72-14,114

MURPHY, Robert Jeremiah, 1936-
OPTIMUM WATER WELL DRILLING EQUIPMENT
FOR REMOTE TACTICAL AREAS.

The University of Oklahoma, Ph.D., 1971
Engineering, civil

University Microfilms, A XEROX Company, Ann Arbor, Michigan

THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

OPTIMUM WATER WELL DRILLING EQUIPMENT FOR REMOTE TACTICAL AREAS

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

DOCTOR OF PHILOSOPHY

BY

ROBERT JEREMIAH MURPHY

Norman, Oklahoma

1971

OPTIMUM WATER WELL DRILLING EQUIPMENT

FOR REMOTE TACTICAL AREAS

APPROVED BY

Geo. W. Reid

Lyle E. Sa

Wm R Smith

Col J Crane Jr

DISSERTATION COMMITTEE

ACKNOWLEDGEMENTS

I wish to express my extreme gratitude to the numerous individuals who contributed immeasurably to the accomplishment of this work. Captain Thomas Grimshaw of the U. S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia, provided invaluable editorial and geological input in constructing the study. Professor George W. Reid must be singled out for his significant contribution in guidance and encouragement throughout the study.

Acknowledgement is extended to members of my committee for their assistance; Dr. Leale E. Streebin, Dr. Ed F. Crim, Jr., and Dr. William R. Southard. Further, my appreciation is given to Dr. Henry B. Crichlow for his criticism and guidance.

I express my thanks to the United States Army, the Corps of Engineers and the Medical Department for their financial support in pursuit of this study and the continuation of my education.

Special thanks are also in order to Carol Vesely for her patience and diligence in preparing the manuscript. And, significantly, to my wife, Nancy, and children, whose contribution is manifest in the love and understanding I am privileged to enjoy every day.

OPTIMUM WATER WELL DRILLING EQUIPMENT

FOR REMOTE TACTICAL AREAS

BY: ROBERT JEREMIAH MURPHY

MAJOR PROFESSOR: GEORGE W. REID

The objective of this study is to evaluate current day (1971) lightweight rotary drilling equipment to determine a configuration of commercial equipment that would best meet the U. S. Army application of constructing water wells in remote tactical areas.

A systematic framework for configuring the equipment is achieved by dissecting a rotary drilling rig for water well construction into four principal elements: the drill system that imparts rotation to drill subsurface formations; the circulatory system which removes hole cuttings during drilling operations; a power unit to support both the circulatory and drill system; and an aggregation of support materials to execute a drilling and well development program. Detailed data are collected and presented to evaluate alternatives of various circulations and drilling various sized holes with different drill pipe combinations.

The method of evaluating the various alternatives generated is a decision weighting model which seeks a measure of objectivity by delineation of the physical performance characteristics of the various commercial drills, circulatory equipment and support materials. The objectives for the well construction system are specified and decomposed into lower level performance criteria and, finally, are quantified by physical performance measures or direct worth estimates for each alternative. This decomposition is followed by weighting each of the criteria to reflect its overall contribution to the objective. Then the criteria are aggregated to provide a single measure of the alternatives' overall worth through a total utility index. The principal criteria used to evaluate the alternatives in this study are: simplicity of operation, equipment versatility, equipment transportability and equipment reliability. Cost effectiveness of the alternative is achieved by graphing the total utility of the alternative against its cost.

The impact of the physical weight of an alternative to air lift the equipment with the U. S. Army's principal helicopter (UH1H Model) greatly controlled the total utility of the alternative. Also, the cost effectiveness analysis was of questionable value since the equipment costs did not include the design costs incident to aggregating various equipment components for an alternative. Nonetheless, the decision model proves invaluable in selecting a specific hole diameter and drill pipe size, circulatory mode and a choice of two drill system alternatives that will best meet the U. S. Army's objectives for this equipment. Significantly, these alternatives were narrowed

from 480 original alternatives in a manner that proved to be superior to conventional subjective decision processes.

TABLE OF CONTENTS

LIST OF TABLES

Table | Page

LIST OF FIGURES

OPTIMUM WATER WELL DRILLING EQUIPMENT FOR REMOTE TACTICAL AREAS

CHAPTER I

INTRODUCTION

Water is the key element woven into the fabric of man's existence, and, in general, engineering technology has been successful in meeting society's increased demand for this essential commodity. Man's requirement for water during combat is no less paramount than that during peacetime. However, during combat, water must be obtained and processed without the luxury of sophisticated power and equipment resources common to peacetime operations.

The importance of water resource development in combat, for any of a number of possible theaters of operation, has long been recognized by the United States Army and has been the focus of significant research and development efforts. Notable successes have been accomplished in the treatment of surface water sources in both remote locations and, also, relatively secure logistical base cantonments (1).

However, the development of groundwater resources has largely been confined to the base complexes by well drilling methodology and equipment, which lacks the configuration to permit flexible employment in remote areas. Lack of equipment which is lightweight and can be flexibly employed has necessitated endless truck and helicopter sorties to import water to smaller camps, or reliance on surface supplies to the exclusion of groundwater. Substantiation of these points is found in recent reports on water supply problems in the Republic of Vietnam (2,3), which noted the deficiency of existing standard military drilling equipment by total reliance on deep well drilling equipment. It is interesting to note that, if the current standardized equipment had a depth capability of just 200 feet, it would have sufficient capacity to have drilled approximately 80% of all the water wells reported to have been completed in the United States during 1966 (4).

The advantages associated with a lightweight water well drilling equipment capability include:

A. Flexibility of selection of a water source.

B. Minimization of logistical support required for water supply (i.e., transportation of water and/or materials required for treating surface water sources, inasmuch as shallow groundwater normally only requires disinfection).

C. Enhancement of response time to develop water resources for civic action projects.

D. Minimization of the possibility of radiological, chemical and biological surface contamination.

E. Common availability of groundwater where surface water is not available (i.e., desert environment) or when the supply of surface water dwindles (i.e., drought).

F. Selection of a groundwater source which places a water supply in closer proximity to the consumer and mitigates security requirements for protection of water supply.

Background and Related Research

Once the requirement for augmenting existing standard groundwater development equipment for the Army was established, a Qualitative

Material Development Objective (QMDO) Plan was formulated by the United States Army Mobility Equipment Research and Development Center (USAMERDC) that includes plans to develop lightweight well construction equipment (5). This effectively placed the development of lightweight water well drilling equipment in the Army Research Planning Sub-Phase of the Concept Formulation (6).

The initial activity in pursuit of the QMDO was execution of an extensive literature search and evaluation of well drilling methodology, completed under contract by Dr. A. B. Rudavsky (7). This same contract promulgated specific mission performance characteristics for the equipment. These performance characteristics and specified parameters are presented in Table 1.

The conclusions of Dr. Rudavsky's study were categorized into six discrete areas; geology, combination rigs and versatility, size and weight considerations, downhole methods, hollow spiral auger application, and novel drill techniques. A brief summary of the conclusions from Rudavsky's study follows. (A glossary of well drilling equipment and operation terminology is attached for the reader's convenience as Appendix 1.)

Geology

Basically only two key drilling processes, cable-tool and rotary, are largely unlimited by geologic formations. Some special techniques for particular special geologic conditions appear warranted. Since the drilling machine should encompass as many geologic formations as possible for Army tactical use, a multi-purpose rig should be seriously

TABLE 1

METHODS AND EQUIPMENT REQUIREMENTS

FOR GROUNDWATER EXPLOITATION*

U.S. Army Requirements	Specified Measurable Parameters
1. Operational Time (Starting time of well development to completion time)	48 hours
2. Depth Limitation	Maximum 150 feet
3. Camouflagability of equipment and operation	(a) Size-(see transportability) (b) Quiet Operation
4. Transportability	(a) Capable of being airlifted in one lift by a UH-1 helicopter, e.g., MAX payload 1000 pounds, MAX volume 48"W, 48"H, and 90"L (internal load) (b) Ability to palletize complete unit or place components in protective containers which can be handled manually
5. Erectibility	None
6. Simplicity of Operation	None
7. Operability in all Climatic Conditions	None
8. Maintainability	None
9. Reliability	None

*Requirements taken specifically from Reference 7.

considered weighed against the inherent disadvantages of such a system relative to weight and complexity of operation.

Combination Rigs and Versatility

Combinations of construction methods are achieved through; multi-purpose drilling machines, using special adapters, and interchangeable use of various tools keyed to basic drilling processes such as percussive or rotary movement. Examination of commercially available multi-purpose units reflects none which directly meet the Army's requirement for tactical use (Table 2). However, it does show areas where modification through miniaturization is possible and reflect useful operating principles for combining various methods. Reviewing methods for versatility indicates that a multi-purpose rig based on the rotary process would be the most promising to fulfill the Army's requirements. Specifically, the use of a coring type unit combining rotary and augering capabilities appears most lucrative. The interchangeability between mud and air circulation also warrants consideration, whereas reverse circulation is unfeasible due to the bulkiness of equipment associated with the process.

Size and Weight Considerations

Most standard well drilling equipment is inordinately overweight and oversized for the Army's specifications. Comparative data of several of the rigs reported is included in Table 3. Redesign and/or configuration of small sub-unit components appears feasible for some commercial equipment. Specifically, two commercial machines, the Acker ACE portable core drill and the Failing CD-3 Copter Drill, warrant investigation.

TABLE 2

EXAMPLES OF COMBINATION RIGS

IN LIGHTWEIGHT CATEGORY(7)

APPLICATION	MANUFACTURER	MODEL	WEIGHT(lb.)	MAST HEIGHT(ft.)	CAPACITY
Rotary and Coring	Gardner-Denver	Mayhew 200	9,500	19	4" to 200 feet
Rotary and Down-hole Capability	WABCO	CFD-1B	10,000	26	5 5/8" to 1000 feet
Rotary and Augering	Gardner-Denver	Mayhew 3TD	3,500	Unknown	4 1/2" to 200 feet
Rotary and Cable Tool Percussion	Koehring	Speedstar SS-71R	13,400	40	4" to 1800 feet
Rotary, Coring, and Augering	Mobile Drilling	B-50	4,204	19	Auger 4 1/2" to 200 feet
Coring and Augering	Mobile Drilling	B-56	5,770	26	Auger 4 1/2" to 250 feet

In summary, standard rig superstructures are not advisable unless a small collapsible rig could be accommodated. A direct relationship exists between efficiency of operation and the necessity for a superstructure. Coring machines hold a great deal of promise to enhance a compact arrangement configured with power draw works and drilling machinery. This concept should be used in assembly considerations for a multi-purpose rig. Coring unit operation is applicable to most desired drilling operations.

Downhole Methods

The prime mover placed directly above the drilling tools offers one a significant advance in drilling techniques. However, since its primary value is keyed to deep hole drilling, its importance relative to this study is consideration of using the prime mover in two capacities; providing energy to advance well hole construction, and, after completion of drilling, reverse its function to provide pumping energy. This dual function, coupled with the reelable drill stem, has excellent possibilities for the Army's tactical purposes.

Hollow Spiral Auger Application

Advantages of the hollow stem, which can be utilized as casing or an expedient insertion of a well point for a screen and a submersible pump, constitutes a practical approach to the Army's requirements. This technique could be put into operation through enlargement of the drill stem and further miniaturization of submersible pumps.

Novel Drilling Techniques

Unusual techniques reviewed, (e.g., ultrasonic decrepitation,

TABLE 3

COMPARATIVE DATA OF SELECTED

REPORTED RIGS (7)

MODEL	MANUFACTURER	DRILLING CAPACITY AND APPLICATION	WEIGHT (lbs.)	DIMENSIONS
		Percussive Rigs		
Cyclone 5	Cyclone Drill Co.	Percussion 5" to 200 ft.	2,900	26 ft. mast
20-IN	Bucyrus-Erie Co.	Percussion 4-8" to 700 ft.	5,900	36 ft. mast
		Most Compact Rotary Rigs		
Mayhew 200	Gardner-Denver Co.	Rotary 4" to 200 ft.	9,500	19 ft. mast
WABCO CFD-2	WABCO, Drilling Equipment Division	Rotary 4" to 350 ft.	12,400	24 ft. mast
Portadrill 501	Winter-Weiss Co.	Rotary 8" to 1500 ft.	17,000	27 ft. mast

explosives, erosion drilling and rock melting) do not provide sufficient reliability or are in the practical development stage for the Army's requirements.

Rotary Drill Systems for Water Wells

Using the basic conclusions from Rudavsky's report, the objective of this study is to evaluate the currently marketed rotary drill equipment and determine the optimum configuration which the Army should include in a single prototype for field evaluation. The proposition of providing such an optimmumization of drilling configurations without the benefit of several prototype field tests can be successfully executed using operation research and decision theory techniques.

Justification for narrowing the focus of this study to only rotary drilling equipment requires a rational explanation at this point. Percussive drilling equipment was eliminated because of its inefficient performance in unconsolidated formations and poor production and cost efficiency in penetrating hard rock (8) (see Table 4). Also, percussive equipment is extremely heavy and bulky. Novel drilling techniques were excluded due to the fact that none have been subjected to extensive field evaluation and most possess inordinate energy requirements (see Table 5) and excessively heavy supporting equipment. Turbodrills demand unusually large supporting pump volume capacities or large pressure differentials (see Table 6), which consequently result in prohibitive pump sizes or quantities of water for the turbodrill's operation. The application of the downhole air percussion tool will be evaluated with rotary drilling systems.

Rotary well drilling operations involve a series of distinct

TABLE 4

PERCUSSION DRILL VERSUS ROTARY

DRILL PERFORMANCE (8)

TYPE DRILL	HOLE SIZE INCHES	TYPE FORMATION	DRILLING RATE ft./hr.	COST PER FOOT
Rotary	6 1/4	Limestone	40	$0.25
Percussion	6 1/4	Limestone	12	0.58
Rotary	6 3/4	Hard Limestone	40	0.27
Percussion	6 1/4	Hard Limestone	9	0.88
Rotary	6 3/4	Hard Dolomite	22	0.55
Percussion	6 1/4	Hard Dolomite	5	1.50

TABLE 5

CHARACTERISTICS OF SELECTED NOVEL

DRILLING TECHNIQUES (7)

TECHNIQUE	POWER REQUIRED	WATER REQUIRED	DRILLING RATE	APPLICATION AND LIMITATIONS
Plasma Drill (Rock Melting)	3-1000 k.w.	250 gal./hr.	2-3 cm./min.	Experimental
Jet Piercing (Rock Spallation)	500-1000 h.p.	800-1000 gal./hr. @ 60 p.s.i.	0-65 ft./hr.	Shallow hole, field
Ultrasonic Tool	Unknown	Unknown	Unknown	Laboratory
Explosive Capsule Drill	17-100 h.p.		6-7 cm./min.	High cost, Russian Origin, Poor unconsolidated formations
Erosion Drill	2000-6000 h.p.	300-500 gal./min.	15-150 cm./min.	Experimental, large water volumes

TABLE 6

COMPARATIVE TURBODRILL DATA

TOOL	MANUFACTURER	RECOMMENDED FLUID VOLUME	RECOMMENDED DIFFERENTIAL PRESSURE
Dyna Drill 6 1/2" O.D.	Dyna Drill Co. Longbeach, Calif.	325 g.p.m.	225 p.s.i.
Turbodrill 6 3/4" O.D. (60 stages)	Eastman Oil Well Survey Company Houston, Tex.	300 g.p.m.	437 p.s.i.

steps. First, the hole is drilled by applying rotation and downward pressure through the drill stem to the bit and removing the cuttings with a circulatory medium of air or water. Casing is set in the hole as the hole is progressively drilled or after the drilling is completed. A well screen is then normally inserted which functions to protect the water lift or well production pump from abrasive particles (i.e., sand) that could enter the well from the water bearing strata and permit entry of the water into the casing. Finally, the well production pump is installed and the well is protected from surface contamination and developed. Well development involves techniques such as surging or overpumping the well to insure that maximum water flow from the aquifer into the well is achieved.

There are two specific rotary drilling applications that will not be evaluated in the course of this study; augering and core drilling. Augering drill systems do not use a circulatory medium at all. Instead, a spiral conveyor attached to the drill pipe or stem removes the cuttings. There are several variations in the manner in which the spiral conveyor removes the cuttings, including a continuous spiral auger, a bucket auger or a hollow-stem auger. The continuous auger removes the cuttings by the mechanical action of rotation moving material up the spiral to the surface, analogous to the mechanism of removing wood cuttings with a wood bit. A variation of this is the hollow stem auger where the continuous spiral is attached to a drill pipe and water circulated through the pipe to facilitate cutting removal. A bucket auger is simply a single section of spiral attached to the bottom of the drill stem which is periodically brought to the surface and rotated rapidly to remove the cuttings by centrifugal action. The bucket auger is used principally at shallow depths (less than 50 feet) to prepare holes for caissons or the like. Augers generate significantly greater friction resistance during drilling operations than conventional rotary drill pipe, since the spirals are in contact with the sides of the hole for the hole's entire depth. Further, they are not effective unless augmented with water circulation in saturated, unconsolidated subsurface formations and can become stuck in the hole if the sides of the hole cave in. Consequently, the drill machines supporting augers must have greater rotational torque ratings and, therefore, they require larger sized power units than conventional rotary drilling rigs. In unconsolidated formations where a sudden change to a hard formation or floating boulders are encountered, the auger will become out of alinement, resulting in a deviated hole that cannot be cased. These limitations (8) and the inherent weight problem of providing sufficient power to support the higher rotational torque requirements of the drill eliminate any further consideration of augers.

Core drilling equipment is similar to conventional rotary drilling equipment and possesses many positive lightweight properties which will be reported later in this study. However, the application of core drills specifically in a manner consistent to coring operations has limitations. Coring operations involve the use of rotation, but at significantly higher speeds with less accompanying downward force on the bit. The bit used is also highly specific. A diamond bit (diamond chips mounted in a matrix) is normally used, which is attached to a core barrel employed to retrieve the formation core samples drilled at the bottom of the hole. The diamond core bit is highly susceptible to impact load, and, therefore, to operator expertise for effective utilization. Currently, most coring operations are carried out exclusively with water circulation. Core drilling operations, therefore, demand an extremely experienced operator to maintain the proper rotation speed and downward pressure relative to the subsurface formation being drilled. Core drill equipment will be evaluated in this study, but diamond bits and coring operations possess limitations (8) and will not be encompassed in the remainder of the study.

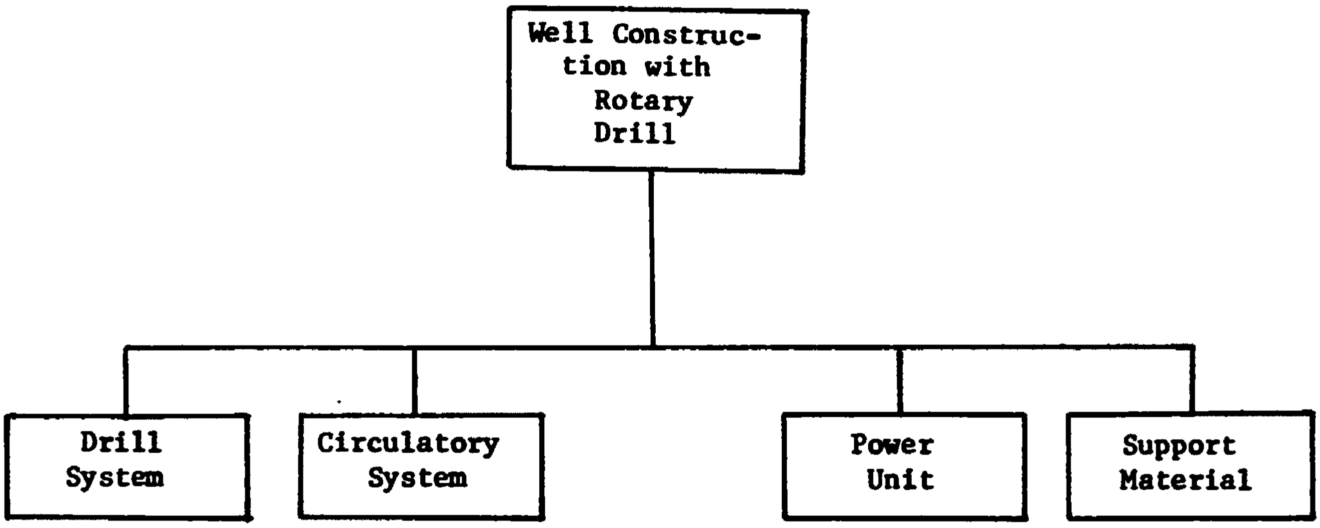
In viewing the objective of the drilling program as a means to develop groundwater resources, a well construction system can be characterized as composed of four key elements (see Figure 1): the drill system includes the mast, hoisting capability, rotary and pulldown mechanisms; the circulatory system is basically the means employed to remove the cuttings from the hole, and the system includes an air compressor or mud pump and any associated mixing and injection equipment for the addition of the circulatory additives; the power unit can be considered as dual or single function, relative to whether it supports just the circulatory system, the drill system, or both; critical to the entire system are such support materials as the additives used in drilling, the drill pipe and casing, bits, well screens, production pumps, and tools which encompass well development and support materials.

All these elements can assume different forms and operating principles to accomplish a water well development effort at different efficiencies and costs. Some of these elements enjoy variable degrees of success as a function of the rock formations encountered and operator skill. The distinction or discrimination between the commercially available alternatives within these elements which will best satisfy the Army's requirements, among various marketed drilling equipment, becomes the task of this study.

