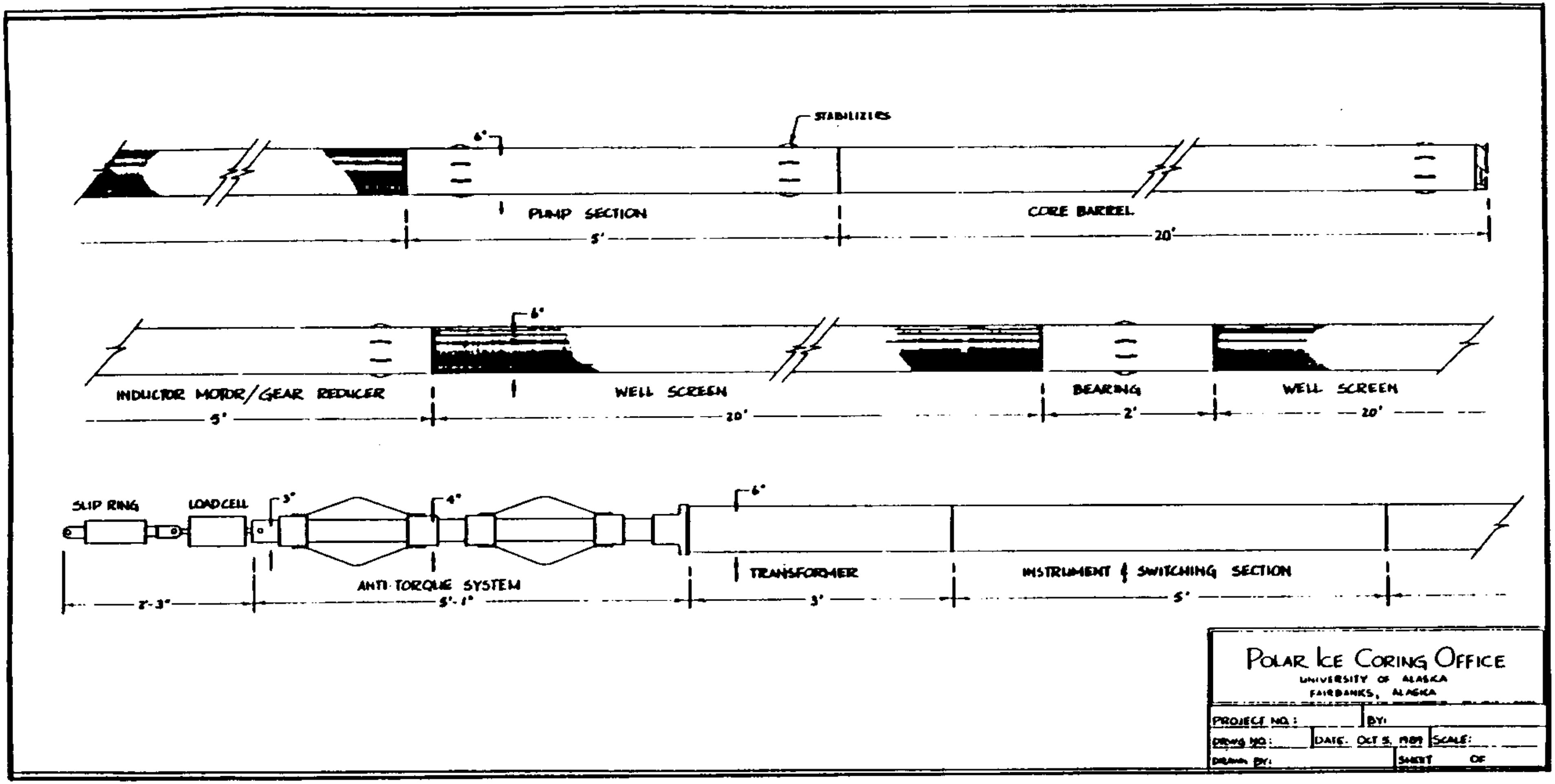


Figure 7.

Downhole Drilling/Coring Unit

positive displacement (Moyno©) pump. The pump is used to assist the upward movement of shavings and fluid into the unit, and to create the rotary motion of the core bit. The downhole unit also contains necessary instrumentation for motor control and for determining the direction of coring. A load cell provides information regarding weight on bit which in turn is used for controlling the surface winch. In addition, a sensor placed at the top of the core barrel determines the vertical position or level of the core in the core barrel. The core barrel has the capacity to hold a 20 ft long core.

The surface equipment consists of a mast 100 ft tall, and a winch capable of storing or reeling 14,000 ft of cable. A carousel-type racking system is used to store the various sections of the downhole unit when on the surface. The carousel can also wash out ice shavings in various sections of the downhole unit and clean it. Washed out shavings are channeled into a pit below the carousel. They are then transported by an auger-type conveyor to a mechanism that separates the chips. The section containing the core barrel can be taken from the carousel for removal of the ice core. Other sections of the downhole system that need maintenance or repair can also be removed as needed.