FIGURE 1

KEY ELEMENTS IN ROTARY DRILLING

RIG FOR WATER WELLS



CHAPTER II

THE STUDY OF ROTARY DRILLING SYSTEMS FOR WATER WELL DEVELOPMENT

Principal Evaluation Factors

The selection of the well construction system's components is a function of subsurface formation conditions, the drill-hole diameter and depth (treated as hole volume), penetration rates, economics, simplicity of operation, and the equipment's reliability and weight.

Subsurface Formations

Since the U. S. Army has world-wide contingency plans and extensive geographical commitments, difficult drilling conditions must be anticipated. Such conditions include: variable rock formations (very soft to very hard); mixed soft and hard formations (e.g., boulders in unconsolidated formations); unstable or caving formations; and lost circulation zones. The nature of the rock formation's influence on penetration rates must be examined in terms of the mission time allowance (48 hours) and the machine's operating characteristics. This area will be addressed subsequently under the subject of penetration rates. Caving formations and lost circulation are directly influenced by the circulatory system and flushing medium used and, therefore, will be discussed under the circulatory topic heading.

The Influence of Hole Depth and Diameter on Pump Size

As previously pointed out in Table 1, depth was fixed for this study at 150 feet. The drill hole diameter is determined in relation to the anticipated volume of water to be pumped and the availability of the appropriate sizes of lightweight casing or marketed well pumps. The volume of water required from the well was not specifically designated for this study and is not feasible for two reasons: first, the wide range of water demanded to support various combat units is dependent on their degree of permanency in a location (3 to 30 gallons/man/day). Second, there is the alternative of drilling several or a series of wells, appropriately spaced, to achieve greater pumping volumes when required. It is assumed here that the aquifer has sufficient yield to sustain pumping the water volumes associated with the various types of pumps. The well production pump is then considered an integral part of the well construction system. At a pumping head of 150 feet there are only two types of pumps that warrant investigation because of weight and energy considerations; submersible and the deep well plunger (reciprocating) pumps. The submersible pump consists of a vertical diffuser type centrifugal pump mounted directly over a small diameter electric motor. The pump and motor are operated submersed in the well water and are held in place by a discharge pipe within the casing (9). A broad range of submersible pumps (volume of 3 to 75 g.p.m.) sized to fit a four inch casing are available from a number of manufacturers (10). However, there is only one currently marketed submersible pump designed to fit into a three inch casing (11). This nominal three inch diameter submersible pump has a capacity of 415 gallons per hour at 150 feet of head. However, engineering representatives of the manufacturer indicated that it is within the scope of current technology to increase this pump's volumetric capacity to approximately 800 gallons per hour.

The deep well plunger pump consists of a close-fitting plunger inside a cylinder which is suspended in the well on a string of pipe called the drop pipe (discharge line). The cylinder and drop pipe are suspended inside the casing. The plunger is attached to the lower end of a pump rod which extends to ground level. The pump rod and plunger are made to work up and down in the cylinder by a mechanism called the working head which is set at the top of the well casing. The working head can be either mechanically or manually driven (9). The necessity for the drop pipe can be eliminated by using a packer cylinder which fits more closely to the sides of the casing. Expected yields of such pumps are reported as 180 gallons per hour at 200 feet of head with a two inch I.D. casing, and 385 gallons per hour at 110 feet of head with a three inch I.D. casing (10).

The alternatives associated with different sizes of pumps and the pump's direct relation to the hole diameter will be evaluated in the course of this study. Table 7 summarizes the effects of the well diameter and the availability of commercial pumps on the expected well yield.

Penetration Rates

Anticipated penetration rates in various subsurface formations are controlled by the rotary drilling machine's characteristics, the bit type and size, circulatory mode, and the drilling strength of the rock (8).

The salient machine characteristics are its speed of rotation, the amount of downward load or thrust available to apply to the bit,

TABLE 7

PUMP CAPACITIES RELATIVE

TO CASING SIZE

CHARACTERISTIC	2 INCH	3 INCH	4 INCH
Relative Anticipated Yield* (%)	1.00	1.05	1.08
Representative Current pump capacities (at 150 feet head, open discarge)** A. positive displacement B. Submersible	A. 180 g.p.h. B. not applicable	A. 385 g.p.h. B. 415 g.p.h.	a. not applicable b. 4500 g.p.h.

*Anticipated yield is the expected radial flow from the acquifer. For purposes to reflect the difference in casing size, holding other variables constant, the radial flow equation presented by Todd for an unconfined acquifer was used (12).

**The assumption incident to "appropriate acquifer", is that its yield is sufficient to sustain pumping the water volumes indicated.

and the torque available to rotate the bit. Speeds of rotation common to rotary drilling operations are 45 to 70 r.p.m. in very hard formations (e.g., chert, granite or basalt) and 120 to 250 r.p.m. in soft formations (e.g., clay, shale or gypsum) (8). The downward thrust of the machine is referred to as axial thrust or pulldown and is expressed in units of pounds. This is, singularly, the machine parameter most frequently used to express penetration rates relative to the rock type drilled. Normally, performance of a machine or bit is expressed in terms of the penetration rate in a specific rock type as a function of the weight of axial thrust per inch diameter of bit. The amount of torque applied need only be sufficient to maintain bit rotation and speed. Torque is generally regarded as inherently adequate based on drilling machine manufacturers' experience (8). The significance of a drilling machine's torque rating becomes more important in situations of caving formations and augering operations. The bit serves to actually cut or bore the formations penetrated. It is attached with a threaded sub to the lower end of the drill pipe. There are three distinct types of bits used in rotary drilling: roller cutter rock bits (Figure 2A); drag bits (Figure 2B); and diamond bits (8). Diamond bits are highly specific in use (e.g., geophysical investigations and quarry drilling) and require a high degree of operator expertise in their use. For these reasons, diamond bits will not be considered in this study. Roller cutter bits have cutters, conical in shape, placed on bearings and attached to the bit body. The cutters roll on the bottom of the hole as the drill stem is rotated. The tooth configuration of the cutter is designed for specific formations, soft to very hard. They are not renewable and,

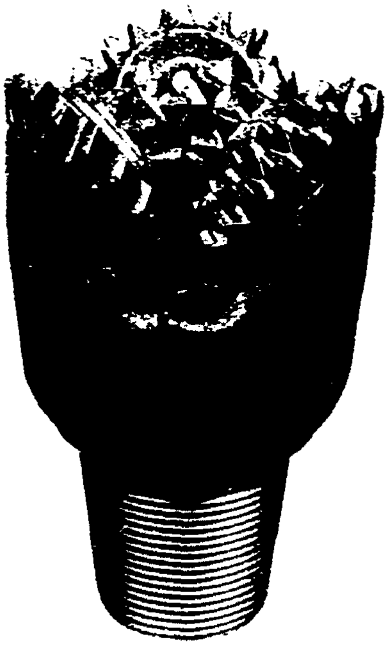


FIGURE 2A: TRI-CONE BIT
(Courtesy Hughes Tool Company)

FIGURE 2B: 3-BLADE DRAG BIT
(Courtesy Hughes Tool Company)

therefore, must be discarded when severely out of gauge or dull. The cutting surfaces are cleaned by the circulatory medium (water or air). Roller cutter bits are available from numerous manufacturers to a size as small as 2-15/16 inches and reputedly can be used in all formations (10). However, drag bits are more economical and achieve higher penetration rates in very soft formations (8). Drag bits, commonly called a fishtail bit, have a shearing or scraping action on rotation as opposed to the roller cutter's chipping and crushing action. They are fabricated of steel or the wings are constructed of a tungsten carbide insert. Both fabrications are amenable to resharpening. Drag bits are commercially available in sizes down to a diameter of 1-7/8 inches (10).

A rock's ability to resist penetration is credited to be a function of drilling strength of the rock (a rock property) and the drilling system (13). Several studies have been made in an attempt to establish a drilling index relating the efficiency of a drill system to penetrate specific rock types. The most notable work in this area has been accomplished by C. G. White (14) and J. Paone (13). White's study attempted to establish drillability indices for 98 different rock types as a function of measurable rock properties (e.g., unaxial compressive strength, Young's modulus, Schmidt impact hammer value, and Shore Scleroscope hardness). Drillability was determined by measuring the time required for the test machine, with a 3/4 inch diameter bit, to penetrate the specimen rock to a depth of three inches. The techniques of regression analysis were used to evaluate the various rocks' drillability as a function of the rock properties. Although no statistically significant correlation was found between rock drillability and any rock properties, a noteworthy correlation between unaxial compressive strength and percussive drillability was shown.

Subsequently, Paone's study took an empirical approach to assessing drilling rates. He established that rock fragmentation was composed of two principle components; machine and rock. He formulated the relationship for rotary drills as shown in equation one:

$$R = \frac{2\pi TN}{SA} \tag{1}$$

R= the penetration rate
T= the torque at the bit
N= the rotational speed (r.p.m.)
S= the drill strength of the rock
A= the cross-sectional area of the drilled hole

Paone also hypothesized that the drilling bit and circulatory flushing medium influenced penetration rates. He attempted to assess these two parameters in an equation to be used to predict penetration rates for percussion drilling equipment, but not for rotary drilling machines.

None of the equations from White's or Paone's study are sufficiently reliable to predict penetration rates for the equipment involved in this study. When the equipment's rated axial thrust is greater than its physical weight, full development of a drill system's axial thrust will be dependent on either anchoring the rig or augmenting the rig's weight when it is at the drilling site (e.g., sand bags). An alternative to developing full axial thrust to drill all formations is to augment the rotary drill system with a down-hole percussion tool. Use of such a tool will necessitate additional air compressor capacity and, intrinsically, including such a compressor with the equipment. The trade-offs associated with weight, complexity of operation and the frequency of coping of hard rock drilling will be appraised in this study.

Economics

The cost effectiveness of various approaches and systems of rotary drilling assumes a lesser role in development of this specific equipment for the Army than it would in a commercial application. The equipment's ability to perform the specified mission with a high degree of reliability and configured for simple operation by inexperienced personnel is of much more significance. However, with the proviso that sufficient data are available (i.e., a sufficient number of drilling rigs are evaluated to be statistically valid), cost effectiveness will be assessed.

Simplicity of Operation

Other than the machine's capability to perform the specified mission, operational simplicity is paramount for the Army. Rapid turnover of young, inexperienced operators briefly characterizes the personnel who will operate this equipment.

There are problems in attempting to quantify operational simplicity. Certainly it cannot be assessed in terms of such parameters as length or weight. There is, however, sufficient distinction between various methods of operating this equipment that a rational discrimination can be made on a relative basis for different equipment configurations. This involves an aperceptive weighting scheme of the mode of operation of various system combinations or alternatives for rotary drilling (15). Reckoning with simplicity of operation will be made in terms of such weighting factors.

Reliability and Maintainability

It would be highly advantageous to quantify different drill systems' reliability. However, both maintainability and reliability measurements are derived from statistical data in terms of mean-time-between-failure and mean-time-to-repair for the equipment (16). Neither parameter could be directly assessed in this study because; drilling equipment operators in the field do not collect such data -- if the machine becomes inoperable, they simply fix it -- and, the possibility of correlating maintainability and the frequency of demand for replacement parts from the drilling equipments' manufacturers proved impractical. Replacement parts are available from too many other sources than the original manufacturer. The Army has an extensive maintenance data reporting and collection system, but data relative to drilling equipment is not an item encompassed in this system. For these reasons, maintainability and reliability will only be qualitatively surveyed through interviews with equipment operators and manufacturers approached during this study.

Weight

The specified weight constraint (see Table 1) for the entire system is 1000 pounds. However, it was quickly obvious that this constraint could not be met. Investigation of the rationale for setting the weight constraint at 1000 pounds revealed that this weight was supposedly the sling load lift (external load) capability of the UH1 helicopter. Obviously the most widely distributed helicopter, normally organic to any type division-sized unit, should be considered the principal resource to move the equipment in remote areas. Therefore, the writer queried Headquarters, Army Aviation Systems Command, for guidance on the performance of the most current model UH1 helicopter. The mission profile for moving the equipment was 80 nautical miles, round trip, loaded only one way. For purposes of establishing the load levels, one crew member and five minutes fuel reserve were specified. The calculated sling load lift capabilities reported and compiled in accordance with references 17 and 18 for the UH1-Model H Helicopter, with an H13 engine, are summarized below:

Conditions	Maximum Sling Load
59 degrees F. (standard day) sealevel	3450 lbs.
95 degrees F., 2000 feet pressure altitude	2250 lbs.

Consequently, the weight constraint was relaxed for this study to seek components for a maximum lift of 2000 pounds per lift, with the number of lifts to be held to a minimum. No technological forecast was available to assess improved lift performance for this helicopter in the future. However, it would seem logical that improved lift capacity to 3000 pounds is within the scope of existing technology.

Alternatives for Well Construction Elements

All of the principal evaluation factors just reported relate in a number of ways to the selection of various equipment elements of the well construction system (see Figure 1). For example, the circulatory system is influenced by the subsurface formation encountered, simplicity of operation and weight. Necessarily, all elements of the system are interrelated to various design concepts that present a framework of alternatives for analysis.

Drill Systems

Drill systems can be categorized in terms of the mode of power transmission to the key components of the drill system. Power transmission to the drill's components may be either mechanical, hydraulic or pneumatic. The latter is currently limited to applications using only downhole powered tools, and, therefore, will not be included in this study. Downhole tools will be considered, but only in the context of their application with hydraulically or mechanically powered drill systems. The other drive systems function to rotate the drill string and bit and provide axial thrust to the bit.

Conventional Rotary and Core Drills

The well construction systems applicable to this study can be characterized by their mode of power transmission; mechanical or hydraulic. Power flow diagrams that reflect the distinction between these power systems are attached as Figures 3A and 3B. Typical of the currently marketed equipment are the mechanically driven rotary drill, the top-head hydraulic rotary drive drill and the core drill (Figures 4,5, and 6 respectively). The principle components of these drills influenced directly by the mode of power transmission include: the method of applying rotation, the manner of speed control, and the mechanism for the application of pulldown force. The mechanically powered system is characterized by chain cases, mechanical transmission assemblies, and drive shafts to control the rotary table, which is mounted stationary to the frame of the rig, and the pulldown mechanism.

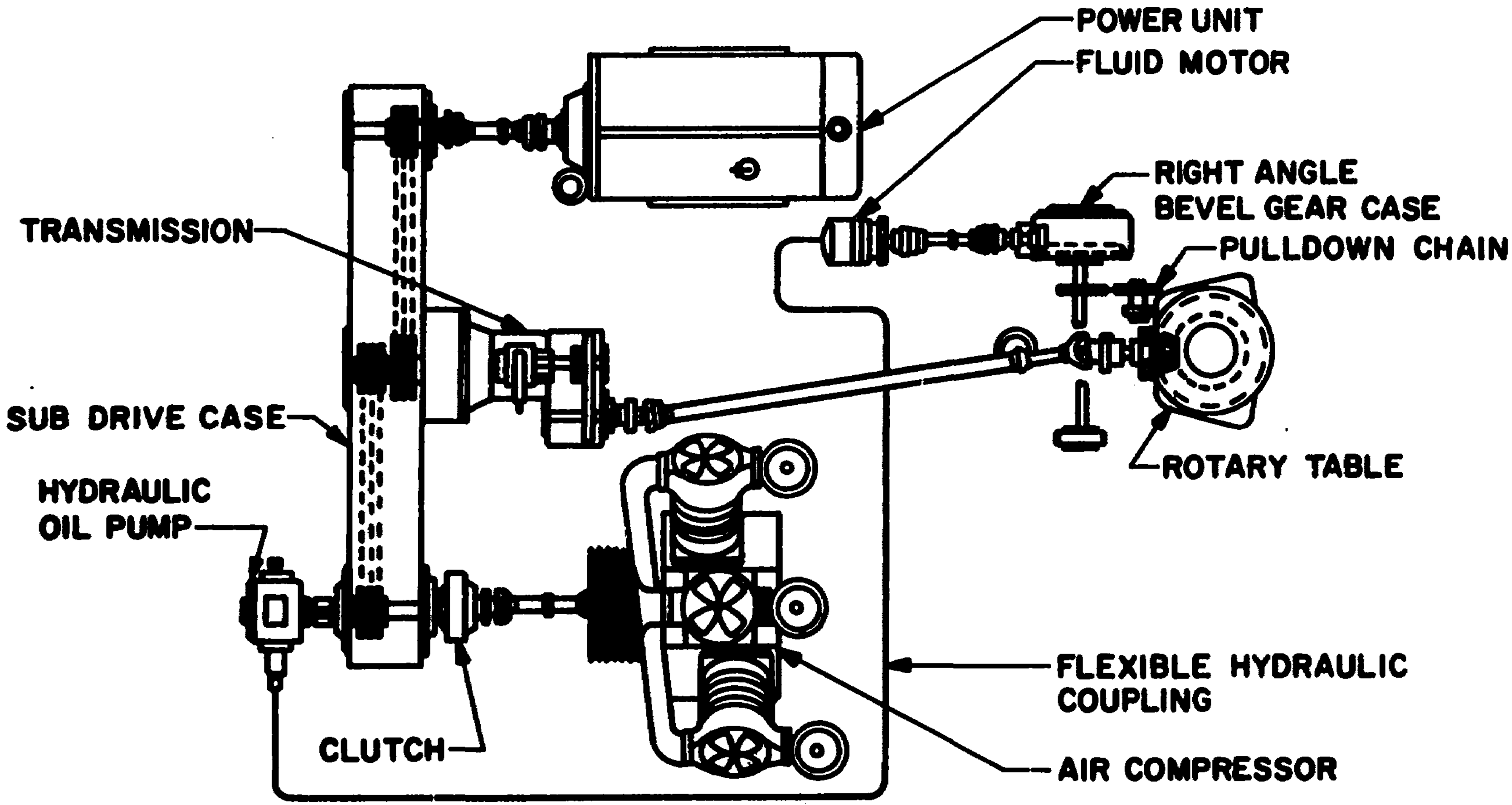


FIGURE 3A: POWER FLOW DIAGRAM
FOR MECHANICAL ROTARY DRIVE

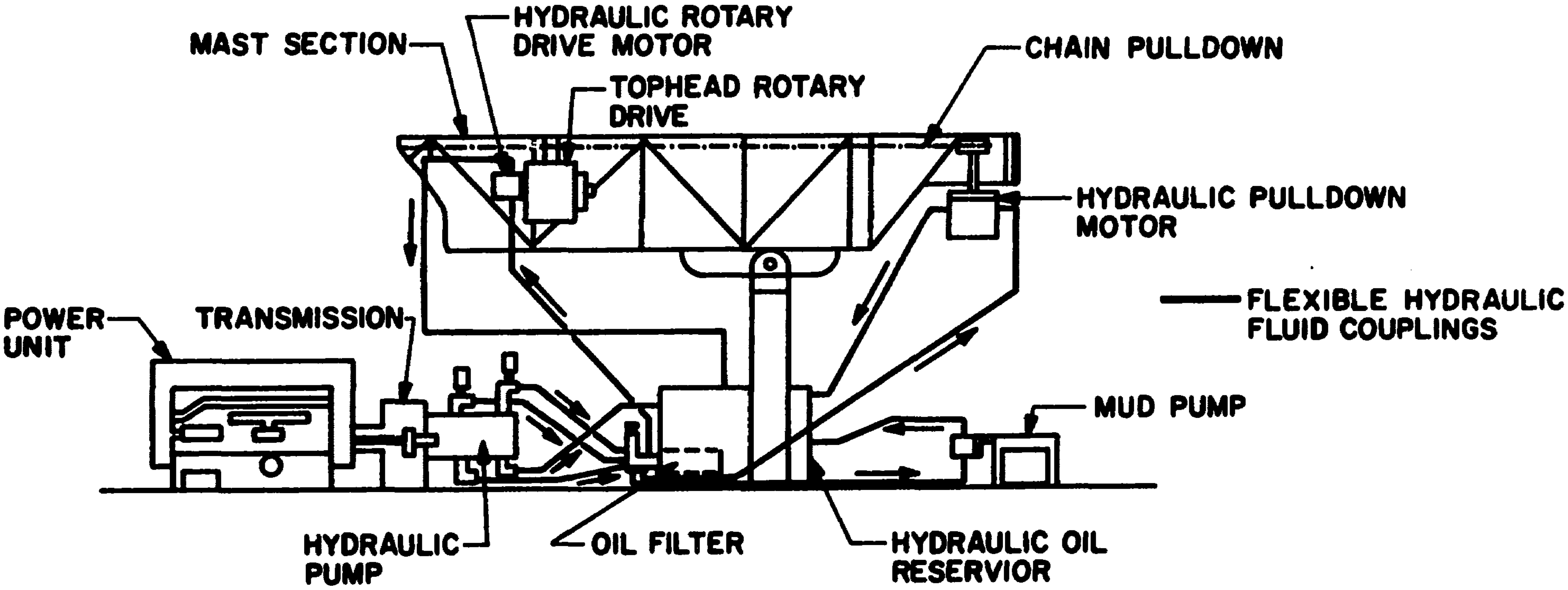


FIGURE 3B: POWER FLOW DIAGRAM FOR
TOPHEAD HYDRAULIC ROTARY DRIVE

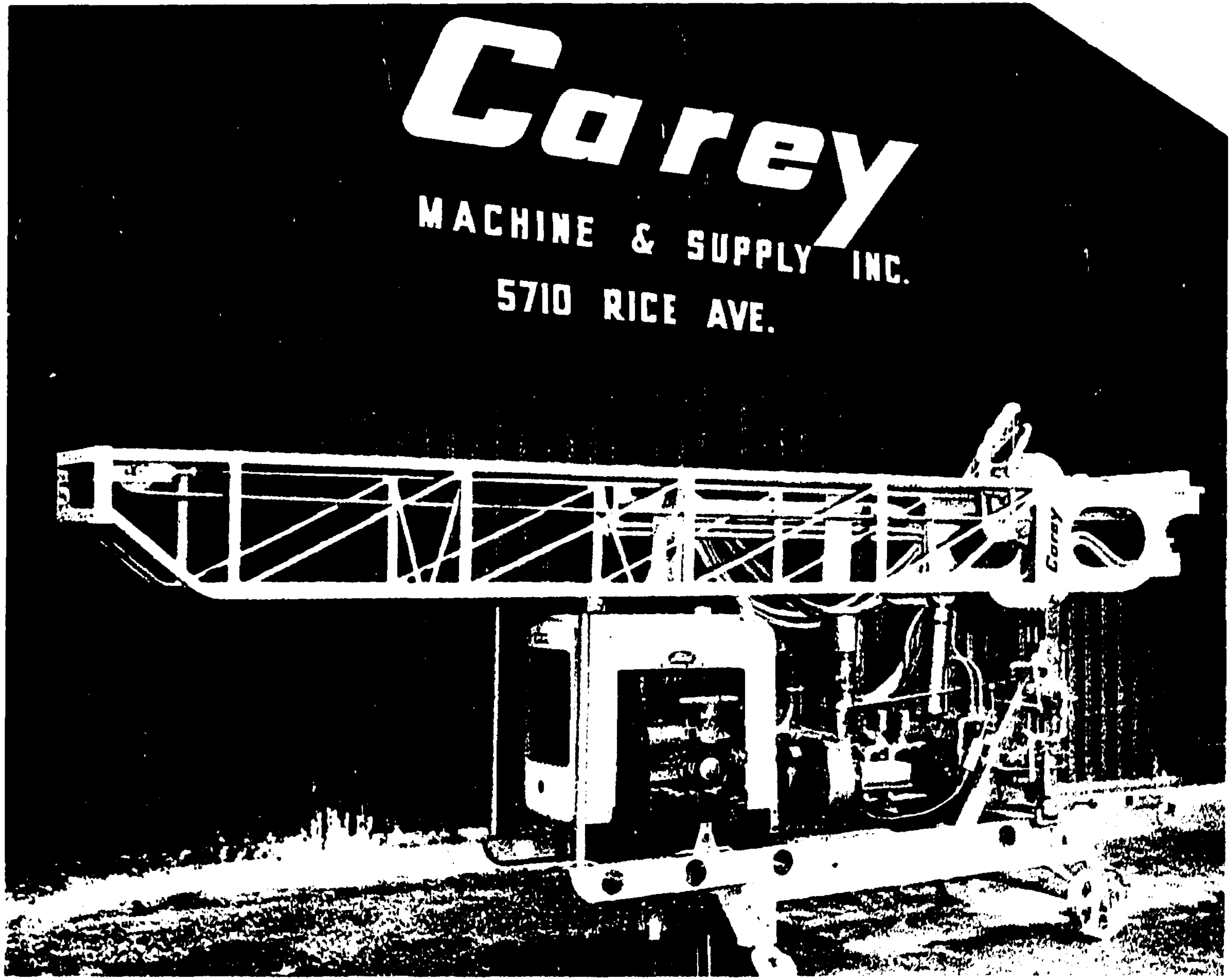


FIGURE 4: TOPHEAD HYDRAULIC POWERED
ROTARY DRILL RIG

(Courtesy Geo Space Corporation)

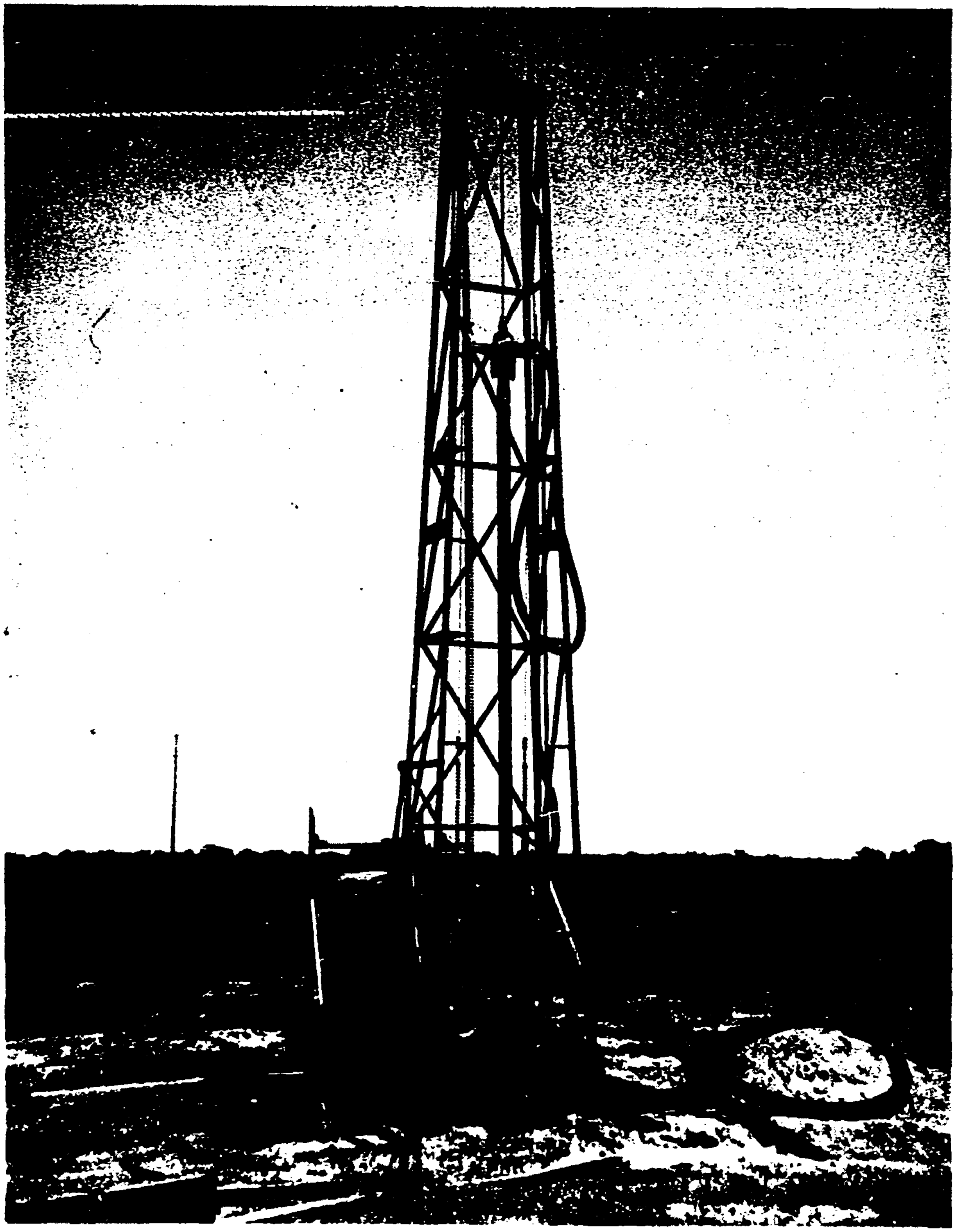


FIGURE 5: MECHANICAL ROTARY TABLE DRIVE DRILL RIG

(Courtesy American Rig Company)

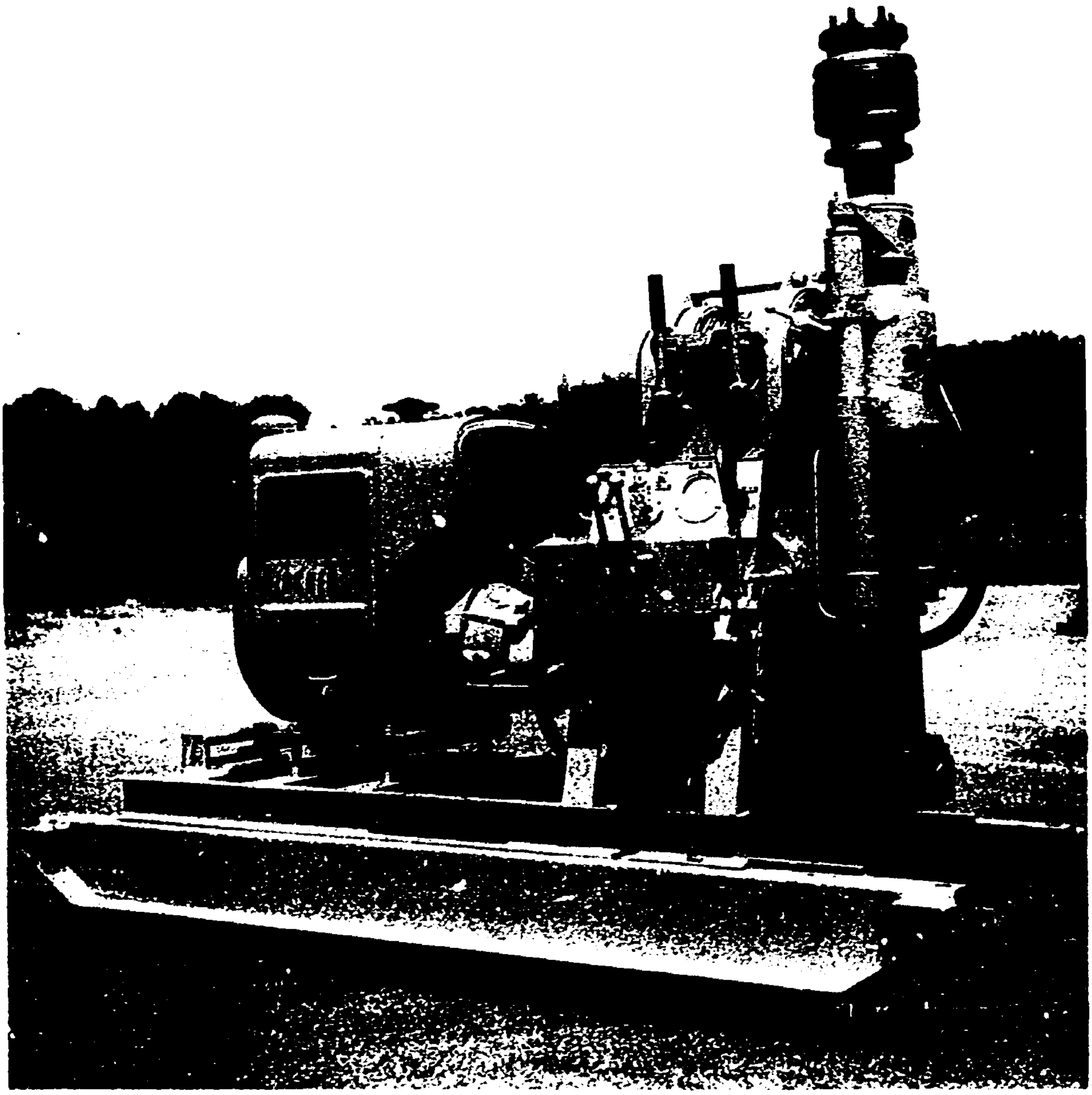


FIGURE 6: ROTARY CORE DRILL

(Courtesy Acker Drill Company)

The rotary table imparts rotation to the kelly, which traverses up and down through the rotary table. The kelly, usually square, octagonal or fluted in shape, serves as the uppermost joint of drill pipe. At the top of the kelly, a water swivel is attached for the purpose of injecting the circulatory medium. After a bit attached to the kelly penetrates to a depth equivalent to the length of the kelly, the kelly and bit are pulled to the surface, the bit removed and attached to drill pipe, which is lowered into the hole, held, coupled with the kelly, and drilling continues. Again, when a depth equal to the kelly's length is reached, the entire drill string is pulled back out of the hole until the kelly can be disconnected, another length of drill pipe added and coupled with the kelly, and drilling resumed. The process is repeated until the desired drilling depth or acquifer is reached. Speed control on the rotary table is a function of the number of speeds associated with transmission controlling the rotary table (usually 3 to 4 forward speeds). Minor speed variations within each gear are provided by the speed range (r.p.m.) of the supporting power unit. Therefore, a three gear transmission principally can provide three different toration speeds with a variation of each by the speed of the power unit. The rotary speed for such a unit is designated by quoting the lowest speed available when in first gear and the maximum speed for the highest gear (e.g., 30-240 r.p.m.). Mechanically powered pulldown is controlled by a clutch mechanism's capability to allow variation in penetration rates, without accompanying clutch slippage, in formations of different hardness. The limitation then on the maximum axial thrust a mechanical system can be expected to deliver is that amount of downward force that induces clutch slippage.

Hydraulically powered drills can be either of the rotary table type or tophead drives. None of the drills incident to the study are hydraulic rotary table and so this facet of rotary drive will not be discussed. Drilling with a tophead hydraulic drive eliminates the use of a kelly. Instead, the tophead moves up and down the mast or derrick, and is powered by a hydraulic motor attached directly to the tophead gear assembly. The hydraulic motor is powered by a variable displacement hydraulic pump via a flexible coupling (hydraulic hose). Since the rotary mechanism traverses the length of the drilling mast, the water swivel for the circulatory medium and drill pipe with bit attached are coupled directly to the tophead drive assembly. Consequently, once the length of the drill pipe has been drilled, the drill pipe is disconnected and held in place, the tophead drive is run to the top of the mast and another section of drill pipe is coupled to the pipe being held in place and the tophead drive. Drilling is then resumed without the limitations imposed by use of a kelly (i.e., pulling back one section of pipe each time additional drill pipe must be added). Speed control is also much more finite with the hydraulic drive, since a broader spectrum of speeds of rotation is provided by a variable flow hydraulic valve rather than a mechanical transmission. Hydraulic valves possess a by-pass mechanism that allows infinite variation in rotation speeds over the drill's rated speed range. Pulldown, controlled hydraulically, permits the operator to vary the weight applied to the bit over the entire spectrum of the machine's rated axial thrust capacity by means of a variable flow hydraulic valve. The hydraulic pulldown control is also equipped with a by-pass mechanism that deters equipment damage that can result if an operator imposes excessive pulldown force on the drill string. The various techniques of providing hydraulic pulldown are: hydraulic cylinders, hydraulically powered chain or cable, and hydraulically powered rack and pinion.

Core drilling systems are typically a mix of hydraulically and mechanically driven systems. The pulldown mechanisms are usually hydraulic cylinders. The rotary mode is usually a hollow spindle to which rotation is imparted by a mechanical linkage whose speed is controlled by a mechanical transmission. Drill pipe is inserted into the spindle and held in place with a chuck. The length of stroke for the spindle is two to three feet, i.e., two to three feet of pipe are drilled, the spindle disconnected and run back up, rechucked and drilling continues for another stroke until the length of pipe is drilled, then another length of drill pipe is added and drilling resumed. Speed control is mechanical, which was previously described. However, core drills are designed to operate at much higher speeds than conventional rotary rigs. The necessity of resetting the chuck manually after drilling for the length of one stroke has been mitigated by installation of automatic chuck break-out (hydraulic) on some core drills. This is provided in deference to manually loosing and resetting the chuck after each stroke.

As pointed out under penetration rates, torque is not generally considered a controlling parameter in conventional rotary drilling because manufacturers generally provide sufficient horsepower to maintain drill stem rotation at the machine's rated capacity (8).

The flexibility provided by the wide spectrum of speeds and axial thrust associated with the hydraulic system can significantly facilitate operation of the drill system. There are some distinguishing maintenance factors of the rotary drives that should be given attention. Failure of mechanically driven drills is frequently associated with gear or shear pin breakage. Replacement of such components demands some mechanical acuity by the operator to dismantle the assembly and replace the part. Mechanical systems are normally too heavy and bulky to permit the replacement of a complete component. However, malfunctions in hydraulic systems are most often the hydraulic pump or motor, either of which are easily replaced by like, lightweight components. The replacement of a hydraulic motor and pump generally only requires bleeding the hydraulic fluid from the flexible coupling and removing the mounted pump or motor and attaching the replacement. Repair of hydraulically driven drills is therefore much quicker and demands significantly less operator skill than does the mechanically driven equipment. Table 8 summarizes the characteristics associated with hydraulic and mechanical drill systems.

Downhole Percussion Tool

The downhole percussion tool (commonly referred to as a downhole hammer or hammer drill) is often used to augment a rotary drill to improve its rate of penetration in hard rock and minimize the axial thrust required to penetrate the rock. Downhole is just what the name implies; the percussion tool is designed to be used at the bottom of the hole, just above the bit. The downhole hammer consists of a steel cylinder in which a reciprocating piston, normally driven by compressed

TABLE 8

COMPARISON OF DRILL

SYSTEM TYPES

DRILLING OPERATION	TOPHEAD HYDRAULIC DRIVE	MECHANICAL ROTARY TABLE -KELLY DRIVE-
Drill Pipe Handling	No pull back of drill pipe from drilled hole required	One-length of drill pipe pulled back from hole
Control of Pulldown	Variable from zero to rated capacity	Fixed as a function of transmission range
Control of Speed	Variable from zero to rated capacity	Fixed as a function of transmission range
Maintainability	Replace entire hydraulic component	Replace component gears
Overload Failure Mechanism	By-pass valve activated	Shear pin failure
Power Requirements	Greater than mechancial system	Less than hydraulic system

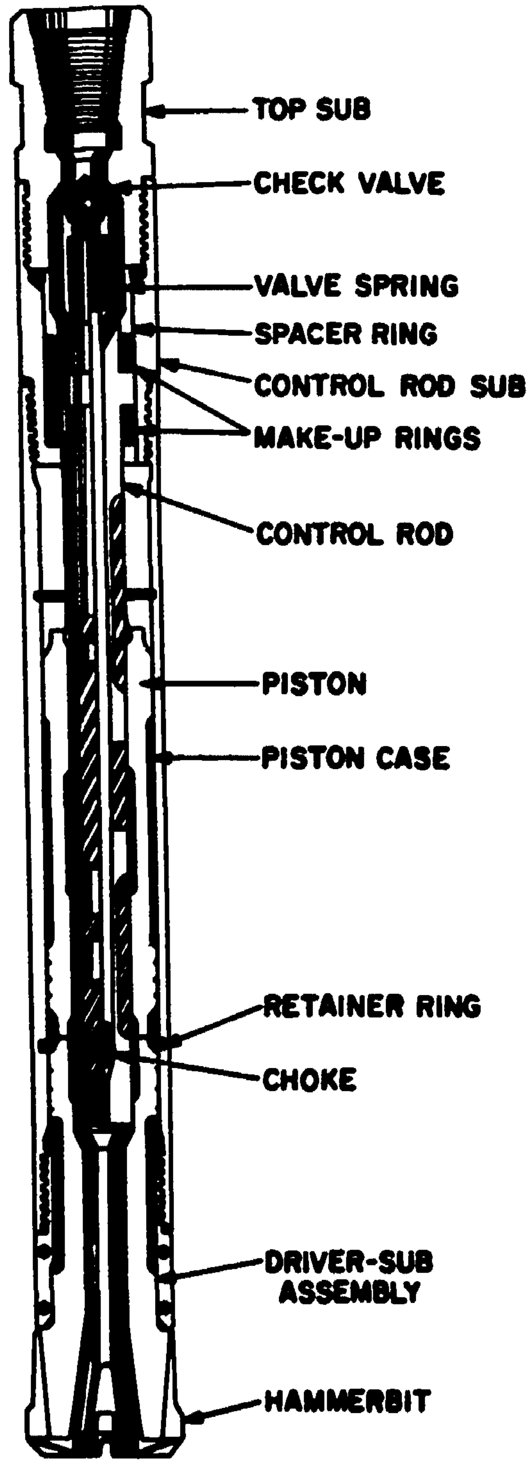


FIGURE 7: CROSS-SECTION OF DOWNHOLE PERCUSSION TOOL

(Courtesy Mission Manufacturing Company) air, continuously hammers the bit, which is essentially a chisel or star drill (Figure 7). Compressed air requirements are significantly greater for the downhole hammer (100 to 250 c.f.m., at 100 to 125 p.s.i. for a four inch hole) as opposed to conventional air rotary drilling (210 c.f.m. at 40 p.s.i. for a five inch hole) (8,10,19). The operating parameters of the rotary drill are drastically altered in using the downhole hammer. The speed of rotation is maintained between 10 and 25 r.p.m. and the axial thrust (pulldown) in the range of 500 to 1500 lbs. (19). Since employment of the downhole drilling capability greatly affects the size of the circulatory system, the study and data collected on the downhole hammer will be included with the circulatory and associated supporting material systems for evaluation. Research will be directed toward evaluating the alternatives associated with improved penetration rates, minimized pulldown requirements, and weight when the downhole tool is used to augment a rotary drill system.