A diesel/hydraulic prime mover and camp supplied generators provide power for the system. This includes the downhole drilling/coring unit, the winch, the carousel, the chip conveyor, the chip separator and other surface units. This cable suspended, deep ice coring system was installed at the GISP II glaciological research site, Greenland, July 1990.

© Robbins Meyers Company

V. SELECTION OF A DEEP ICE CORE DRILLING SYSTEM

Selection of an acceptable deep ice coring system will be accomplished by comparing three systems to the design requirements noted in Section II. Each system will be evaluated against each design requirement and then against each other to determine their comparative value. The results of the comparative ratings will be tabulated in Table 6. A rating of one (1) denotes the highest value and three (3) the lowest value.

A. *Bit/Ice Interface Control*

Control of various parameters (torque, speed, weight-on-bit, etc.) that relate to the bit/ice interface interaction is essential for obtaining quality core. This can only be achieved by development of a means for transmitting and receiving data between downhole and surface sensors and controls. This concept is referred to as "a closed loop telemetry system."

The development of downhole control systems have developed over many years in the petroleum industry. Systems such as transmission of data by electric signal through the drill pipe, low frequency transmission through the surrounding rock and other techniques have all been tried but none have been successful. No system has ever been developed that can both transmit and receive information between the surface and downhole instrumentation. To date the only system of commercial value is "Mud Pulse" telemetry. This system transmits downhole information to the surface by pulsing the mud column. The time interval between pulses is detected at the surface and then translated into meaningful data. However, this system has not been adapted for use with either the drillstring-conveyed core barrel or the pipe-driven wireline core barrel.

The wireline utilized in the pipe-driven, wireline core barrel system could possibly be utilized as a transmission link. However, this cable is detached during drilling/coring operations and pulled back to the surface.

Considerable redesign work and experimentation would be required to convert this system to a closed loop telemetry system.

The cable utilized in the cable-suspended ice core drilling system can be utilized as a transmission link for a closed loop telemetry system as it is permanently attached to the downhole coring system. At present, this cable is used to transmit power from the surface to the downhole coring system. It also transmits data from the downhole system to the surface. Considering this, the cable-suspended system has greater potential for adaptation of a bit/ice interface control system than either of the other two systems.

B. *Simplicity of Design*

Both the drillstring-conveyed and the pipe-driven wireline systems require drillstrings and similar type surface auxiliary systems. The pipe-driven wireline system is somewhat simpler in design than the drillstring-conveyed system because it requires less drilling fluid, and therefore a smaller drilling fluid system. In addition, its drillstring (3$^1/_2$ in versus 4$^1/_2$ in for the drillstring-conveyed system) is lighter, thereby requiring a smaller winch and a lighter mast. These design requirements are less complex because of lower stress requirements, simpler bearing/oiling systems, fewer components, and other design considerations.

The cable-suspended ice core drilling system is simpler in design than either the pipe-driven or drillstring-conveyed system. It does not require a drilling fluid circulation system because its drilling fluid is not circulated. it is used for hole stabilization purposes. The drilling fluid system used by the other two systems is used to transport chips to the surface and for bit cooling in addition to hole stabilization. In addition, no drillstring is used in the cable-suspended system thereby eliminating the need of a heavy duty drawworks, and a heavy mast with a block and tackle. Slips, tongs, a pipe racking system in the mast and a pipe lay down area are also eliminated. Because the drillstring and the fluid circulation system are eliminated, the power system can be smaller in size and simpler in design.

C. *Light Weight Design*

As noted above, the cable-suspended system is simpler in physical design than either of the other two systems because of the reduction in number of components, the lower stresses involved, and the smaller power supply needed. This simplicity is reflected in a weight reduction as noted by comparing weight characteristics of the three systems (Tables 3, 4 and 5). However, the cable-suspended system drills a larger hole (7-in diameter versus 3.99-in diameter for the pipe-driven system) and does not use drill pipe. This in turn requires a larger volume of drilling fluid for hole stabilization purposes. Thus, although the cable-suspended system is lighter than the pipe-driven system, the need for a larger volume of drilling fluid makes these two systems close in weight. However the cable suspended system supplies 5.2-in core versus 3.3 in for a wireline system. Both systems, however, are significantly lower in weight than the drillstring-conveyed system.

D. *Low Fuel Consumption*

In normal drilling operations the vast majority of fuel is consumed during tripping operations and when circulating drilling fluid. in coring operations trip time is significantly increased (Section III,B) over conventional drilling operations, thereby increasing fuel consumption.