Circulatory Systems

There are two principal media for removing the cuttings from the hole; air and water. There are, however, a number of variations of both types. The cogent characteristics and purpose of these variations are as follows:

Air

Air supplied by an air compressor is routed through a flexible air line to the top of the kelly or tophead drive, forced through the drill pipe and out the holes at the bottom of the bit. The air cools the bit and forces the cuttings to move up the annular space between the drill pipe and wall of the hole to the surface of the ground. The basic relationship to compute free air volumes required for air curculation for different hole and drill pipe sizes is given by equation two (8):

$$Q = \frac{V}{183.33} (D^2 - d^2) \qquad (2)$$

where: V = ascending velocity in the annulus, feet/minute (fpm)
D = hole diameter, inches
d = drill pipe outside diameter, inches
Q = cubic feet of free air per minute (cfm)

In air drilling, the minimum annulus velocity is taken as 3000 feet per minute (19). Variations in air drilling, encompassing the use of additives, are employed to: aid in dust suppression; improve penetration rates; overcome the lack of sufficient annular velocity (therefore, air volume) to support drilling larger diameter holes. These variations are air-foam, air-foam-gel, air with downhole hammer and air-foam with downhole hammer. Foam and foam-gel injection with air serve to reduce the annular velocity requirements for air drilling to 1000 feet per minute and 200 feet per minute, respectively (10,20). Air or air-foam injection, augmented with the downhole hammer, increases penetration rates at a compromise of additional compressor size and complexity of operation. The basic additives associated with these various modes of circulation, including water, and their characteristics will be delineated in Chapter III. Air circulation is tentatively attractive in that it is simple for the operator to use (no additives), and is not routinely dependent on copious amounts of water to support its function. Further, in Arctic envirions, it represents the only plausible means of circulation without resorting to excessively heavy heat exchange equipment to prevent drilling fluids from freezing. The major limitation in using air is the problem associated with drilling in unstable or caving formations. In such conditions, when the air pressure is shut down to add pipe to the drill string or to remove the drill pipe from the hole to place casing, the hole will cave in, causing the pipe to become stuck. There are alternatives to circumvent this limitation: change to drilling with drilling mud circulation to stabilize the walls of the hole; use of expendable drill pipe so that the drill pipe becomes the casing on completion of the hole; and drive the casing with a drop or pneumatic hammer and then drill out the material inside the casing. The feasibility of these alternatives will be evaluated in the course of the study.

Water

Water or drilling mud circulation is essentially the same as air drilling except that the air compressor is replaced by a mud pump. The pump must have sufficient capacity to maintain an annular velocity of 100 feet per minute and sufficient pressure head to overcome pressure losses in surface connections and friction losses in the drill pipe, bit and the annulus (19). Equation three is used to determine water volume required for water circulation (19).

$$\text{(3)} \qquad \text{Volume} = \frac{(D^2 - d^2)\ V}{25}$$

where: Volume = pump volume required (gal./min.)
D = hole diameter, inches
d = drill pipe O.D., inches
V = annular velocity (ft./min.) normally taken as 100 ft./min.

For the size of hole(s) and drill pipe(s) incident to this study, a pump with a rated capacity of 34 to 114 gallons per minute at 100 to 150 pounds per square inch pressure will be adequate. Additives associated with water are drill mud (Bentonite clay) or synthetic polymers which serve principally to increase the drilling fluid's viscosity and density. These additives improve the efficiency of removing larger or denser cuttings and provide hole stability to the walls of the hole in loose or caving formations. The drilling fluid is prepared in a slurry form in a pit at the surface of the ground and recirculated through the drill pipe back to the top of the hole. Although the use of additives greatly facilitates coping with drilling problems, the complexity in using such additives will demand extensive operator training. Mud technology is in itself an art that demands extensive training and experience on the part of the equipment operator. Characteristics of various polymers and drill mud will be outlined in Chapter III. The significant limitations in using water or drilling fluids are the complexity of dealing with the additives and, more importantly, the necessity for large volumes of water to support the operation. There is no specific set rule as to the amount of water required; water requirements will vary with the type of formation drilled. Consolidated formations generally require 3 to 4 gallons per foot of hole drilled, whereas, if fissures or extremely porous formations are encountered, an entire water supply of 500 to 1000 gallons can be lost in a matter of minutes (21). For purposes of this study, the volume of water required to support drilling fluid circulation will be taken as 600 gallons. In the event that a water source is not available in proximity of the drilling site, the water must be airlifted in with the equipment. At a total weight of approximately 5000 pounds, this is an unpleasant prospect. Water quality can also affect the performance of the drilling fluid. Water with chloride concentrations on the order of 10,000 milligrams per liter or acidic water (PH$\leq$8) impairs the properties of drilling mud (22). An organic polymer additive is reported to be much less susceptible to saline water (23).

Power Units

Basically, power units will be researched from the standpoint of providing maximum performance at the least weight. Only gas-driven power units will be considered since the fuel to support it is the most widely distributed in the theater of combat operation. Both air and water cooled power units will be included in the evaluation. Gas turbine engines have not been included in the study since there is no experience in the field with such engines in the applications of lightweight drilling equipment.

Supporting Materials

Construction of a well involves numerous auxiliary tools and materials to accomplish the drilling program, develop the well, and, finally, provide a means to lift the water from the well to the surface. Again, there are options that influence the size and weight of the various supporting materials that accompany the drill system, circulatory system and power unit. For example, the size of well pump to be employed and the size and type of bits, casing and drill pipe all have impact. And, there are many sources for procurement of such materials. Consequently, the study will be directed to selection of those items which can be regarded as the optimum from the weight and performance aspect for a particular alternative.

Alternatives to Study

The interrelation of well construction elements and principal evaluation factors has presented numerous alternatives that must be closely analyzed in the course of this study. Figure 8 reflects the various alternatives available to be considered. Point two in Figure 8 represents the initial decision in sizing the entire system, i.e., hole and drill pipe size. The five alternatives shown will be appraised in light of the trade-offs associated with total weight of the system, volume of water supply the well is expected to produce, compressor size, and availability of the appropriate size water supply pumps. Point three denotes the available choices of the drill systems. The advantages and disadvantages of this decision point are a function of weight, mechanical characteristics, and simplicity of operation. Six options in selection of circulatory systems are available at decision point four. Each will be weighed in terms of: subsurface formation drilling constraints (e.g., unstable formations, penetration rates, lost circulation and hydrostatic head); total system weight; simplicity of operation.

Further, there are various design concepts in configuring the rotary drill system for the U. S. Army's objectives that can be viewed in terms of the essential elements outlined in Figure 1. Therefore, the options available with each alternative will be delineated following that outline of the elements.

Drill System

The principle variations encountered with drill systems are the mode of power transmission, mode of rotation, means of hoisting and

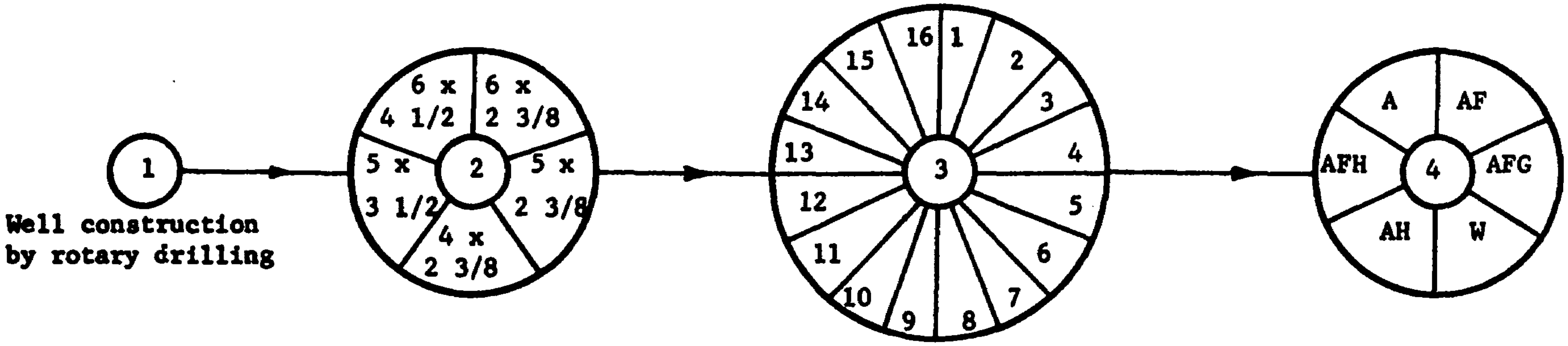


FIGURE 8

DECISION OPTIONS FOR WELL

CONSTRUCTION ELEMENTS

LEGEND: Node 1. Complete Well Construction System.
Node 2. Options for Hole Size (in.) X Drill Pipe Size (in.).
Node 3. Alternative Drill Systems (see Table 9 for drill designations).
Node 4. Circulatory System Alternatives: A is Air; AF is Air-Faom; AFG is Air-Foam-Gel; W is Water/Mud; AH is Air with Downhole Hammer Capability; AFH is Air-Foam with Downhole Hammer Capability.

applying axial thrust to the bit, the range and selection of rotary speeds, the torque developed by the drill, and the mode of raising and lowering the mast and leveling the equipment.

The selection of power transmission will significantly influence the selection of other elements of the drill. For example, mode of rotation can be: mechanical rotary table; hydraulic rotary table, or tophead drive; mechanical or hydraulic spindle.

Hoisting and axial thrust can be selected from hydraulically operated cylinders, rack and pinon, or chain/cable; or mechanical chain/cable. Speed can be controlled through a mechanical transmission or hydraulically with a variable flow valve. Torque is an inherent design characteristic of the drill's speed and axial thrust capability.

Raising and lowering the mast, as with equipment leveling, can be accomplished with mechanical screw jacks, hydraulic cylinders or simply manually.

Circulatory Systems

The circulatory alternatives are air, air-foam, air-foam-gel, water or mud, air or air-foam augmented with the downhole hammer, each of which must be sized to drill a specified hole diameter with a specific drill pipe.

Power Units

Power units can be categorized as reciprocating piston (gasoline or diesel) and gasoline turbines. They may also be air or water cooled. Gas turbines and diesel fueled engines were not included within the data alternatives reported, but they may be easily integrated into the model formulation.

Support Materials

As with circulatory materials, the supporting materials (drill pipe, bits, tools, casing, well screens and pumps) vary with hole diameter. They are also significantly influenced by the material required to support the circulatory system (e.g., water), and, therefore, the availability of water to support the operation.

Herein lie the alternatives associated with drilling caving formations, driving the casing when using air circulation, or using water circulation, with the addition of drilling mud, to stabilize the hole.

CHAPTER III

DATA PRESENTATION

General

A comprehensive survey was made of the currently marketed rotary drill systems. The initial solicitation for data was made by letter and telephone with manufacturers' representatives. This action was then followed up with personal interviews to obtain more definitive data on the equipment. The survey provided for the possibility of overlooking applicable equipment by: advising manufacturers to include their equipment if it could be modified, without incurring changes in their normal production activity, into modular configurations which did not exceed 2000 pounds per module; relaxing the hole size and depth constraints to include lighter weight equipment. The follow up interviews were conducted using the data sheet included as Appendix 2. The data was substantiated with the manufacturers' technical bulletins, where possible. Since the manufacturers were asked to achieve any weight savings possible that would not inhibit production or incur significant cost deviations, the accuracy of the data should be regarded as approximate. Further, the equipment was principally limited to American firms because of possible procurement difficulties from other countries in times of national emergencies.

Unfortunately, data were not available either from manufacturers or operators of the equipment to quantify the constraints of maintainability and reliability, nor are the physical dimensions of the equipment included since the equipment is being configured for an external load for a helicopter which is unrestricted by physical dimensions.

As previously mentioned, the data collection was amenable to presentation in terms of the four principle elements of the system; the drill system, curculatory system, power unit and support materials. This division proved equally necessary in terms of maintaining weights at 2000 pounds or less per group of elements. However, there were circumstances where combinations of various elements could be achieved in less than 2000 pounds. These combinations will be analyzed later.

Data collection was not limited solely to equipment manufacturers. Numerous water well drillers, hydrologists, geologists and groundwater consultants were contacted. Their experiences provided valuable information on literature and drilling methodology and techniques. Site visits to field drilling operations were also a facet of these undertakings. These findings will be discussed in Chapter V. A list of the manufacturers and other personnel contacted is included as Appendix 3.

Drill Systems

Table 9 lists all the salient characteristics of the various drill systems. The reported weight may not be the same as those in manufacturers' technical bulletins because the drill mast and skid mounting could be lightened with structural aluminum. The drill systems' costs and weights do not include a supporting power unit. The reported total weights are dry weight of the rotary mechanism, pulldown and hoist, mast and skid mounting. Drill frames one through eight are hydraulic tophead drive; nine through 13 are core drills; and the remaining three are mechanical drives. Downhole percussion tools have been segregated and are reported in Table 10. Apparently, the Mission Manufacturing

TABLE 9

DRILL SYSTEM CHARACTERISTICS

CHARACTERISTIC	(1)BIG INDIAN 300	(2)CYCLONE	(3)WABCO FA100	(4)MOBILE B30S
Application Rotary (R) Auger (A) Coring (C)	R	RA	RAC	RAC
Rating Hole Size & Depth	R-4 1/2" to 300'	R-5" to 300'	A-6" to 100' C-2" to 250'	A-4 1/2" to 100' A-6" to 50' C-2" to 175'
Maximum Hole Volume (c.f.)	33	42	(est.) 29.5	(est.) 29.5
Type Rotation	Tophead Rotary	Tophead Rotary	Tophead Rotary	Tophead Rotary
Speed Range (r.p.m.)	0-300	0-125	39-300	58-455
Number of Speeds	Infinite	Infinite	Infinite	Infinite
Torque (ft. lbs.)	1185	850	2800	2100
Power (b.h.p.) Required for Drill System	35	25	35	36
Type Pulldown	Hydraulic Cylinder	Hydraulic Rack & Pinon	Hydraulic Cylinder	Hydraulic Cylinder

TABLE 9

DRILL SYSTEM CHARACTERISTICS (cont'd)

CHARACTERISTIC	(1)BIG INDIAN 300	(2)CYCLONE	(3)WABCO FA100	(4)MOBILE B30S
Pulldown Force (lbs.)	9620	6000	7000	6362
Mast Height/Mast Capacity (lbs.)	14'/Not specified (NS)	12'/NS	8.75'/NS	14'/3000
Mast Raising	manual	manual	hydraulic	fixed with hand raised extension
Leveling	3-Hydraulic Cylinders	manual*	none	Pin Rods
Hoisting Capability (lbs.)	9620	6000	8000	2000 Cathead
Rotary Size/Gear Ratio	NA/NS	NA/2.2:1	NA/1:1	NA/3.77:1
Hydraulic Reservoir Capacity (gals.)	12 w/cooler	5 w/cooler	30	40
Length of Drilling Stroke	10'	10'	6'	5'
Weight (lbs.) less power with skid mount	973	750	1900	2870
Cost	$16,217	$6500	$6600	$5220

TABLE 9

DRILL SYSTEM CHARACTERISTICS (cont'd)

CHARACTERISTIC	(5) SCHRAMM	(6) CAREY HLT4	(7) ARCO Tophead S	(8) CAREY HHP
Application	R	RAC	RC	RA
Rating Hole Size & Depth	R-4 3/4" to 300'	R-4 1/2" to 300' A-3" to 50' C-2" to 200'	R-4" to 300'	R-3 1/3" to 150' A-3" to 50'
Maximum Hole Volume (c.f.)	36.7	33	26.1	9.9
Type Rotation	Tophead Rotary	Tophead Rotary	Tophead Rotary	Tophead Rotary
Speed Range (r.p.m.)	37-120	0-240	0-175	0-127
Number of Speeds	Infinite	Infinite	Infinite	Infinite
Torque (ft. lb.)	1250	325	240	238
Power (b.h.p.) Required for Drill System	14	35	35	14
Type Pulldown	Hydraulic Cylinder	Hydraulic Chain	Hydraulic Chain	Hydraulic Cable
Pulldown Force (lbs.)	10,000	1800	5000	1800

TABLE 9

DRILL SYSTEM CHARACTERISTICS (cont'd)

CHARACTERISTIC	(5) SCHRAMM	(6) CAREY HLT4	(7) ARCO Tophead S	(8) CAREY HHP
Mast Height/Mast Capacity (lbs.)	12'/NS	16'/NS	15'/5000	9.75'/NS
Mast Raising	Hydraulic Cylinder	Hydraulic Cylinder	Hydraulic Cylinder	Hand
Leveling	Hydraulic	Manual	Manual	Manual
Hoisting Capability (lbs.)	10,000	2300	4000 Cathead	Not specified
Rotary Size/Gear Ratio	NA/6.75;1	NA/5.67:1	NA/3:1	NA/NS
Hydraulic Reservoir Capacity (gals.)	25	22	35	5
Length of Drilling Stroke	10'	10'	10'	5'
Weight (lbs.) less power with skid mount	2572	1477	1780	449
Cost	$9200	$6495	$5800	$4848

TABLE 9

DRILL SYSTEM CHARACTERISTICS (cont'd)

CHARACTERISTIC	(9) SPRAQUE AND HENWOOD 40C	(10) ACKER HILLBILLY	(11) CME 55	(12) CME 45C
Application	AC	AC	RAC	RAC
Rating Hole Size & Depth	C-2" to 1000' C-3" to 650'	C-2" to 1600' C-3" to 1000'	A-4" to 200'	A-4" to 100'
Maximum Hole Volume (c.f.)	32	49	(est.) 29.5	(est.) 29.5
Type Rotation	Hydraulic Rotary Spindle	Hydraulic Rotary Spindle	Mechanical Tophead w/fixed Kelly	Mechanical Tophead w/fixed Kelly
Speed Range (r.p.m.)	235-1500	77-900	100-650	75-475
Number of Speeds	4	8	4	4
Torque (ft. Lb.)	500	1800	4300	3000
Power (b.h.p.) Required for Drill System	20	38	40	30
Type Pulldown	Hydraulic Double Cylinders (2")	Hydraulic Double Cylinders (3 1/2")	Hydraulic Double Cylinders	Hydraulic Double Cylinders
Pulldown Force (lbs.)	3900	4700	12,000	10,000

TABLE 9

DRILL SYSTEM CHARACTERISTICS (cont'd)

CHARACTERISTIC	(9) SPRAQUE AND HENWOOD 40C	(10) ACKER HILLBILLY	(11) CME 55	(12) CME 45C
Mast Height/Mast Capacity (lbs.)	10'/300	14'/NS	18'/5000	12'/NS
Mast Raising	Manual	Manual	Hydraulic	Hydraulic
Leveling	Manual	Manual	Hydraulic	Hydraulic
Hoisting Capability (lbs.)	3900	7100	5000 Cathead	5000 Cathead
Rotary Size/Gear Ratio	Maximum Spindle Size 3 7/8"/NA	Maximum Spindle Size 3 1/2"/NS	NA/NS	NA/NS
Hydraulic Reservoir Capacity (gals.)	NS	NS	NS	NS
Length of Drilling Stroke	2'	2'	5-8'	5-8'
Weight (lbs.) less power with mast and skid mount	2275	2900	4380	2270
Cost	$7000	$7052	$7865	$5719

TABLE 9

DRILL SYSTEM CHARACTERISTICS (cont'd)

CHARACTERISTIC	(13)LONGYEAR DESIGN	(14)MAYHEW 200	(15)ARCO 'S' Model	(16)ARCO 100AR-C
Application	RC	R	RC	R
Rating Hole Size & Depth	C-2 1/4" to 1000'	R-4 1/2" to 350'	R-4" to 300'	R-3 1/2" to 100'
Maximum Hole Volume (c.f.)	(est.) 29.5	37.5	26.2	6.7
Type Rotation	Tophead Rotary Spindle	Mechanical Kelly Drive	Mechanical Kelly Drive	Mechanical Kelly Drive
Speed Range (r.p.m.)	0-1800	85 & 175	69-200	125
Number of Speeds	Infinite	2	3	1
Torque (ft. lb)	3700	900	1100	NS
Power (b.h.p.) Required for Drill System	34	20	16	7
Type Pulldown	2-Hydraulic Cylinders	Mechanical Chain (1")	Mechanical Chain	Mechanical Chain (5/8")
Pulldown Force (lbs.)	10,600	4000	4000	1000

TABLE 9

DRILL SYSTEM CHARACTERISTICS (cont'd)

CHARACTERISTIC	(13)LONGYEAR DESIGN	(14)MAYHEW 200	(15)ARCO 'S' Model	(16)ARCO 100 AR-C
Mast Height/Mast Capacity (lbs.)	18'/NS	17'/20,000	Alum. 15'/500	12'/NS
Mast Raising	Manual	Hydraulic	Manual	Manual
Leveling	Manual	Screw Rods	Manual	Manual
Hoisting Capability (lbs.)	5400 Hoist	4000	5000	750 Cathead
Rotary Size/Gear Ratio	NA/NS	5 1/4" Rotary Table/NS	5 3/8" Rotary Table/NS	3" Rotary Table/9:1
Hydraulic Reservoir Capacity (gals.)	12 gal. w/ oil cooler	NA	NA	NA
Length of Drilling Stroke	6'	10'	10'	5'
Weight (lbs.) less Power with mast and skid	945	1150	1100	350
Cost	$17,000	$6600	$5300	$2475

NOT SPECIFIED (NS) -Item not specified by manufacturer
NOT APPLICABLE (NA)-Item not included with drill
*MANUAL LEVELING -Operator required to use any available means to level equipment

TABLE 10

DOWNHOLE PERCUSSION TOOL DATA

MANUFACTURER AND MODEL	OPERATING CHARACTERISTICS	TOTAL WEIGHT WITH BIT (lbs.)	TOTAL COST
Ingersoll-Rand DHD-14	4 inch bit 185 c.f.m. of air at 125 p.s.i.	235	$1600
Ingersoll-Rand DHD-15	5 inch bit 240 c.f.m. of air at 125 p.s.i.	425	3125
Ingersoll-Rand DHD-16	6 inch bit 295 c.f.m. of air at 125 p.s.i.	510	3695
Mission Mfr. Co. B32-10	4 inch bit 100 c.f.m. of air at 100 p.s.i.	89	2403
Mission Mfr. Co. D42-10	5 inch bit 190 c.f.m. of air at 100 p.s.i.	159	3010
Mission Mfr. Co. C51-10	6 inch bit 320 c.f.m. of air at 100 p.s.i.	239	3300

Company's percussion tool possesses the more attractive weight and requires less supporting compressed air volumes.

All drill systems are currently marketed equipment, except those designated as designs (i.e., Longyear and Big Indian Drilling Company designs). The prototypes for these designs have not yet been fabricated, but the complete engineering designs have been accomplished.

Circulatory Systems

As previously pointed out, the selection of a circulatory system is dependent on a number of factors. The effects of additives, use of the downhole percussion tool, hole size and drill pipe size have all been discussed. To size the circulatory system it will be necessary to fix these variables. The necessary operating characteristics for various circulatory systems are listed in Table 11. These volumetric and pressure requirements can then be compared with a tabulation of currently marketed circulatory equipment in Table 12. The proper compressor for equipment that includes a downhole hammer is chosen as a function of providing sufficient air volumes to both support the tool and provide sufficient annular velocity. Certainly, there are a much greater number of manufacturers of circulatory equipment. However, those reported are either generally representative for the industry or they possessed unusual lightweight characteristics.

Power Units

Data on power units were limited to two types and two manufacturers. This seemed to be the most reasonable approach since: there is only one principle manufacturer of air cooled engines in the size required; and,

TABLE 11

VOLUME REQUIREMENTS FOR VARIOUS

MODES OF CIRCULATION

CIRCULATORY MODE	HOLE AND DRILL PIPE (d.p.) SIZES				
	6" hole 4 1/2" d.p.	6" hole 2 3/8" d.p.	5" hole 3 1/2" d.p.	5" hole 2 3/8" d.p.	4" hole 2 3/8" d.p.
Water (g.p.m.) 100 p.s.i. V=100 f.p.m.(RE eqn.2)	65	124	53	79	42
Air (c.f.m.) 30-40 p.s.i. V=3000 f.p.m.(RE eqn.3)	260	495	210	315	168
Air-Foam (c.f.m.) V=1000 p.s.i.	86	165	70	105	56
Air-Foam-Gel (c.f.m.) V=250 f.p.m.	22	41	15	26	14
Air for downhole hammer operation (c.f.m.) 100-125 p.s.i.	320[a]	320[a]	190[b]	190[b]	100[c]

V = Annular Velocity
a = Minimum Air Volume for Mission Mfr. Co. C51-10 Hammer Drill
b = Minimum Air Volume for Mission Mfr. Co. D42-10 Hammer Drill
c = Minimum Air Volume for Mission Mfr. Co. B32-10 Hammer Drill

TABLE 12

CHARACTERISTICS OF SELECTED MARKETED

CIRCULATORY EQUIPMENT

NO.	(a) TYPE CIRCULATION	(b) MANUFACTURER AND MODEL	(c) OPERATING CHARACTERISTICS	(d) WEIGHT (lbs.)	(e) COST ($)
1.	Water	Mission Mfr. Co. R-11, 2" x 3" Centrifugal	200 g.p.m. 138 p.s.i. @ 34 h.p.	190	330.00
2.	Water	ARCO[a] 2½" x 2" Centrifugal	300 g.p.m. 75 p.s.i. @ 9 h.p.	62	820.00
3.	Water	John Bean Co. Positive Tri-Plex Model 435-11	35 g.p.m. 400 p.s.i. @ 22 h.p.	365	1013.20
4.	Air*	WABCO[b] Le Roi 60S2	265 c.f.m. 125 p.s.i. @ 65 h.p.	2770	7825.00
5a.	Air	WABCO Le Roi 50S1	295 c.f.m. 50 p.s.i. @ 51 h.p.	1070	4085.00
5b.	Air	WABCO Le Roi 50S1	485 c.f.m. 40 p.s.i. @ 85 h.p.	1070	4085.00

TABLE 12

CHARACTERISTICS OF SELECTED MARKETED

CIRCULATORY EQUIPMENT (cont'd)

NO.	(a) TYPE CIRCULATION	(b) MANUFACTURER AND MODEL	(c) OPERATING CHARACTERISTICS	(d) WEIGHT (lbs.)	(e) COST ($)
6.	Air	WABCO Le Roi 50S2	210 c.f.m. 40 p.s.i. @ 50 h.p.	1780	4900.00
7.	Air	Gardner-Denver Co. Model ACH	245 c.f.m. 30 p.s.i. @ 34 h.p.	475	2900.00
8.	Air-Foam	WABCO Le Roi 4AWS	150 c.f.m. 40 p.s.i. @ 16 h.p.	510	1439.00
9.	Air-Foam*	WABCO Le Roi 25S2A	107 c.f.m. 125 p.s.i. @ 25 h.p.	925	2900.00
10.	Air-Foam	WABCO Le Roi 3AVS	67 c.f.m. 80 p.s.i. @ 15 h.p.	312	746.00
11.	Air-Foam*	Schramm Skid Mtd., Self-Powered Model 160	160 c.f.m. 100 p.s.i. (excess power 14 h.p.)	1775	4995.00

TABLE 12

CHARACTERISTICS OF SELECTED MARKETED

CIRCULATORY EQUIPMENT (cont'd)

NO.	(a) TYPE CIRCULATION	(b) MANUFACTURER AND MODEL	(c) OPERATING CHARACTERISTICS	(d) WEIGHT (lbs.)	(e) COST ($)
12.	Air-Foam	WABCO Le Roi 4AWC	76 c.f.m. 125 p.s.i. @ 20 h.p.	520	1431.00
13.	Air-Foam-Gel	WABCO Le Roi 3AVC	34 c.f.m. 125 p.s.i. @ 8 h.p.	270	746.00
14.	Air-Foam-Gel	WABCO Le Roi 2AVS	27 c.f.m. 100 p.s.i. @ 7½ h.p.	191	405.00
15.	Air*	WABCO Le Roi 100S2	450 c.f.m. 125 p.s.i. @ 100 h.p.	3000	8525.00
16.	Air*	WABCO Le Roi 50S2	210 c.f.m. 125 p.s.i. @ 50 h.p.	2000	5050.00
17.	Air*	WABCO Le Roi 75S2	344 c.f.m. 125 p.s.i. @ 75 h.p.	2900	7400.00

TABLE 12

CHARACTERISTICS OF SELECTED MARKETED

CIRCULATORY EQUIPMENT (cont'd)

NO.	(a) TYPE CIRCULATION	(b) MANUFACTURER AND MODEL	(c) OPERATING CHARACTERISTICS	(d) WEIGHT (lbs.)	(e) COST ($)
18.	Air*	WABCO Le Roi 100SDS	450 c.f.m. 125 p.s.i. @ 100 h.p.	3200	9100.00

a. ARCO (American Rig Company)

b. WABCO (Westinghouse Air-Brake Co., Pneumatic Equipment Div.)

* Compressors capable of supporting downhole percussion tool

NOTE: All volumes are free air discharge.

the data relative to industrial water-cooled engines are somewhat consistent between various manufacturers. The data for the power units are presented in Table 13.

Supporting Materials

Supporting materials to execute a drilling program include two broad categories: those items necessary for any type of well construction and/or development (i.e., drill pipe, production pumps, well screens, etc.) and those additives required to support a particular type of circulatory system. The former will be referred to as fixed support materials and the latter as variable. In this case, there are distinctions relative to the size hole drilled, type of well production pump and materials to drive casing, and type of drill pipe and casing. The fixed support materials are presented in Table 14 and the variable materials in Table 15. Characteristics of the various circulatory additives are delineated in Table 16.

There are numerous commercial sources from which to procure the material included in Table 14. The only items sensitive to the source or procurement are drill pipe, casing, and the pumping unit if a three inch casing is used. For these items the manufacturer was designated because they represent the lightest weight equipment commerically available. The well screen has been sized based on recommendations of two manufacturers for 12 to 15 feet in length and a standard slot size of 0.015. The remaining items (bits, well screens, and miscellaneous tools) are available from numerous sources. Representative bit weights and costs are similar for either drag or tri-cone bits. Therefore, a single bit weight will be held as representative for either bit type.

TABLE 13

POWER UNIT DATA

NO.	MANUFACTURER AND MODEL	WEIGHT (lbs.)	COST* ($)	HORSE POWER APPLICATION AND SPEED
1	Ford[a] CID104	415	1127.00	28 b.h.p. @ 3000 r.p.m.
2	Ford CID172	780	1104.00	35 b.h.p. @ 2200 r.p.m.
3	Ford CID240	900	1794.00	60 b.h.p. @ 2200 r.p.m.
4	Ford CID300	900	1794.00	75 b.h.p. @ 2200 r.p.m.
5	Ford CID330	1200	2021.00	90 b.h.p. @ 2200 r.p.m.
6	Ford CID391	1200	2021.00	105 b.h.p. @ 2200 r.p.m.
7	Wisconsin[b] VH4D	410	775.00	16 b.h.p. @ 2000 r.p.m.
8	Wisconsin VG4D	595	956.00	22 b.h.p. @ 2000 r.p.m.
9	Wisconsin V465D	650	1343.00	39 b.h.p. @ 2400 r.p.m.

* Costs are list prices with no discount applied.
a Ford weights and costs include power take-off (PTO) clutch and cooling system. (Add 105 lbs. and $400 for T-9, 4 speed transmission.)
b Wisconsin weights and costs include clutch with PTO.

TABLE 14

FIXED SUPPORT MATERIAL REQUIREMENTS

TYPE MATERIAL	HOLE AND DRILL PIPE (d.p.) SIZE				
	6" hole 4 1/2" d.p.	6" hole 2 3/8" d.p.	5" hole 3 1/2" d.p.	5" hole 2 3/8" d.p.	4" hole 2 3/8" d.p.
Drill pipe(10 ft long): Source, unit weight and cost	Longyear Co., Flush Joint Casing: 11.3 lb/ft, 6.10 $/ft	American Rig Co. (ARCO): 3.3 lb/ft,2.72 $/ft	Longyear Co. CQ Drill Rods: 5.73 lb/ft, 5.32 $/ft	ARCO: 3.31 lb/ft, 2.72 $/ft	ARCO: 3.31 lb/ft, 2.72 $/ft
Drill Pipe: total weight (lbs.)/cost	1700/$915	510/$410	862/$800	510/$410	510/$410
Casing (10 ft long): Source, unit weight and cost	Jess & Lowell Well Casing Co., (4" I.D.) 1.11 lb/ft 1.1 $/ft	Jess & Lowell Well Casing Co., (4" I.D.) 1.11 lb/ft 1.1 $/ft	A.P. Ruth Co.: 3" plastic, .82 lb/ft .80 $/ft	A.P. Ruth Co.: 3" plastic, .82 lb/ft .80 $/ft	A.P. Ruth Co. 2" plastic, .63 lb/ft .57 $/ft
Casing: total weight (lbs.)/ cost	165/$155	165/$155	123/$120	123/$120	94/$81
Representative Bit: Source, size, unit wt. and cost	Williams Rock Bit, Inc.: (6") K-Type,26 lb. $107	Williams Rock Bit, Inc.: (6") K-Type, 26 lb.	Williams Rock Bit, Inc.: (5") 15 lb., $60	Williams Rock Bit, Inc.: (5") 15 lb., $60	Williams Rock Bit, Inc.: (4") 9 lb., $48

TABLE 14

FIXED SUPPORT MATERIAL REQUIREMENTS (cont'd)

TYPE MATERIAL	HOLE AND DRILL PIPE (d.p.) SIZE				
	6" hole 4 1/2" d.p.	6" hole 2 3/8" d.p.	5" hole 3 1/2" d.p.	5" hole 2 3/8" d.p.	4" hole 2 3/8" d.p.
Bits: 3 each total weight/ cost	78/$320	78/$320	45/$180	45/$180	27/$144
Representative Steel Well Screen, .015 slot: Source, and data	Cook Well Strainer Co. 6.5 lb/ft 16.90 $/ft	Cook Well Strainer Co. 6.5 lb/ft 16.90 $/ft	Cook Well Strainer Co. (3") 4 lb/ft 12.10 $/ft	Cook Well Strainer Co. (3") 4 lb/ft 12.10 $/ft	Mustang Well Supply Corp., 3.7 lb/ft 6.75 $/ft
Representative Plastic Well Screen, .015 slot: source, and data	Mustang Well Supply Corp., (4") 2.6 lb/ ft, 9.3 $/ft	Mustang Well Supply Corp., (4") 2.6 lb/ ft, 9.3 $/ft	Mustang Well Supply Corp., (3") 2.1 lb./ ft, 8 $/ft	Mustang Well Supply Corp., (3") 2.1 lb/ ft, 8 $/ft	Mustang Well Supply Corp., (2") 1 lb/ft 6 $/ft
Well Screen: Optimum Weight (lbs.)/cost (12 ft. long)	31/$112	31/$112	25/$95	25/$94	12/$73

TABLE 14

FIXED SUPPORT MATERIAL REQUIREMENTS (cont'd)

TYPE MATERIAL	HOLE AND DRILL PIPE (d.p.) SIZE				
	6" hole 4 1/2" d.p.	6" hole 2 3/8" d.p.	5" hole 3 1/2" d.p.	5" hole 2 3/8" d.p.	4" hole 2 3/8" d.p.
Well Production Pump: Basic data	Reda Pump Co. Submersible Model 9D-52TA 3 hp; 54 gpm @ 150 ft head	Reda Pump Co. Submersible Model 9D-52TA 3 hp; 54 gpm @ 150 ft head	Reda Pump Co. Submersible Model 9D-52TA 1/2 hp; 7 gmp @ 150 ft head	Reda Pump Co. Submersible Model 9D-52TA 1/2 hp; 7 gpm @ 150 ft head	Jensen Bros. Co. Pump Jack Model 11W; 1 3/8" cylinder; 1/4 hp; 1.6 gpm @ 150 ft
Pump: total wt. (lbs.)/cost	225/$1141	225/$1141	105/$377	105/$377	180/$215 (incl. sucker rod)
Representative Drop Pipe: Type, Weight (lbs.), and cost	Celanese Plastics Co., Golden Jet, 1", plastic 23/$35	Celanese Plastics Co., Golden Jet, 1", plastic 23/$35	Celanese Plastics Co., Golden Jet, 1", plastic 23/$35	Celanese Plastics Co., Golden Jet, 1", plastic 23/$35	U.S. Steel Co., Buttweld Galvanized 1 1/2"; 410/$575
Supporting Power Unit for pump	5 KW Mil Std Generator, 525 lb.	5 KW Mil Std Generator, 525 lb.	1 1/2 KW Mil Std Generator, est. 100 lb.	1 1/2 KW Mil Std Generator est. 100 lb.	Wisconsin Model BKNGE, 7 hp eng. 76 lb. ($165)
Misc. Tools: Designation	Suction hose, subs, drill collars, operator tools	Suction hose, subs, drill collars, operator tools	Suction hose, subs, drill collars, operator tools	Suction hose, subs, drill collars, operator tools	Suction hose, subs, drill collars, operator tools

TABLE 14

FIXED SUPPORT MATERIAL REQUIREMENTS (cont'd)

TYPE MATERIAL	HOLE AND DRILL PIPE (d.p.) SIZE 6" hole 4 1/2" d.p.	6" hole 2 3/8" d.p.	5" hole 3 1/2" d.p.	5" hole 2 3/8" d.p.	4" hole 2 3/8" d.p.
Misc. Tools Est. Wt. (lbs)	250	250	250	250	250
*Representative Drive Pipe (10 ft) Source, total weight (lb)/cost	Acker Drill Co. (4") 2250/$700	Acker Drill Co. (4") 2250/$700	Acker Drill Co. (3") 1500/$450	Acker Drill Co. (3") 1500/$450	Acker Drill Co. (2") 750/$250
*Pneumatic casing pusher: source, weight (lbs)	Schramm, Inc. Ringhammer (62 cfm air @ 70 psi) 330	Schramm, Inc. Ringhammer (62 cfm air @ 70 psi) 330	Schramm, Inc. Ringhammer (62 cfm air @ 70 psi) 330	Schramm, Inc. Ringhammer (62 cfm air @ 70 psi) 330	Schramm, Inc. Ringhammer (62 cfm air @ 70 psi) 330
*Representative well point: .018 slot, source, weight (lb)/cost	Clayton Mark & Co., Stainless Steel 4" drive point 76/$178	Clayton Mark & Co., Stainless Steel 4" drive point 76/$178	Clayton Mark & Co., Stainless Steel 3" drive point 35/$89	Clayton Mark & Co., Stainless Steel 3" drive point 35/$89	Clayton Mark & Co., Stainless Steel 2" drive point 10/$21

* Material used as substitute for casing and well screen when driving casing is considered with air circulatory mode.

TABLE 15

VARIABLE SUPPORT MATERIALS*

ADDITIVES OR EQUIPMENT REQUIRED	MODE OF CIRCULATION					
	Air	Air-Foam	Air-Foam-Gel	Water	Air with Downhole Hammer	Air-Foam with Downhole Hammer
Water rates required[A]	0	15 gal/hr	7 gal/cu.ft. of hole	3-4 gal/ft of hole depth	2 gal/min	2 gal/min
Total Water weight	0	1250	4"hole- 765 5"hole-1190 6"hole-1700	4400	10,000	10,000
Quik-Foam Weight	0	6	12	0	0	6
Revert weight	0	0	30	0	0	0
Chemical Feed Hopper weight (estimate)	0	0	20	20	0	0
Foam Injection pump and mixing Tank weight (est.)	0	250	250	0	0	250
Oil Injection pump (estimate)	0	0	0	0	20	20
Water Holding Tank weight	0	250	250	250	250	250

*All units are in pounds, except where indicated.

A. References 19, 20, 22. Computations are based on a 10 hour drilling schedule.

TABLE 16

CIRCULATION ADDITIVES

Additive Name	Type Circulation	Total Amount for Mission*	Function	Limitations	Reference
Quik-Gel	Water	165 lbs.	Bentonite additive for hole stabilization and prevention of lost circulation	Inhibited by salt water, volume of water & difficulty in well development with mud lining on sides of hole	10 (Baroid Div., Nat'l Lead Co.)
Quik-Trol	Water	9 lbs.	Long-chain polymer additive, miscible with water for hole stabilization and prevention of lost circulation	Inhibited by salt water, volume of water required, can be mixed with water but easiest in deisel slurry, thorough mixing equipment required	10 (do.)
Revert	Water	30 lbs.	Self-destructive natural organic additive for hole stabilization and prevention of lost circulation. Breaks down in viscosity to permit rapid well development and is compatible with salt water	Volume of water, and thorough mixing equipment	10 (UOP Johnson Div.)

TABLE 16

CIRCULATION ADDITIVES (cont'd)

Additive Name	Type Circulation	Total Amount For Mission*	Function	Limitations	Reference
Quik-Foam	Air-Foam	6 lbs.	Biodegradable foaming agent for dust suppression, reduce annular velocity required, prevent mud rings, reduce hole erosion and reduce hydrostatic head	Volume of water required, injection pump and no recirculation of mixture possible	10 (Baroid Div., Nat'l Lead Co.)
Roto Foam	Air-Foam	2 lbs.	Biodegradable foaming agent for dust suppression, reduce annular velocity required, prevent mud rings, reduce hole erosion and reduce hydrostatic head	Volume of water required, injection pump and no recirculation of mixture possible	20
Gel-Foam	Air-Foam-Gel	70 lbs. Quik-Gel 23 lbs. Quik-Foam	Reduces annular velocity required, stabilizes hole, reduces hydrostatic head	Volume of water, thorough mixing equipment, and difficulty in well development	10 (Baroid Div., Nat'l Lead Co.)

*Amount of additives required computed on basis of ten hour drilling mission.

The total bit weight provides for three bits, one drag and two tri-cone.

Complete Well Drilling Systems

Two complete rotary drill systems were discovered that are currently being deployed by helicopter in geophysical survey exploration. These are the Westinghouse Air Brake Company (WABCO), Edmondton, Alberta, Canada, CD-3 Model Copter Drill; and Big Indian Drilling Company, Calgary, Alberta, Canada, Nomad Heli-Drill Model 500. Both of these rigs are configured to be deployed in three helicopter lifts of 3000 to 3500 pounds per lift. Consequently, these specific drilling rigs were too heavy and not included in the study.

However, Big Indian Drilling Company has completed the engineering design relative to a lighter weight heli-drill designated as Model 300, configured to comprise two lifts of 2000 to 3000 pounds each. One of the modules weighs approximately 2600 pounds and includes: a base section (280 lbs.) with three-point hydraulic leveling which serves as a frame to mount the remaining equipment; a power unit and the supporting hydraulic equipment (800 lbs.) for operating the drill and circulatory equipment; a compressor, aftercooler and mud pump (870 lbs.); mast and hydraulic rotary tophead drive (673 lbs.). The other module is simply a steel wire frame basket to carry the necessary supporting materials, (i.e., drill pipe, bits, subs, etc.). This design provides for three-point hydraulic leveling and operation of the drill on the center of gravity of the complete equipment system. Both of these characteristics are patented features of the current (Nomad) Big Indian Company's production model. The principle of drilling on the center of gravity, rather than off one end of the frame, has significance in achieving maximum axial thrust and, in turn, improved penetration rates for lightweight drilling rigs. Figures 9 and 10 show a portion of the existing Model 500 being transported and the drill rig set up for operation, respectively. The data for this design of Big Indian Drilling Company's have been included and will be evaluated in the course of this study.