Fuel consumption during coring operations of the drillstring-conveyed system is considerably higher than that of the pipe-driven wireline system. To retrieve its core barrel it must trip its drillstring in and out of the hole, whereas the core barrel of the pipe-driven wireline system can be winched in and out without tripping the drillstring. The only time it trips the drillstring in and out of the hole is to change the bit. In addition, the drillstring-conveyed system uses a much larger volume of drilling fluid than the pipe-driven system (Tables 3 and 4). Thus it requires more fuel for this operation.

By comparison the cable-suspended system has no drill pipe to trip in and out of the hole. It retrieves its core barrel and bit by winching the downhole drilling unit in and out as required. Further, it does not circulate its drilling fluid in the same manner as the other two systems. Therefore, its fuel consumption is less than the pipe-driven system and significantly less than the drillstring-conveyed system.

E. *Limited Crew Size*

Both the drillstring-conveyed system and the pipe-driven system use similar size crews (Tables 3 and 4). If more than one working shift is used, a supervisor (Tool Pusher) is added to the crew. In ice coring operations one working shift is normally used. Hence, crew sizes for all three systems are similar unless additional work shifts are considered.

F. *Ease of Maintenance*

The more complex surface equipment of the drillstring-conveyed system will require more maintenance than the less complex equipment of the pipe-driven wireline system. However, the components of the retrievable core barrel used in the pipe-driven system are more complex than the coring system of the drillstring-conveyed system. Thus, the two systems are fairly equal in amount and ease of maintenance required.

The cable-suspended ice core drilling system does not have a complex fluid system nor does it use drill pipe and its associated equipment (tongs, slips, pipe racks, etc.). In addition, its power system is smaller and less complex, and its mast does not incorporate a complex sheave and block system. Thus, its overall maintenance requirements are significantly less than the other two systems.

G. *Ease of Operation*

As previously noted, the drillstring-conveyed system is more complex to operate than the pipe-dirven system, because the drillstring must be tripped in and out of the hole every time the core barrel is retrieved. In addition, its more complex equipment (noted above) requires greater individual attention. The pipe-driven wireline system, however, utilizes a cable-winched core barrel which is more complex than the drillstring system. Hence, both systems are essentially equal with regard to ease of operation.

The cable-suspended ice core system is the easiest to operate because it does not have a drillstring to trip in and out of the hole and its winching cable is permanently attached to the downhole system, thereby making it easier to retrieve. The added surface components (the carousel and the chip conveyor) are fairly simple to operate and no operational difficulties are anticipated.

With regard to erecting each of the systems in an arctic environment, the erection of the drillstring-conveyed system and the pipe-driven wireline system will be difficult because of the weight of each system and the lack of on-site heavy construction equipment to move components around. The cable-suspended system, although lighter, may still present problems because it does not have the built-in systems (as do the other two systems) for erecting the mast and the carousel. Thus, no system will be easy to erect.

Considering the above, each of the three systems has individual problems that make all three relatively equal with regard to ease of operation.

H. *Safety*

When operating oil field equipment, most accidents occur during pipe handling operations. This is due to the number of hand operations that must be performed. As an example, slips are removed and set by hand. Pipe joints are torqued and untorqued using hand-operated tongs, and are coupled or uncoupled from each other by hand spinning a chain around the upper pipe section. The other end of the chain, which is attached to the drawworks, is then tightened and the upper pipe section can be spun into or out of the lower section. During these operations a single (30 ft) section, a double (60 ft) section or a triple (90 ft) section of pipe, weighing between 600 and 2,000 lbs, is moved around the rig floor. Any of these operations that are not carefully controlled will result in serious injuries, such as the loss of hands, arms, fingers, or toes. unfortunately, such accidents are common and result in high insurance rates. Considering the cold environment in which ice coring equipment has to operate, the accident frequency could be significantly higher.

Because the cable-suspended ice core system does not have a drillstring, a major cause of accidents is eliminated. In addition, this system is simple and easy to operate. Therefore it should have a lower accident frequency rate than the other two systems.

I. *Core Size*

A requirement for a 5.2-in core has been established. As noted in Tables 2, 3, 4 and 5, both the drillstring-conveyed system and the cable-suspended system are capable of obtaining core of this diameter. The pipe-driven wireline system as yet cannot obtain core of this size. However, there are no design problems preventing its development.

J. *Penetration Into Dirty Ice and/or Rock*

As stated in Section I.2, conventional rock coring systems (i.e., drillstring-conveyed and pipe-driven systems) have been used successfully for years by both the petroleum and mining industries. Therefore, there is no question regarding their coring ability in dirty ice or rock. Unfortunately very little experience has accumulated with conventional since coring systems in these two areas. As presently designed, ice coring systems will have in these two areas. As presently designed, ice coring systems will have extreme difficulty coring either area. hence, the cabel-suspended system, in its present design, will be of little value in these types of operations.