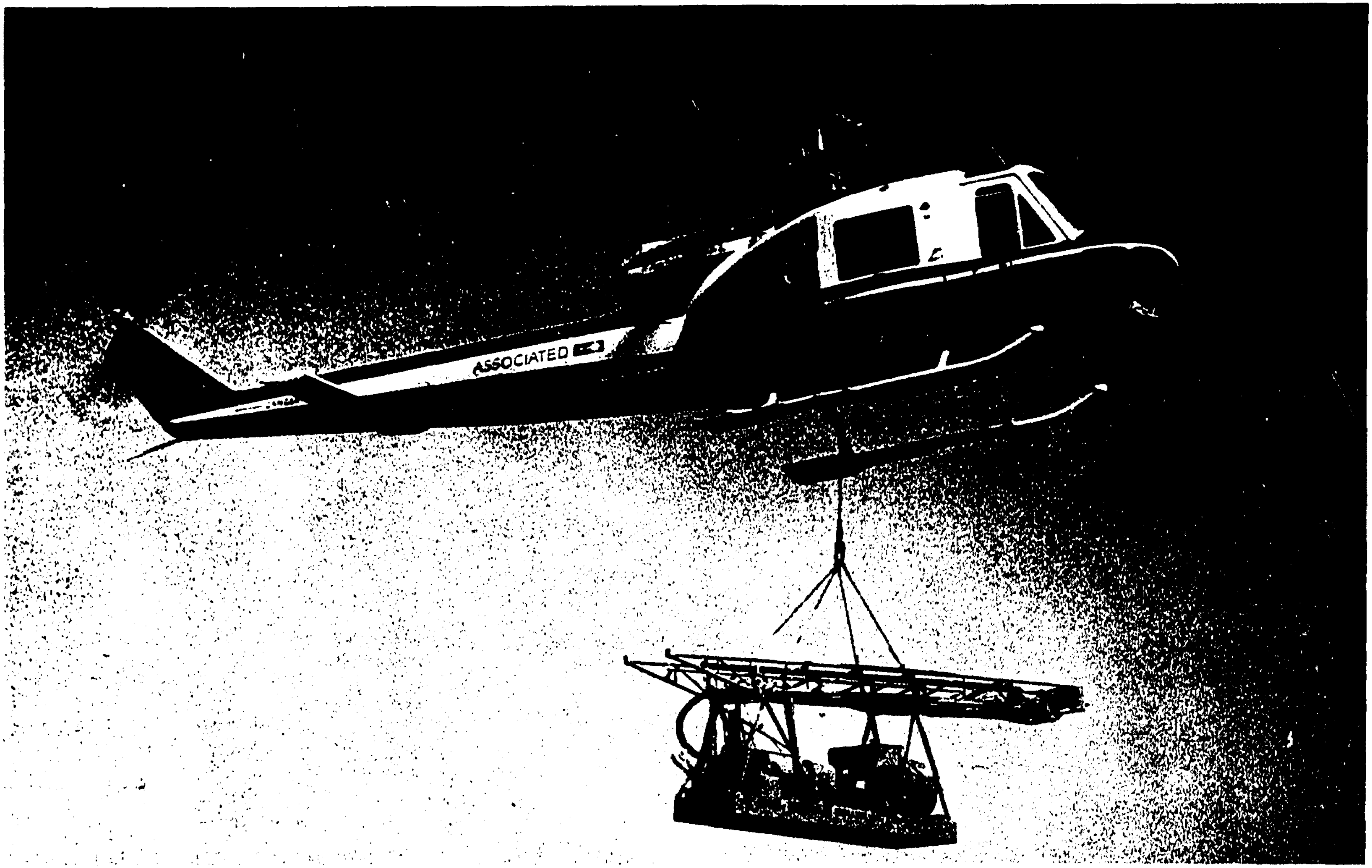


FIGURE 9

HELIDRILL IN TRANSPORT

(Courtesy Big Indian Drilling Company)

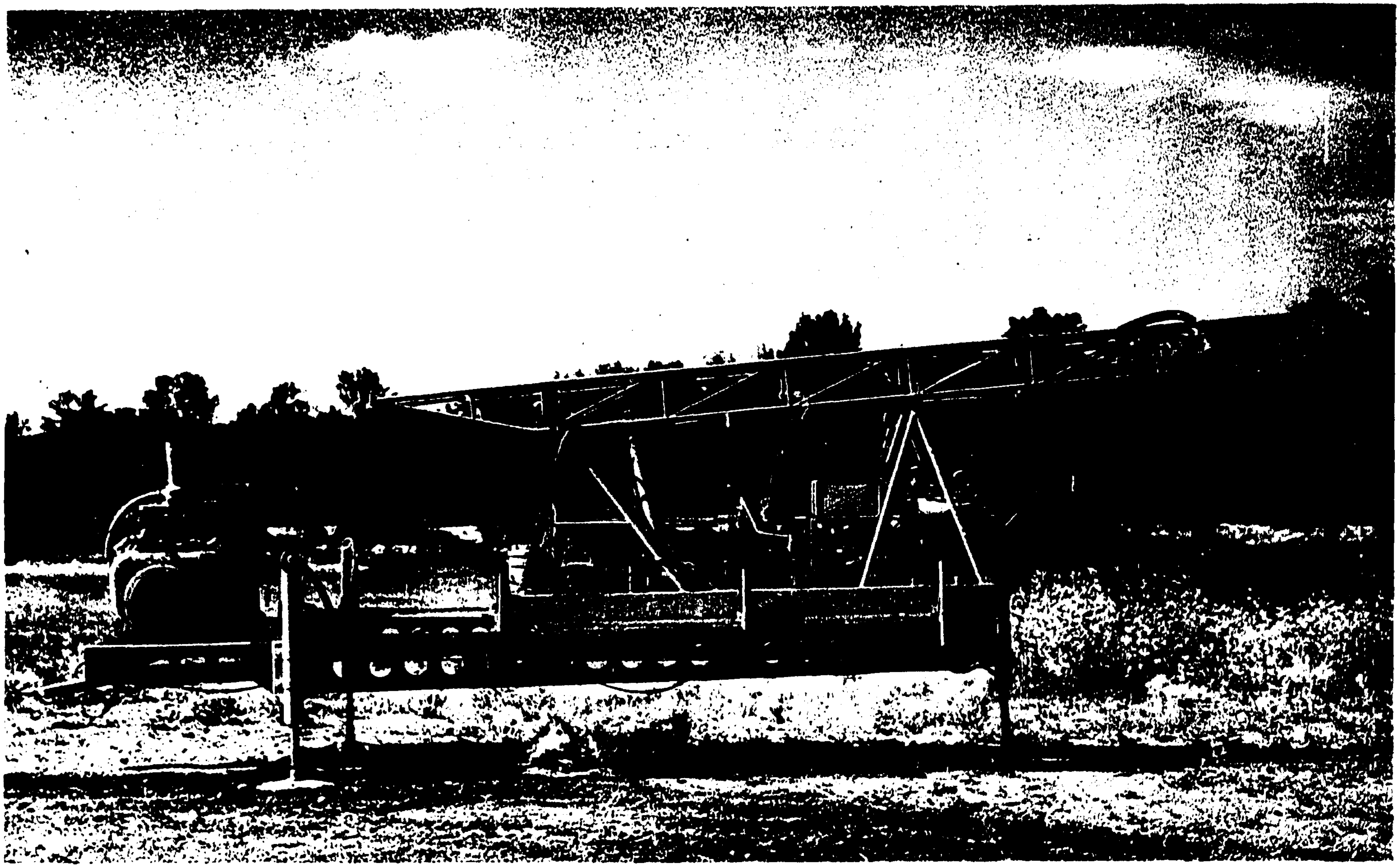


FIGURE 10

HELIDRILL IN DRILLING POSITION

(Courtesy Big Indian Drilling Company)

CHAPTER IV

ANALYSIS METHODOLOGY

The only obvious characteristic subject to immediate assessment is weight. However, the physical weight of a well construction system is only a single objective that has been specified by the U. S. Army. Other characteristics of the system require analysis to establish an equipment alternative's <u>overall utility</u> in meeting not just a single objective, but on the entire spectrum of objectives that have been delineated; for example, the impact on simplicity of operation by hydraulic or mechanical power transmission and drill additives associated with the circulatory system, subsurface drilling limitations and the volume of water produced incident to production pumps and hole size. These represent only a few of the various equipment alternatives that must be aggregated in such a manner as to reflect the degree that an alternative is successful in meeting the objectives.

Traditionally, the approach to multiple-criteria decision problems has been based on subjective or intuitive judgement. In such cases the decision makers' choices of trade-offs between a system's effectiveness at various levels of performance, problems of interaction between performance criteria (size, simplicity of operation, etc.) and interdependence among such criteria have been confined in the recesses of the decision maker's mind and, therefore, never laid bare to systematic scrutiny to insure explicit, logical consistency which is inherent to a uniform applicable procedure.

Given a decision which is rather simple in nature, the subjective process may be best. However, even relatively complex problems or situations where a poor decision has significant implications, reliance on subjective or intuitive judgement, which has not been formally qualified, could invite disaster. The use of a formal procedure in assessing the worth of various alternatives does not serve to eliminate subjective judgement. Rather, its purpose is to insure that when subjective judgement is used, it be made explicit, formulated in a systematic procedure and thoroughly scrutinized for logical consistency. The essence of such a procedure is to make what would normally be a subjective decision some degree more objective by imposing procedural tests for and bounds on judgements to insure that inconsistencies and erroneous assumptions are eliminated.

The framework for evaluating the well construction equipment in this study is a decision weighting model which will be used to assess the effectiveness (in measures of worth) of each of the various equipment alternatives in relation to objectives the equipment should fulfill. The basic procedure presented is that developed, tested and reported by Miller (15). Facets of this weighting model have also been employed by Drobny, et al (24), and tested for reliability by Eckenrode (25). Modifications in the model to enhance its predictability in evaluating the unique characteristics of rotary drilling equipment for the United States Army's application will be offered by the writer.

Decision Weighting Methodology

The assessment procedure is based on concepts of preference, aversion and indifference. Preference is categorized as positive if an object or activity elicits a positive emotional reaction, and, conversely, aversion or negative if its contemplation prompts such feelings as distress or anxiety. An individual who feels indifference neither possesses a preference or aversion to a circumstance. Consequently, the concept of worth is defined as an individual's conscious perceptions related to his fundamental feelings of preference, aversion or indifference. The worth of an object or activity reflects the degree of utility it or its consequences hold for a given individual based on his preferences. Worth need not be the same or consistent for one or more individuals since everyone does not have the same preference or preferences can change with time and circumstances. The formulation of worth is such that measures of physical characteristics and/or unique circumstances are not in themselves sufficient, although what can be ascribed in terms of objects and activities of the situation are appropriate for assessment. Necessarily, worth assessment is then subjective in nature and seeks a form of limited objectivity by compelling the decision maker to delineate and formulate his preferences relative to a specific decision and the alternatives available. The obvious criticisms of this concept are its lack of complete objectivity and, by the very nature of worth judgement, it is scientifically untestable. The option available to seek full objectivity is implementation of a random selection technique, which could hardly be regarded as palatable to a decision maker choosing between alternatives. Further, the fact that a worth judgement is untestable certainly does not preclude its evaluation over sensitive ranges of values or in terms of a concensus based on informed opinions. Regardless of these speculations, in the final analysis, one cannot repudiate the fact that where alternatives exist, the decision maker must make a choice. His task is to ensure he assesses all factors in such a manner that the true conceptual worth of all alternatives is revealed. An outline of the procedure and an illustrated example follow.

Formulating Procedure

The formulating procedure encompasses five distinct steps, the first of which is to explicitly detail the constituents of the desired major performance criteria. These represent the overall objectives and are articulated under the following guidelines:

A. The list should be complete and exhaustive.

B. All items listed must be mutually exclusive (i.e., an objective listed should not encompass or be encompassed by any other objective listed).

C. Restrict the list to only objectives of the highest order of significance.

D. The objectives should be free of interdependence on any other objective listed.

After establishing the overall objectives, the second step involves disaggregating these higher-level performance standards into lower level criteria which are included in the higher level's meaning.

This is followed by step three, where a single physical performance measure is selected for each lower level standard. This requires a judgemental choice of a well defined, easily measurable attribute of an alternative which serves to interpret, in physical terms, the intended meaning of the lowest level criterion under consideration.

In step four, a scoring function is formulated which acts as a mathematical rule to assign worth or utility points to every possible physical performance measure. This, in effect, serves to bridge the physical characteristics of the alternative with a worth structure. To insure consistency in the scoring conventions the following ground rules are applicable:

A. Standards or criteria possessing positive preference will be assigned positive numbers.

B. Standards toward which aversion is felt will be assigned negative numbers.

C. The scale of worth is bound by plus and minus one. All real numbers between this range are permissible. Plus one will be used only where complete satisfaction is accomplished for the job objective. Conversely, minus one will be used only in cases where nothing worse is logically possible in terms of the stated job. Zero will be assigned to situations toward which indifference is felt.

D. If one situation is preferred to another, a higher worth number will be assigned the preferred situation. However, if two situations are considered to possess identical worth, equal worth points will be assigned.

E. Partial success or failure in accomplishing the objectives will be assessed within the scale relative to the proportion or percentage the stated objectives are accomplished.

F. Scoring functions will be formulated to encompass the <u>entire logical possible</u> range of physical performance, in terms of mathematical formulas and/or curves or assigned direct worth scores judgementally by the decision maker.

G. In circumstances where a single worth number is inappropriate a range of values can be specified indicating the maximum and minimum value the decision maker would anticipate for the objective. These values can be used to determine the Sensitivity of the total worth score relative to each objective over the appropriate range.

H. Details for the specific formulation of scoring function and the associated worth points are characterized in terms of whether or not the physical performance measures of the criteria are discrete or continuous. An absolute frequency of integers belongs to the discrete category, whereas, continuous physical measures are those that vary over a broad spectrum; for example, time duration of an event. However, discrete categories that contain a large number of values (≥ 5) in scale, are treated as continuous in formulating the scoring function. All of the physical measures associated with this study are discrete, but those which have greater than five scale categories must be treated as continuous. Scoring the continuous functions will be discussed in subparagraph I; discrete functions are formulated as follows:

1. If there are two discrete categories in the scale (i.e., a case of the presence or absence of a desirable attribute) assign zero worth points for its absence and a

value between zero and one point indicating the relative proportional satisfaction provided by the presence of the attribute in view of the decision maker(s).

2. For more than two discrete categories, delineate the merits of the desirable attributes to the decision maker(s) and have them rank-order the attributes by successive paired comparisons of the performance categories. The least valuable should be at the bottom of the list and the most valuable should be at the top. The topmost category is compared to the second. If it is perceived more valuable than the first, their places should be interchanged on the list. No position change is warranted if their position is perceived appropriate. The second is then compared with the third, etc., until the complete list of categories has been successively compared with the next lower category on the list. Upon satisfying the rank-ordering, the decision maker(s) assign a value between zero and one worth points to each category to indicate the proportional satisfaction provided by each to the attribute being considered. The sum of these values must be one.

I. The continuous or discrete function with greater than five categories of physical measure is formulated as follows:

1. A natural order of scale categories should exist or have been established by rank-ordering the categories in the manner described in Paragraph 8b above. All physical measures in this study will have a logical lower bound

condition of zero performance.

2. If the physical measure is not restricted by a logical upper bound, determine the direction of preference; that is, is more performance better, or the reverse (less better)? If more performance is best, assign a zero value to the worth scale (ordinate on Cartesian coordinates) and one worth point to infinite performance on the performance scale (abscissa). The general case of this function is graphed in Figure 11. The unique graphical configuration for a specific scoring function is explained in Paragraph d below.

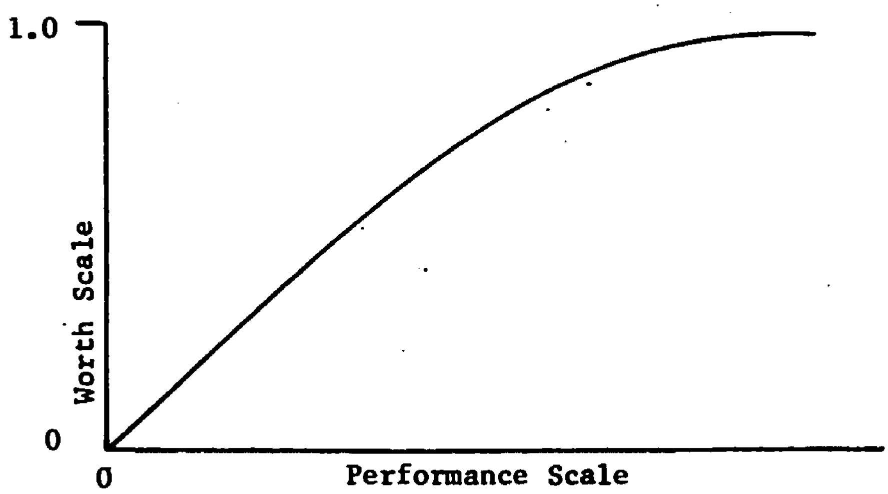


FIGURE 11

GENERAL SCORING FUNCTION

If the reverse relationship holds for zero performance, i.e., zero performance is best, the general function is represented by Figure 12. Again, the unique case is determined as outlined in Paragraph D.

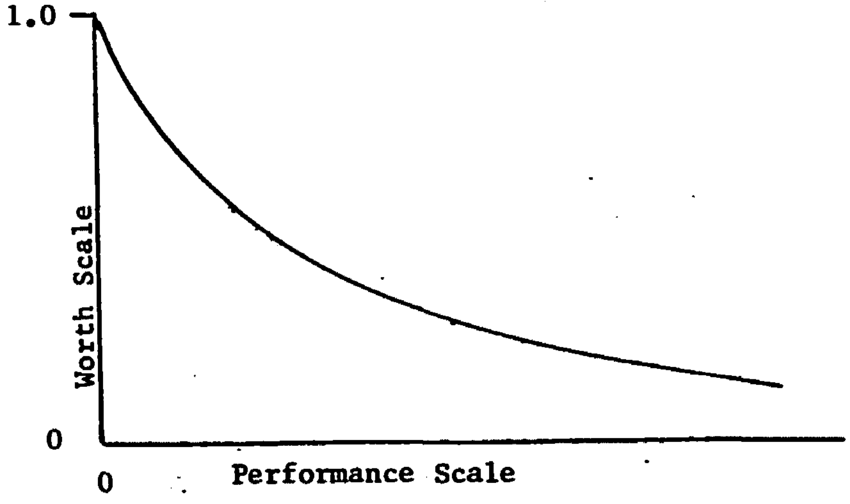


FIGURE 12

GENERAL SCORING FUNCTION

3. If a logical upper bound exists for performance and more performance is better, assign zero worth points to zero performance and 1.0 worth points to the logical upper bound. This general case is shown in Figure 13.

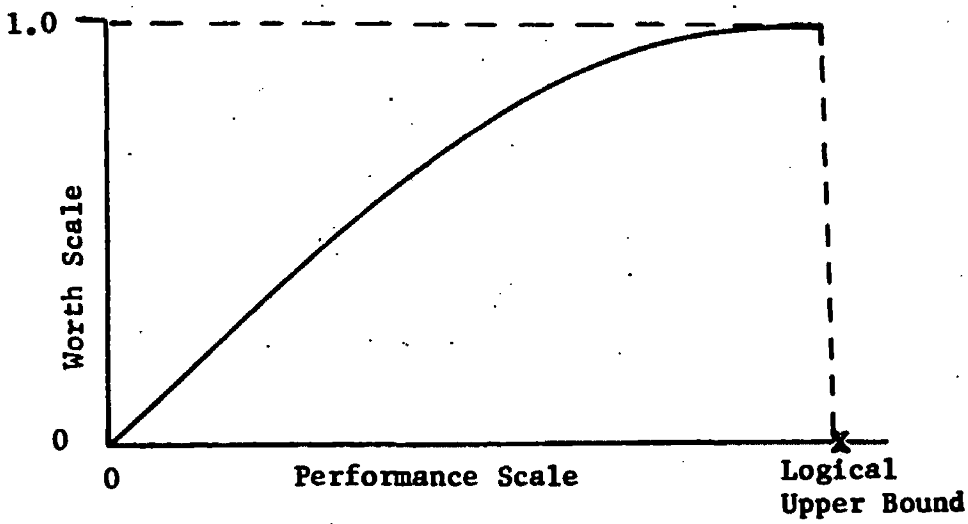


FIGURE 13

GENERAL SCORING FUNCTION BOUNDED

For the reverse relationship, less performance is better, assign zero worth points to the logical upper bound and 1.0 points to zero performance. The general case for this function is given in Figure 14. Both cases for conditions where a logical upper boundary exists are formulated explicitly following the explanation in Paragraph d below.