It may, however, be possible to modify this system to accommodate this type of coring. Appendix B of this document discusses this possibility.

K. *Cost*

Cost is a factor inherent in each of the design requirements stated above. Low fuel consumption, ease of maintenance, and safety directly relate to operational costs. Light weight design, low fuel consumption (i.e., low fuel volume to transport) and overall system weight (including fluid system volume) relate to logistics problems which in turn relate to transportation costs. Some costs such as fuel consumption relate to both operational cost and transportation cost. Thus, to determine the system with the best overall cost characteristics, the design requirements that relate to operational costs, transportation costs, and initial cost must first be determined. Each cost category will then be evaluated against each of the three operating systems. The composite of these three cost evaluations will then determine the system with the best cost characteristics.

Operating cost factors are inherent in bit/ice interface control, fuel consumption, crew size, maintenance, ease of operation, and safety. The more effective a system is in each of these areas, the lower its operating cost will be. Comparison of the three operating systems regarding these factors, as noted in Table 6, shows that the cable-suspended system has the best rating or is equal to each of the other systems. Thus, the cable-suspended system will have the lower operating cost.

Transportation cost factors are inherent in light weight design, fuel consumption, and crew size. Table 6 indicates that the cable-suspended system is

more effective regarding these factors than the other two systems. Thus, its transportation costs should be lower.

Initial cost or purchase cost will be based on relative cost and not specific cost because the cable-suspended system is not being built for commercial purposes as are the other two systems.

In industry, raw material costs and manufacturing costs per pound of metal are used to develop a cost estimate. Since the raw material used for construction of the drillstring-conveyed and pipe-driven wireline systems are essentially the same, the manufacturing cost per pound of metal should also be similar. Thus, the weight ratios of these two systems can be used as a rough estimate of their cost ratios. Using the weights of the two rig systems (minus the weight of the drilling fluids) as noted in Tables 3 and 4, the 3.5-in drillstring system is roughly 10-20% more expensive than the pipe-driven system. Similarly, the 5.25-in drillstring system is roughly 20-30% more expensive than the pipe-driven system. If drilling fluid is incorporated into these estimates, the ratio would increase because of the larger volume of fluid used by the drillstring-conveyed system.

Comparing the pipe-driven system to the cable-suspended system is more difficult because aluminum is used for many parts of the cable-suspended system. However, considering this fact and eliminating the weight of the drilling fluid, comparison of system weight ratios, as noted in Tables 4 and 5, indicates the cost of the pipe-driven system to be twice as expensive as the cable-suspended system. Considering the higher cost of aluminum compared to steel, this cost ratio will be reduced. When incorporating the larger volume of fluid required by the cable-suspended system, the cost of both systems will be similar.

Considering the three cost factors noted above, the cable-suspended system and the pipe-driven system are similar in overall cost. The drillstring system, however, is more costly than either of the other two systems.

Table 6. Evaluation of System Criteria.

Design Requirement	Drill String Conveyed Core Barrel	Pipe-Driven Wireline Core Barrel	Cable-Suspended Ice Core Drilling System
Bit/Ice Interface Control	3	2	1
Simplicity of Design	3	2	1
Light Weight Design	3	2	1
Low Fuel Consumption	3	2	1
Limited Crew Size	1	1	1
Ease of Maintenance	2	2	1
Ease of Operation	2	2	2
Safety	2	2	1
Core Size	1	2	1
Penetration Into Dirty Ice and/or Rock	1	1	2
Cost	2	1	1

Rating Criteria: 1 - Most Compliant
2 - Least Compliant

VI. SUMMARY

Evaluation of Table 6 suggests the superiority of the cable-suspended system to either the drillstring-conveyed core barrel of pipe driven wireline with regard to ice coring. The key factors creating this advantage are the elimination of the drillstring and the lack of need for a drilling fluid circulation system, both of which add weight, increase operation time and system cost, and present significant safety problems. The advantage of the cable-suspended system is further enhanced by its potential for incorporation of a closed loop telemetry system for bit/ice interface control. This advantage is by far the most important.

The pipe-driven wireline core barrel system can be used for ice coring operation. however, its cost factors, its logistics problems (size and weight), and its use of a drillstring and a fluid circulation system make it far more complex and costly to use than the cable-suspended system. At present, its only real advantage is its ability to core dirty ice and rock.

APPENDIX A

SIDEWALL CORING

APPENDIX A

SIDEWALL CORING

During ice coring operations and after a core has been obtained and examined, it may be desirable to obtain additional samples or information from a particular ice zone. Sidewall coring provides a means to obtain the samples.