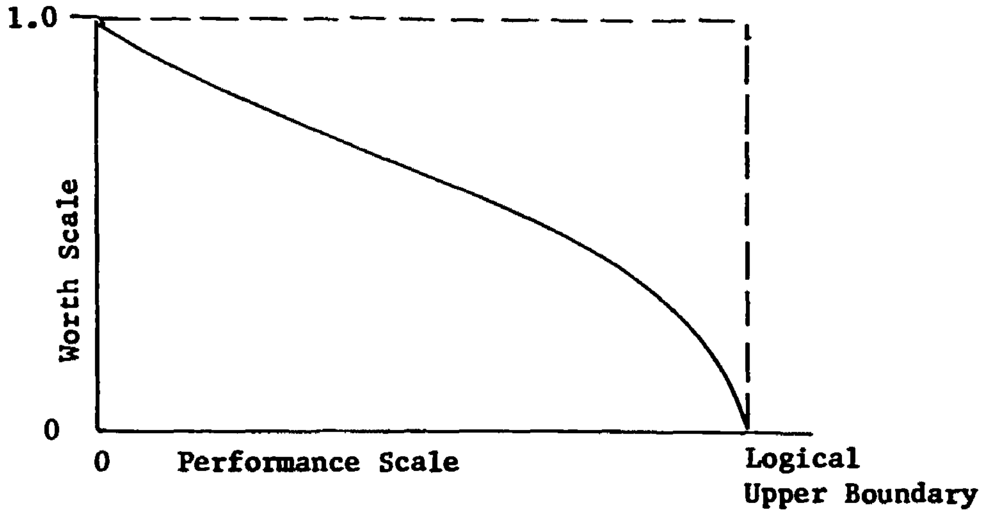


FIGURE 14

GENERAL SCORING FUNCTION BOUNDED

4. It is now necessary to establish the unique graphical configuration for each scoring function. First, one or more decision makers are assembled and given Cartesian coordinate paper laid off with zero worth points and zero performance points at the origin. The ordinate scale of worth points is marked off in one-tenth increments to a maximum value of one. The abscissa performance scale is laid off to either the logical upper boundary or some

excessive amount (50% greater) of performance. The decision maker(s) then ask themselves what level of performance, if provided by the alternative being considered, comprises 10% success in satisfying the lowest level criteria. This is accomplished by the decision maker(s) marking the graph at the estimated level of performance which corresponds to the one-tenth worth point level. This procedure is repeated at 10% increments to the 90% (if an upper bound exists) or 100% worth point level. This graphed function, or for more than one decision maker the normalized graph, is used to assess the corresponding worth point score for each alternative's physical performance measure.

Assigning Weights

The fifth and final step in the assessment procedure is to combine each separately assigned worth score into a single index which proportionalizes each criterion contribution to the overall system objectives. An additive weighting function will be used for this purpose. This is accomplished in three phases. Initially, all the subcriteria in the hierarchical objective tree are rank-ordered by the paired comparison technique. A value of one is assigned the topmost subcriterion, then the second is compared to the first and its importance assessed in terms of ratio or fraction. The third subcriterion is then compared to the second, and again a relative importance is assigned. Assuming that a value of 0.50 was assigned to the second and the third is judged to be one-half as valuable as the second, its relative weight would be 1/2 X 0.50 or 0.25. Successive paired comparisons are quantified in this manner until the list is exhausted. The weights are summed, each divided by the total, and are reported as normalized weights.

The second phase in weighting is to establish each subcriterion's proportional weight in the hierarchy of the objective tree. Each subcriterion is assessed for its relative contribution to its hierarchical objective. Then each subcriterion's effective weight is the product of all weights in the chain of hierarchy.

The illustrated example will clarify formulating the effective weight and, for that matter, the final phase of introducing an adjusting factor that serves to assess the thoroughness of the physical performance measure to interpret the intended meaning of the lowest level criterion. The adjusting factor is quantified by using a percentage scale where one hundred percent indicates that the physical measure perfectly interprets the criterion, whereas zero relates that the measure is completely inadequate to define the criterion. The adjusted effective weights are then the product of the adjusting factors and effective weights, which are again normalized.

Utility Index

The worth points for each alternative must now be resolved with the adjusted effective weight for each physical measure to derive a utility index. This simply involves multiplying the worth score for each criterion by its corresponding adjusted effective weight for each alternative. The sum of these products is the utility index for the alternative. The alternative with the highest utility index indicates the preferred alternative, provided the following details of testing the algorism substantiate the consistency of the procedure:

A. Tabularize the calculated utility scores of each criterion for all alternatives. Select a subset or the entire set of performance measures and rank-order the alternatives in perceived overall worth, intuitively or subjectively, without consulting the scores or weights of performance measure being considered. Compare the computed partial or overall worth scores from the table with the subjectively assigned ranks. If scores and rankings agree, repeat the process by including more performance measures and continue until all of the measures are included in the list.

B. If disagreement arises between the subjectively ranked set and computed worth scores, scrutinize the list for completeness, incorrect scores or adjusting factors, interdependency and attempt to effect appropriate corrections.

Illustrated Example

The example will be presented in context of the problem addressed in this study. That is, of the currently marketed rotary well drilling systems, which will best meet the Army's objectives? The procedure example will encompass the evaluation of two drill systems, at a single hole size with six possible circulatory modes. This example will also serve as the illustration of the detailed computations so that further analysis of all alternatives can be computerized and only the pertinent final utilities of the alternatives reported.

A detailed list of the objectives or criteria which encompass the drilling equipment's expected performance was reported in Table 1. At first glance, this list appears sufficiently complete, whereas, it is not. The list fails to provide delineation of the performance expected relative to the equipment's versatility or simplicity of operation, nor does it reflect limitations relative to the amount of water to be produced or subsurface formation drilling problems. Further, the list contains readily identifiable interdependence between maintainability and reliability, since both of these criteria are quantified by the same parameters. Therefore, a new list of objectives was constructed and a hierarchy of criteria, worth scores and weighting factors were established on a concensus basis with various personnel assigned to the U. S. Army Mobility Equipment Research and Development Center.

Objective or Criteria Hierarchy

Four principle objectives were established as the highest level performance criteria. Reported in their rank-ordered sequence they are: simplicity of operation; equipment versatility; transportability; and reliability. The decomposition of each of these criterion will be addressed in the succeeding paragraphs.

Simplicity of Operation

The complexity of operating a drilling system and completing the construction of a well involves three distinct operations on the part of the operator: moving the equipment into a drilling site and preparing to execute the drilling operation; the actual process of drilling the hole; and, finally, developing the well to produce water. Each of these distinct operations constitutes criteria that have inherent operational complexity among the alternatives to be scrutinized. Each of these second order criteria, and others to be succeedingly presented, will be discussed and decomposed in sequence of their perceived rank-order.

Hole construction involves several subcriteria that reflect the complexity of operation and alternative processes. Certainly, various modes of circulation have inherent complexity, as does the number of rotary speed selections available to the operator. Obviously, a single rotary speed is best from the operator's standpoint of operational simplicity. However, since a wide spectrum of speeds is desirable for the penetration of various formations, it is important to articulate the distinction here. At this juncture <u>only</u> simplicity of operation is being considered. Rotary speeds' relation to equipment versatility will be considered later, cognizant of the possibility of interdependence or interaction. Finally, other operational features that influence the ease of hole construction are the mode of up and downfeed and mode of rotation, both of which are intrinsic to the drill system.

Well development encompasses two subcriteria that can be assessed from the ease of operation standpoint; installation of the casing and well screen; and installation of the pump.

Erecting the equipment to begin drilling operations involves raising the mast and leveling the equipment. There are, of course, other preparations required, but the two cited are those that involve distinctions between the various alternatives.

Equipment Versatility

This principal criterion is cited to reflect an alternative's capability to perform the prescribed mission. Versatility encompasses drilling most subsurface formations encountered to the proper hole size, in most climatic regions of the world. The ability of a well-construction alternative to perform these functions is characterized by the subcriteria; formation character, hole size and climatic flexibility.

The qualities of the drill system that reflect on its ability to penetrate various characters of formations are its inherent capability to stabilize the sides of the drilled hole in caving formations, the drill's rated rotary speed range, rated axial thrust and torque. Formation penetration at optimum rates is a function of balanced rotational speeds and axial thrust (19). Rotary speeds relative to formation penetration are generally established in ranges as a function of the formation drilled; 40-80 r.p.m. for hard formations and 125-250 r.p.m. for soft formations (8, 19). Therefore, speed in this context, will be defined as an alternative's ability to produce at least a single speed within each of these ranges. The alternative's capability to produce multiple speeds within the ranges will not be considered since variable rotary speeds can be achieved with variations in power units' output speed. Further, use of a range of rotary speeds eliminates possible interaction with the number of speeds which was used with simplicity of operation. Torque rating of the drill has principle significance in drilling loose or soft formations.

Hole size is directly a function of hole diameter and hole depth. Hole depth was specified (see Table 1) at 150 feet, whereas, the hole diameter becomes a function of the desired well yield relative to the size of pump that a particular hole diameter can accept.

Climatic flexibility is defined in terms of temperature sensitivity, and at that, freezing temperature sensitivity since there is no difference in any of the alternatives' ability to operate in tropic or hot ambient temperature climatic zones. The principle components of a well construction system susceptible to freezing are the power unit coolant and certain circulatory media (i.e., those that involve water injection).

Transportability

The obvious subcriteria incident to transportability (and specifically helicopter transportability in this study) is an equipment alternative's physical weight. The dimensions of the equipment have little bearing on the alternatives to be studied since they are all basically configured in the same manner and the physical dimensions are relatively unconstrained since the equipment will be carried as an external sling load.

Reliability

Reliability of an equipment alternative is related to the frequency of equipment failure and the time required to return it to operation. However, since there was no data available to substantiate these performance criteria, a distinction between the mode of power transmission performance will be assessed.

Summary

Note that in the criteria delineated above there has been no reference made to operational mission time or camouflagability objectives that were specified in Table 1. There is no effective manner to predict what subsurface formations will be encountered or to project expected penetration rates even if they could be predicted. Consequently, the time to complete the drilling mission cannot be estimated. However, it is expected that any of the equipment alternatives to be studied can complete the well construction mission within the specified 48 hour mission time. Camouflagability does not vary significantly between the various alternatives to warrant assessment.

The criteria and subcriteria decomposition are summarized in the criteria tree, and appropriate physical performance measures are specified in Figure 15.

Formulation of Scoring Functions

Scoring functions must now be established for the nineteen performance measures specified in Figure 15. Nine of the performance measures will be quantified graphically and the remaining ten will be assessed and articulated as direct estimates.

Graphical Scoring Functions

The complexity of circulatory material associated with air and

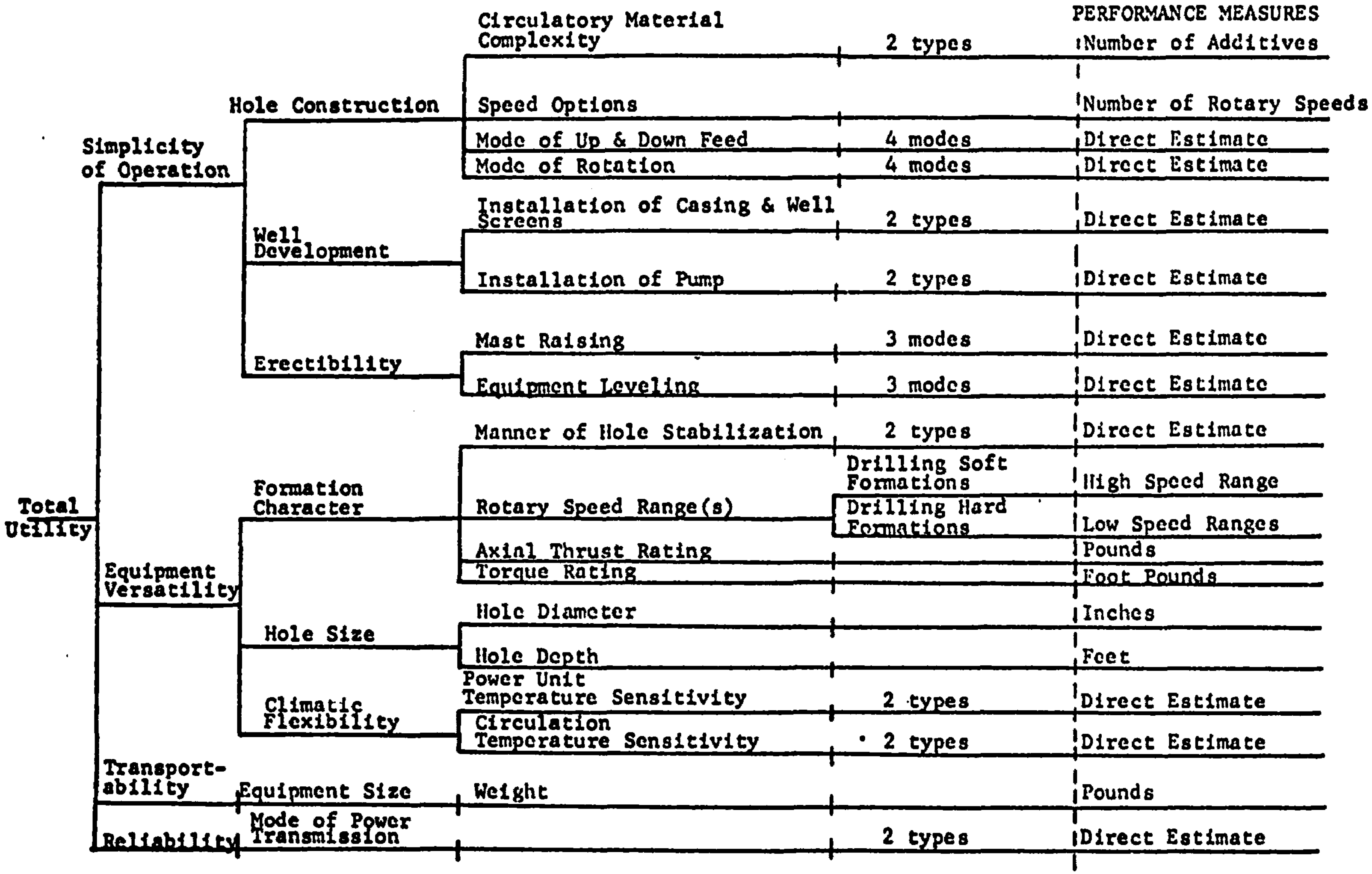


FIGURE 15: CRITERIA HIERARCHY

water media requires two curves. This is due to a perceived distinction in difficulty for an operator to deal with the number of additives incident to air or water circulatory systems. Air and water, without additives, will be regarded as the standard and each assigned a worth score of one. Therefore, additional additives must be regarded as less than an optimum circumstance. Judgemental values assigned for each media and associated increase in the number of additives are reflected in Figures 16 and 17.

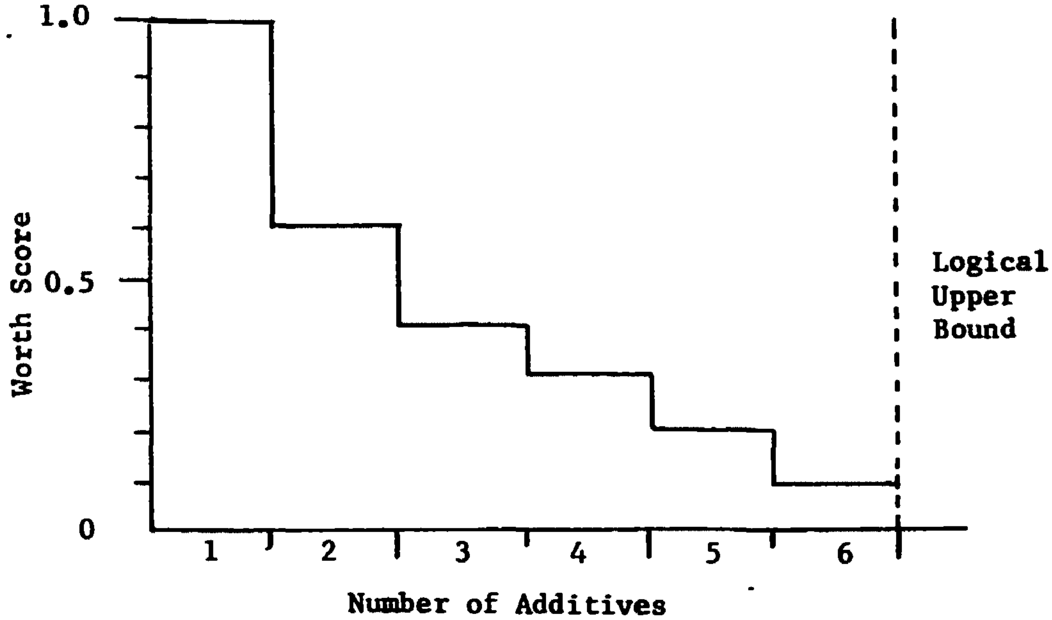


FIGURE 16

AIR CIRCULATION ADDITIVES

SCORING FUNCTION

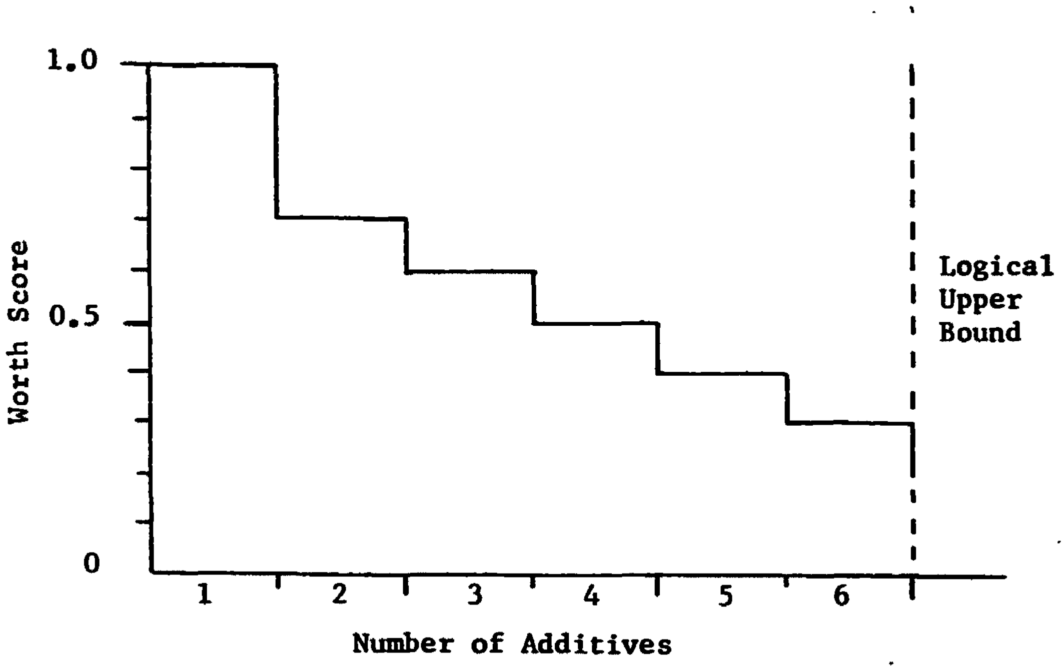


FIGURE 17

WATER CIRCULATION ADDITIVES

SCORING FUNCTION

Simplicity of operation related to speed options is quantified by the number of speeds available to the operator. From the operators point of view a worth score of one will be assigned to alternatives with just one rotary speed and judgemental values assessed for any number of speeds greater than one. This scoring function is graphed in Figure 18.

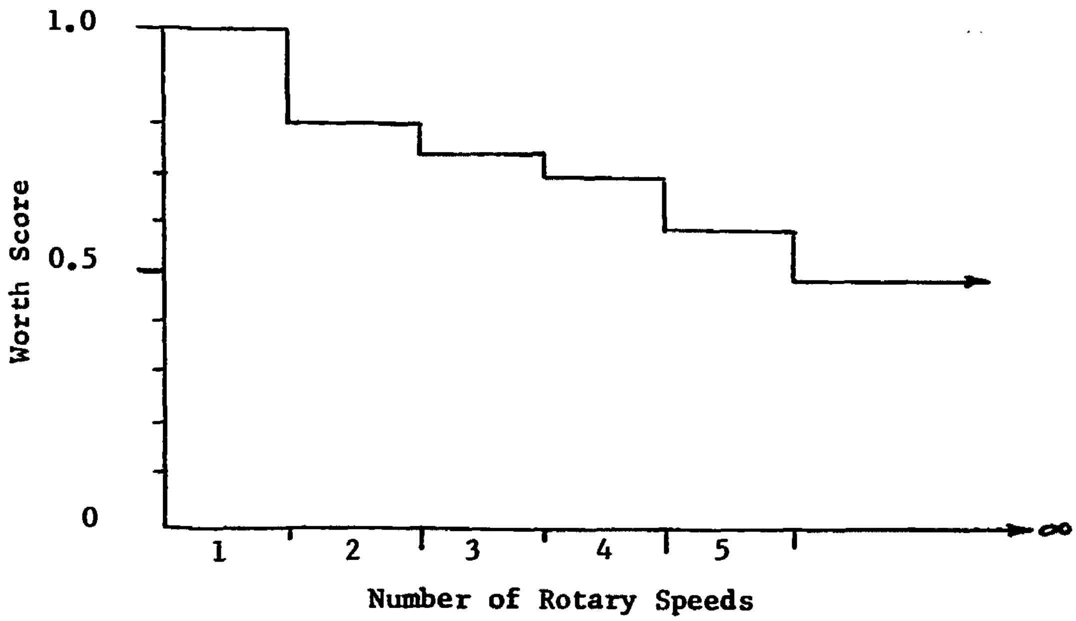


FIGURE 18

NUMBER OF SPEEDS

SCORING FUNCTION

Under the principle criterion of equipment versatility of rotary speed ranges, axial thrust rating, torque rating and hole size will be formulated graphically. Rotary speed ranges possess a characteristic high and low range. And, as qualified earlier, any alternative that possesses a speed of rotation rating within the specified ranges will be assigned a worth score of one. Those alternatives which do not possess a speed rating within this range will be given a worth score of zero. These relationships are reflected in Figures 19 and 20.