Sidewall coring is not new. It has been performed successfully for years in the oil and gas industry. It is sued primarily to obtain rock samples (truth) needed to verify logging information after a well has been drilled and logged. The industry has developed numerous systems. Some are applicable to ice coring and others are not. This is due to the brittle nature and low strength characteristics of ice as compared to rock. A series of the more applicable ones and their potential for ice coring are described below.

- **Rotary Sidewall Coring Tool (Figure A1)**

  This tool is deployed on a powered wireline cable. It has a small diameter core bit and tube that can cut a cylindrical core normal to the bore hole. The length of the core will be small due to the geometry of the tool and the requirement of turning the flexible drive shaft 90° within the tool housing. The diameter of the core will, therefore, be smaller than the diameter of the tool housing.

  The tool can be adapted to ice coring operations. Its value is questionable in its present form due to the very short length of core it can obtain. This problem may possibly be overcome by redesign of the flexible drive shaft in which case very long cores (2-3 ft in length) might be obtained.

- **Tricore Coring Tool (Figure A2)**

  This system has two small electric motors driving thin circular diamond saw blades. The tool is run downhole on a powered cable to the hole section in question, where it is then pressed against the hole wall. The two blades move down the side of the tool cutting a section of the sidewall as it moves ahead. Wall sections up to three feet in length have been obtained. In the oil and gas industry, the tool has been field tested with good results in hard rock and poor results in soft rock.

The tool can be adapted to ice coring requirements. its main drawback may be the smallness of the cross section area of the sample obtained.

- **Rotary Sidewall Coring Tool (Figure A3)**

In its present form this tool (4 7/8 inch in diameter) is capable of cutting 5/16 in diameter by 1 3/4 in long core. With redesign the tool could probably core a larger diameter and longer core. The tool is lowered into the hole by a powered cable.

This tool is presently available in the oil and gas industry. To date the results of its field operations have been fairly good, although the size of the core it obtains is very small for oil field operations. With redesign to obtain a larger core, it may be practical for ice coring operations.

- **Rotary-Type Sidewall Coring Tool (Figure A4)**

This coring tool works in conjunction with a drill string. After the drillstring has been lowered into the hole, the fluid circulating system flushes out the positioning tool at the end of the drillstring. The drillstring is then suspended on slips set in the rotary table of the drilling rig. The core barrel is lowered by wireline down the inside of the drillstring until it comes to rest on the tool at the bottom of the drillstring. The core barrel is then at an angle to the well bore as noted in Figure A4. Rotation is obtained by hydraulic power from the fluid circulating system.

Use of this system for ice coring is questionable because of the need for a drillstring and a circulating fluid system, which will greatly increase the cost of the ice coring system. In addition, the diameter of the core wall will be small, although its length could be several feet long.

- **Strata-Punch Sidewall Coring Tool (Figure A5)**

This tool is lowered into the well bore on a wireline system. it is designed to obtain six (6) small cores at one time. As noted in Figure A5, when the tool is in position in the well bore the lower coring mechanism is retracted and the core barrels are forced into the wall. Because of the tool geometry the core barrels move in changing angular direction toward the well bore wall and then angularly into the wall. Although the manufacturer claims the cores are neither shattered or compressed with this type of movement, it is doubtful if good ice cores can be obtained.

In addition to the tools noted above, others are available in the petroleum industry. However, because of their nature of operation (use of explosives to force the core barrel into the side wall) it is very doubtful if good ice core could be obtained.

Evaluation of the above tools notes that several use a powered wireline to power and control the tool, and several are capable of taking multiple cores. in some instances radioactive markers are used to determine where to core. Modifications of some tools could make them adaptable to ice coring operations with little effort.

Considering these factors the probability of developing a tool that would obtain core 3 to 4 inches in diameter and 3 to 4 inches in length is quite good. The same tool could obtain multiple cores if desired. However, a design program would be required for a tool of this size.

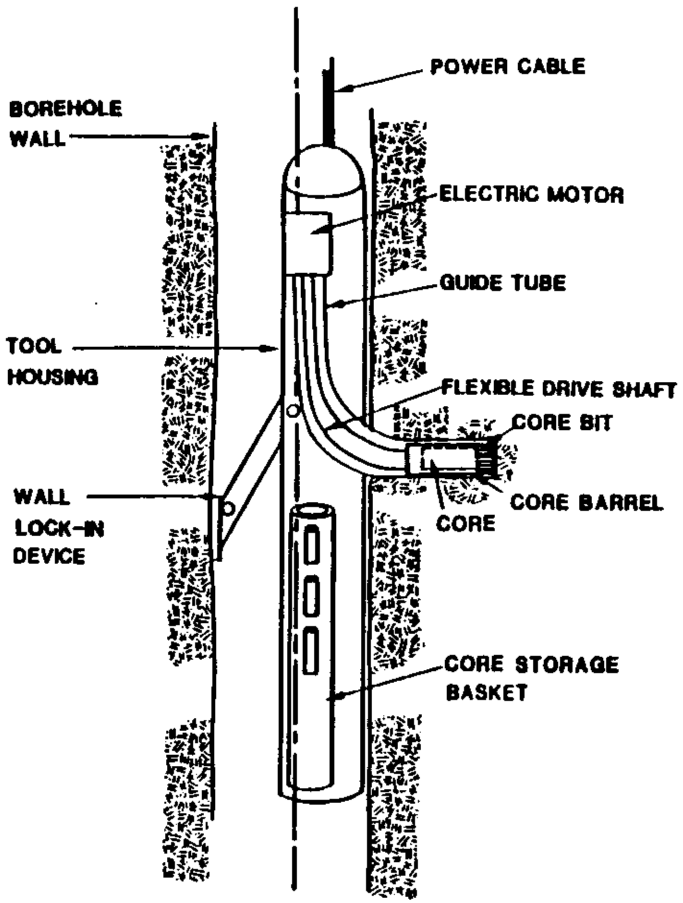


Figure A1.

Rotary Side wall Coring Tool

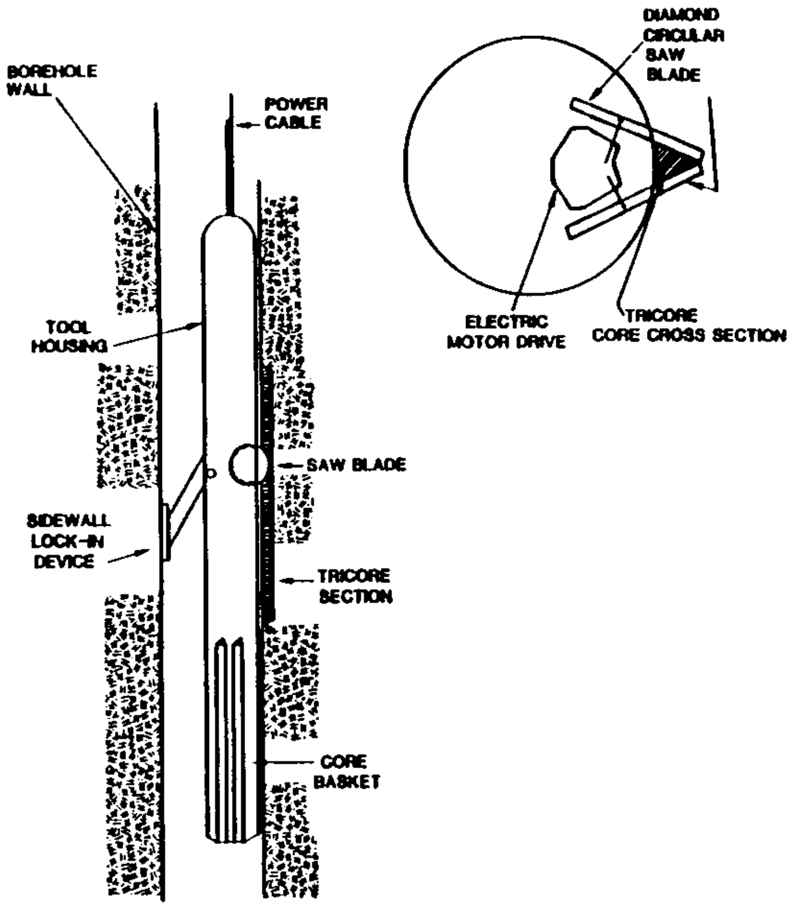


Figure A2.

Tricore Coring Tool

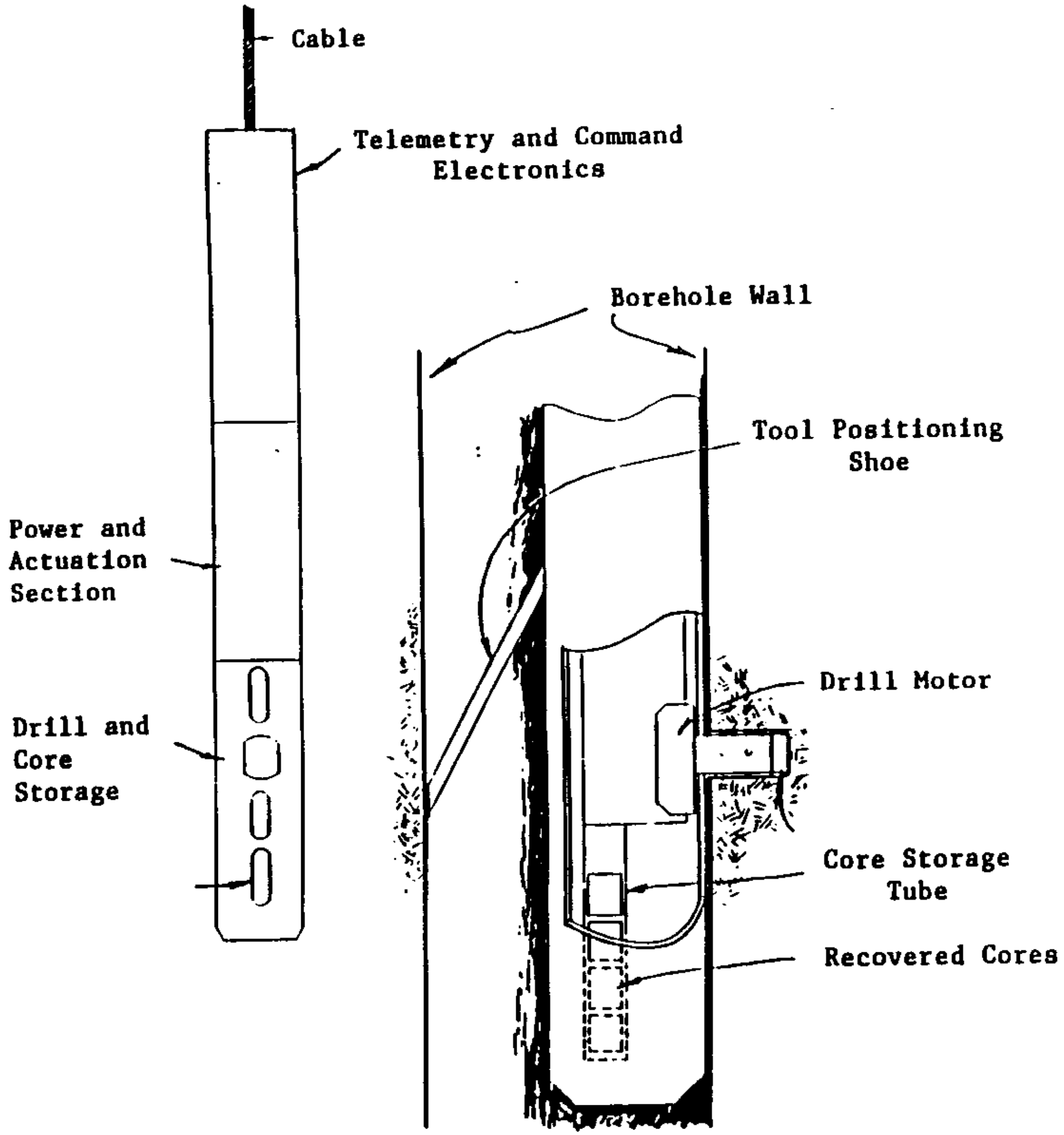


Figure A3.

Rotary Sidewall Coring Tool

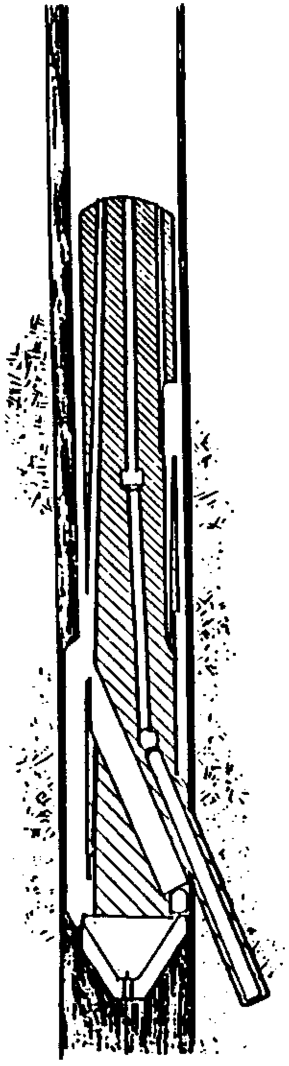


Figure A4.

Rotary-Type Sidewall Coring Tool

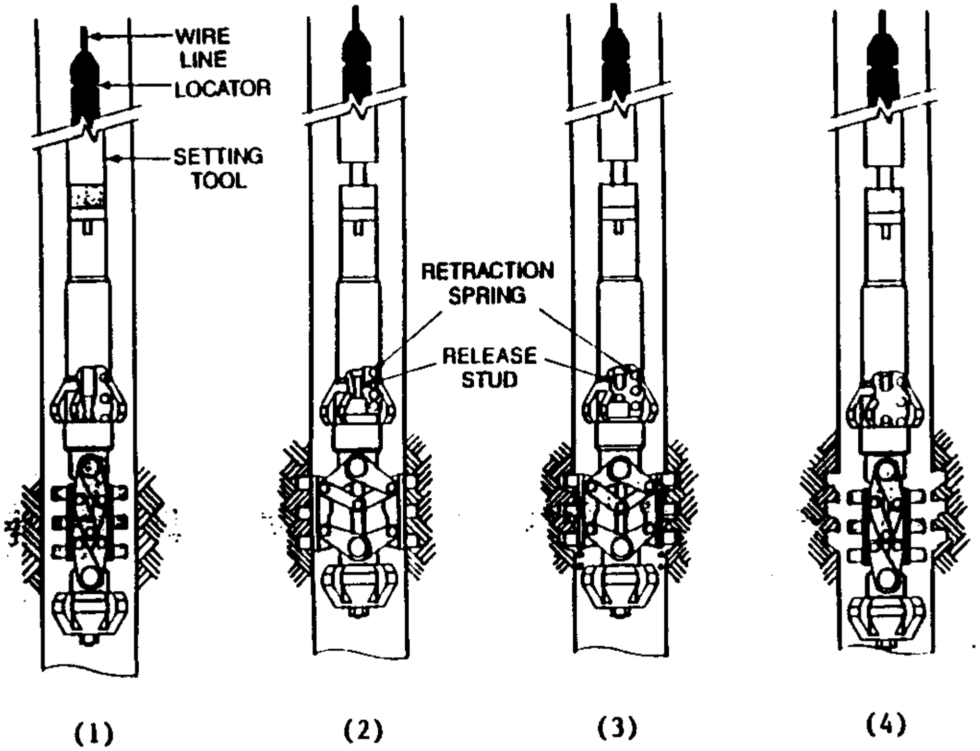


Figure A5.

Strata-Punch Sidewall Coring Tool Reference: Baker Service Tools, Houston, Texas

APPENDIX B

CORING DIRTY ICE AND ROCK

APPENDIX B

CORING DIRTY ICE AND ROCK

A. CONCEPT OVERVIEW

Coring through dirty ice and/or rock with a cable suspended ice core drilling system might be accomplished by modification of the downhole coring system and extensive experimentation to determine and understand the interaction between the bit and the surface directly below it. Modification to the downhole system includes:

- Incorporation of a downhole fluid circulation system.
- Improved anti-torque mechanisms.
- Use of narrow kerf diamond impregnated bits.
- Development of a closed loop, downhole telemetry system.

However, it will be necessary to obtain an understanding of the operational characteristics of narrow kerf diamond impregnated bits in ice and dirty ice.

The development of this system must be approached with care because of the complexity of the problems involved and the need to develop a cost effective system. It is possible that a modified cable suspended system can be developed to accomplish this task. However, developing one that is efficient and cost effective will take time.

B. SUGGESTED PROGRAM APPROACH

To develop this system, it is suggested that system requirements and a conceptual design be developed.

Having determined a potential design, an experimentation program must be established to determine bit/surface interaction in ice and dirty ice. This experimentation will investigate the coring capability of different narrow kerf bit designs in both ice and dirty ice. Extensive knowledge is available on this type of bit in rock coring operations, and some knowledge may be available on its operation capability in perma-frost. However, considering the available weight on bit, and the limited fluid circulation system that will be sued, knowledge must be obtained regarding magnitude and relationship of bit rotation speed, weight on bit, torque and removal of debris from below the bit when drilling in the different media. These factors must be evaluated in light of obtaining quality core and not just obtaining a hole.

Based on design criteria and determination of the types of bits to be used, a preliminary design of the downhole fluid circulation system can be made. Concurrent with this effort a compact system for removal and storage of ice and rock chips onboard the downhole coring system can be developed. The preliminary design of the power system and the downhole closed loop instrumentation and telemetry system can be developed next. Upon completion and integration of theses preliminary designs a housing system and adequate anti-torque mechanism can be established.

With the preliminary system design accomplished, a thorough review of it must be made to assure that all components are as small and compact as possible and all stress and load factors have been thoroughly evaluated. When these factors are assured, the final design of this system can be made. Only after this design is well established and the weight, length, power requirements and surface control requirements known, should attention be given to surface equipment.

The system described is far more complex than present day ice coring systems, thus, the need for proper system design evaluation and the development of a downhole closed loop instrumentation and telemetry system. The need for bits capable of coring rock and for a downhole fluid circulation system are also important.

C SUMMARY

Although difficult design problems may be encountered, it is possible to develop a rock coring modification of the cable suspended ice coring system. The use of a cable suspended system is superior to either a drillstring or pipe-conveyed system for the same reasons noted earlier in this report. Further, the development of this type of system will eventually lead to modifications that could allow coring under fast moving ice and/or offshore ice.