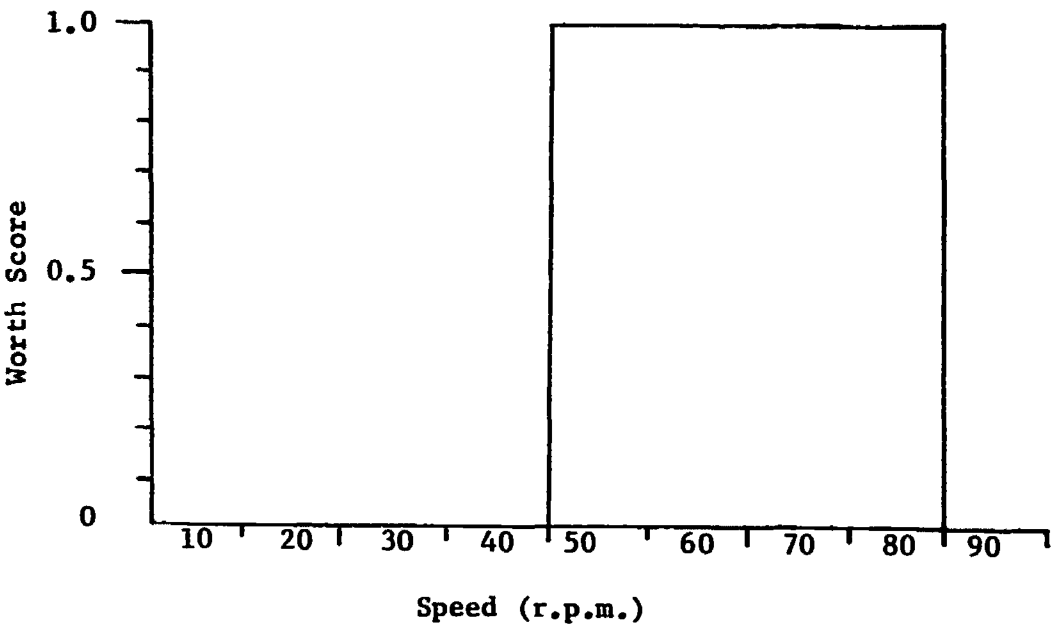


FIGURE 19

LOW ROTARY SPEED

SCORING FUNCTION

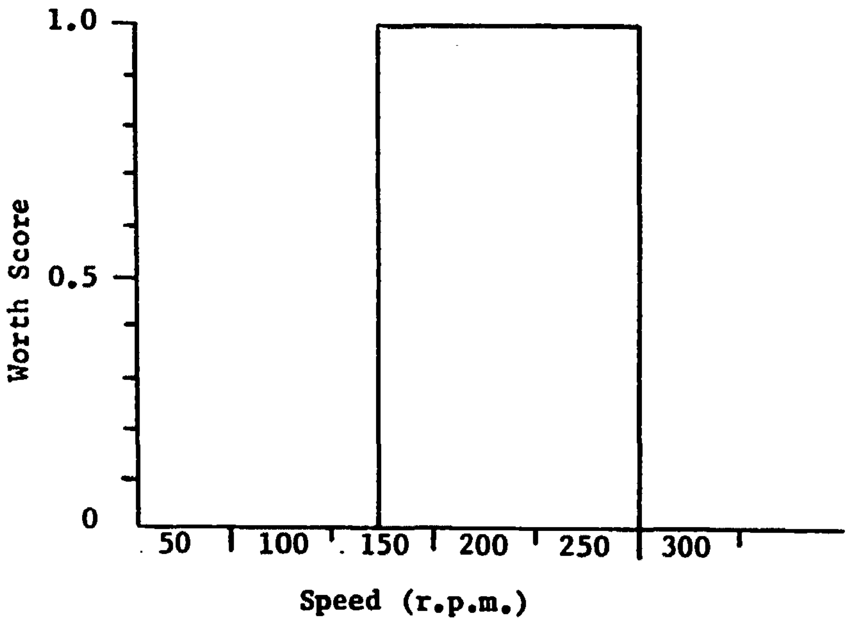


FIGURE 20

HIGH ROTARY SPEED

SCORING FUNCTION

The amount of axial thrust available with an equipment alternative has significance only in cases where a down-hole percussion tool is not included in the equipment's configuration. Where such a tool is included the amount of axial thrust required is minimal and will be assigned a worth score of one. In other cases, it appears that a logical upper bound of 10,000 pounds should be regarded as adequate (8). This amount of pulldown would provide an estimated penetration rate of three to four feet per hour for a five inch bit in very hard formations (basalt). Therefore, a value of one will be assigned to 10,000 pounds and lesser amounts will be scored based on informed concensus judgement. This function is shown in Figure 21.

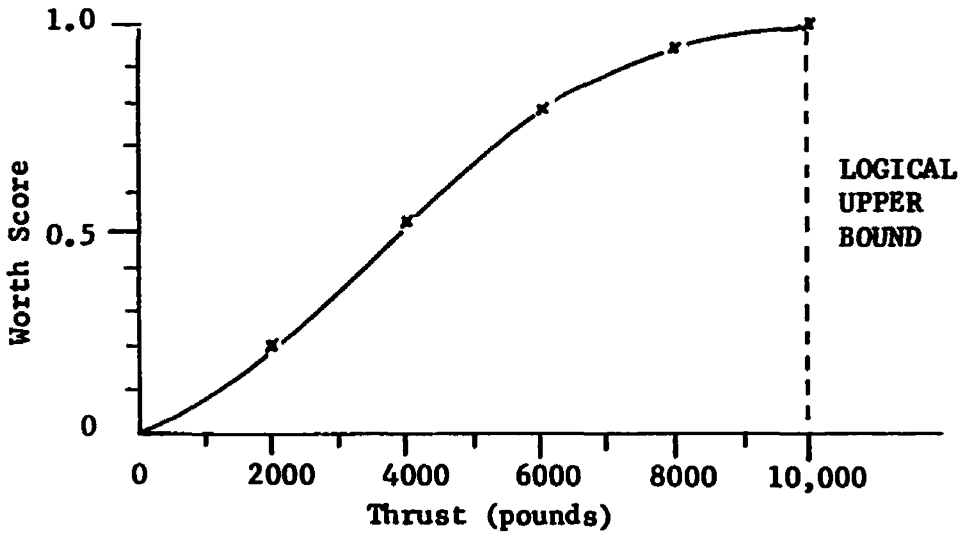


FIGURE 21

AXIAL THRUST

SCORING FUNCTION

Quantification of torque required for executing drilling operation is highly judgemental. Drilling loose and caving formations has the greatest impact on the torque required of the drilling system. Field survey of experienced operators, to be reported in entirety in Chapter V, reflects a judgemental choice of 2000 foot-pounds of torque as an adequate equipment rating to cope with most circumstances. Hence, 2000 foot-pounds and greater will be assessed a worth score of one and a judgemental score to lesser values as reflected in Figure 22.

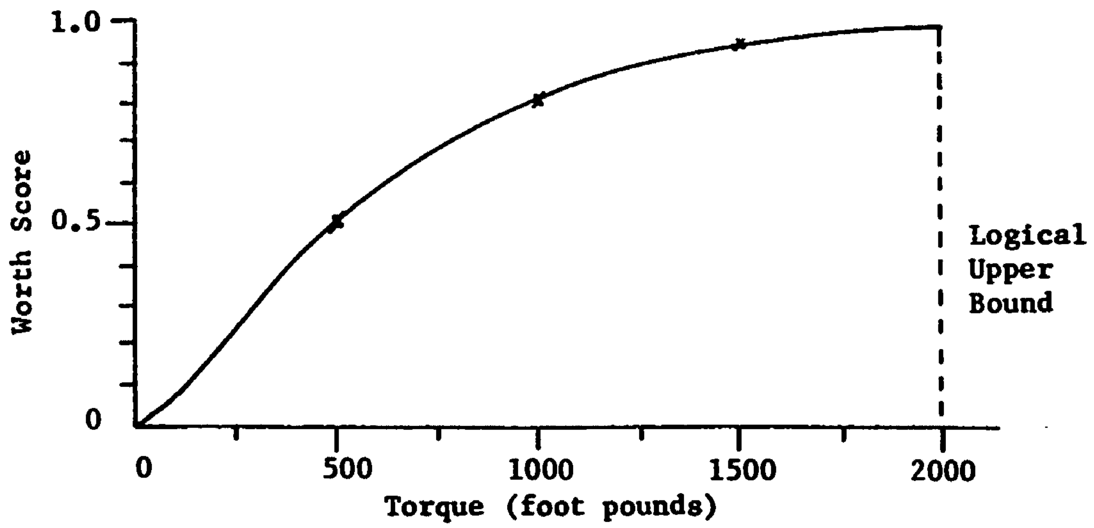


FIGURE 22

TORQUE SCORING FUNCTION

Hole size is characterized by the depth of and the diameter of the hole that an alternative can reasonable expect to deliver. Optimum depth has been specified at 150 feet, which comprises a logical upper bound. Therefore, 150 feet rating and any depth greater will be assigned a worth score of one. The score assigned between an alternative's depth rating less than 150 feet is jugemental and reflected in Figure 23.

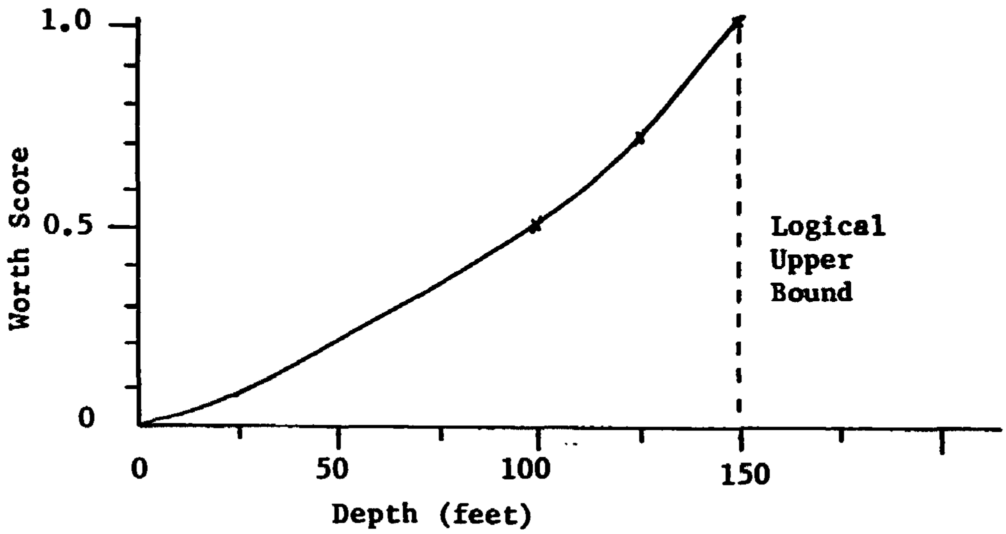


FIGURE 23

HOLE DEPTH

SCORING FUNCTION

A hole diameter of six inches must be regarded as optimum since this hole will accommodate a well production pump for almost any reasonable amount of water. Equipment rated for a hole size of six inches or greater will be assigned a worth score of one. Again, for hole sizes down to four inches in diameter the worth score is judgemental. The value of drilling a hole less than four inches diameter is highly questionable and assigned a worth score of zero (see Figure 24).

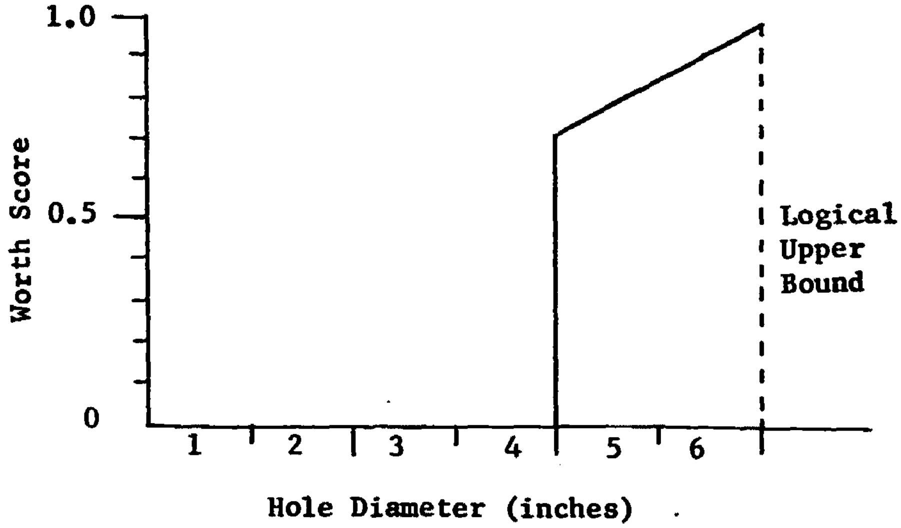


FIGURE 24

HOLE DIAMETER

SCORING FUNCTION

Finally, the manner of scoring the equipment alternative's physical weight must be considered. Since 2000 pounds is the maximum lift capability of the UH1H helicopter and one entire lift is required for a load of zero to 2000 pounds, a worth score of 1.0 will be assigned to this range of alternative weights. Between the performance level of 2000 to 3000 pounds a worth value of 90% is provided to anticipate improved performance in the UH1H's lift capability as a rational technological projection. Once the 3000 pounds performance level is exceeded, two lifts or two helicopters are required to carry the loads between 3000 to 6000 pounds. Logically, this range cannot be assessed a worth of any greater than 50%. Beyond 6000 pounds, three lifts are required which is considered highly undesirable. Consequently, zero worth points are assigned to alternatives whose weight performance is greater than 6000 pounds. This step function is graphed in Figure 13.

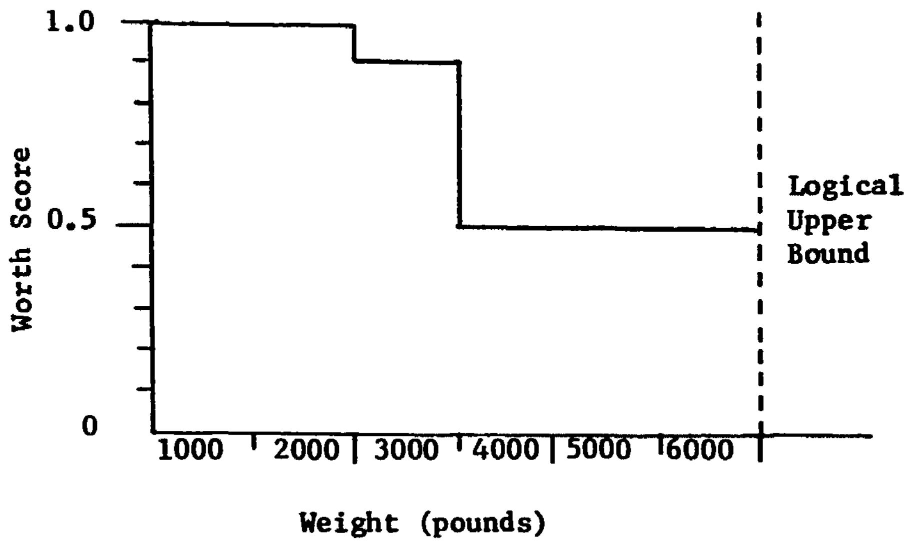


FIGURE 25

EQUIPMENT WEIGHT

SCORING FUNCTION

Direct Estimate Scoring Functions

Assignment of worth scores for the criterion of simplicity of operation are summarized in Figure 26. The mode of up and down feed deals with the manner of applying thrust, feeding and retracting drill pipe from the hole. The hydraulic mode is favored since fewer controls are required. Chains and cables for such linkages are less desirable since they represent a source of accidents to operators who may inadvertently come in contact with them.

Tophead drive as a mode of rotation is held more valuable than the rotary table or spindle since less operations are required to add drill pipe to the drill string and mitigates problems of caving in loose formations. Controls of the hydraulic system are easier with a variable variable flow hydraulic valve in deference to selecting from various

FIGURE 26

SIMPLICITY OF OPERATION

SCORING FUNCTION

- Mode of Up & Down Feed
  - Hydraulic Cylinders (1.0)
  - Hydraulic Rack and Pinion (.85)
  - Hydraulic Chain or Cable (.76)
  - Mechanical Chain or Cable (.45)
- Mode of Rotation
  - Tophead Hydraulic (1.0)
  - Tophead Mechanical (.65)
  - Mechanical Rotary Table (.65)
  - Spindle (.45)
- Installation of Casing and Well Screen
  - Conventional Casing and Screen (1.0)
  - Driven Well Point and Casing (.4)
- Installation of Pump
  - Submersible Type (1.0)
  - Positive Displacement Type (.7)
- Mast Raising
  - Hydraulic (1.0)
  - Mechanical (.5)
  - Manual (.3)
- Equipment Leveling
  - Hydraulic (1.0)
  - Mechanical (.6)
  - None (.2)

mechanical transmissions, the proper gear and adjusting the power unit's speed.

The installation of conventional casing is less demanding than driving the casing. Conventional casing can normally be handled by hand, whereas driving the casing requires another facet of equipment operations in addition to normal drilling requirements.

The installation of a submersible pump can be accomplished using conventional electrical cable and lightweight plastic drop pipe. Further, submersible pumps possess greater pumping capacities that will facilitate well development by simply overpumping the acquifer. Positive displacement pumps have lesser capacities and require the use of steel drop pipe and coupling sucker rods to suspend the pump cylinder in the well.

Both mast raising and leveling are erectibility characteristics that contribute to safety of the operator and the ease of preparing the equipment for operation. Hydraulic control is again easier to control and safer than mechanically controlled systems.

The equipment versatility criterion requires direct estimates of the worth for the manner of hole stabilization and climatic flexibility performance measures. Hole stabilization deals with the manner in which an alternative provides for drilling caving formations. There are two options available: installing casing as drilling progresses; or using drilling fluid to stabilize the sides of the hole. There are situations where the former technique may prove inadequate (e.g., the hole caves in before the casing can be set), whereas, the latter can be regarded as almost universally successful. Therefore, hole stabilization by fluid will be assigned a worth score of one with the casing alternative as 0.5.

Climatic flexibility will be reflected in terms of power unit's and circulatory media's sensitivity to freezing temperatures. Obviously, an air-cooled power unit is more flexible than a water-cooled one, and will be given a worth score of one. Water-cooled alternatives will be given a score of 0.5. Alternatives which include a form of water injection circulation will be given a score of 0.2 and those requiring only air a score of one.

The final direct estimate to be qualified is for the principal criterion of reliability. Reliability will be estimated based on whether the drill system alternative is mechanically or hydraulically powered. A case favoring hydraulically powered systems was presented earlier (Chapter II, page 28) and a worth score of 1.0 will be given to such alternatives. Mechanically powered systems will be given a worth score of 0.7. The foundation for these scores is subjective judgement on the part of the writer based on field interviews with drillers.

Compiled worth scores can now be formulated for the two drill alternatives being considered. The physical performance measures and converted worth score for each alternative are summarized in Table 17 and Table 18. Worth scores were those specified graphically or articulated as direct estimates.

Formulation of Weighting Functions

The principal criteria were rank-ordered and the simplicity of operation objective was assigned 100% relative value. (Note that the weighting functions associated with this study will be expressed in terms of total percentages and <u>not</u> their decimal equivalents.) Equipment versatility was perceived as 97% as important as the simplicity

TABLE 17

ESTIMATED PERFORMANCE/WORTH SCORE $(Si)_j$*

BIG INDIAN DESIGN (Model 300)

Performance / Circulation	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
Equipment Weight	4161/.5	4721/.5	4139/.5	4146/.5	6018/.5	6275/0
Pump Installation	Submer./ 1.0	1.0	1.0	1.0	1.0	1.0
Power Unit Cooling	Water/ .5	.5	.5	.5	.5	.5
Circulatory Material Complexity	0 Add./ 1.0	1 Add./ .6	2 Add./ .4	1 Add./ .7	1 Add./ .6	2 Add./ .4
Speed Options	Inf./.5	.5	.5	.5	.5	.5
Mode of Up & Down Feed	Hyd. Cyl./ 1.0	1.0	1.0	1.0	1.0	1.0
Mode of Rotation	Tophead/ 1.0	1.0	1.0	1.0	1.0	1.0
Installation of Casing	Driven Casing/ .5	.5	.5	Conv. Casing/ 1.0	.5	.5
Mast Raising	Hyd./1.0	1.0	1.0	1.0	1.0	1.0

TABLE 17

ESTIMATED PERFORMANCE/WORTH SCORE $(Si)_j$*

BIG INDIAN DESIGN (MODEL 300) (cont'd)

Performance \ Circulation	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
Equipment Leveling	Hyd./1.0	1.0	1.0	1.0	1.0	1.0
Hole Stabilization	Casing/.5	.5	.5	Fluid/1.0	1.0	1.0
Rotary Speed Range	High-1.0 Low-1.0	H-1.0 L-1.0	H-1.0 L-1.0	H-1.0 L-1.0	H-1.0 L-1.0	H-1.0 L-1.0
Axial Thrust Rating	9620/.97	.97	.97	.97	1.0	1.0
Torque Rating	1185/.85	.85	.85	.85	.85	.85
Hole Diameter Rating	4½/.82	.82	.82	.82	.82	.82
Hole Depth Rating	300/1.0	1.0	1.0	1.0	1.0	1.0
Circulation Temperature Sensitivity	1.0	.2	.2	.2	.2	.2
Reliability	Hyd./1.0	1.0	1.0	1.0	1.0	1.0

*Performance based on drilling a 5" hole with 2 3/8" drill pipe.

TABLE 18

ESTIMATED PERFORMANCE/WORTH SCORE $(Si)_j$

ARCO S MODEL

Performance / Circulation	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
Equipment Weight	4008/.5	4568/.5	4039/.5	3993/.5	6192/0	6448/0
Pump Installation	Submer./ 1.0	1.0	1.0	1.0	1.0	1.0
Power Unit Cooling	Water/.5	.5	Air/1.0	.5	.5	.5
Circulatory Material Complexity	0 Add./ 1.0	1 Add./ .6	2 Add./ .4	1 Add./ .7	1 Add./ .6	2 Add./ .4
Speed Options	2 speeds/ .8	.8	.8	.8	.8	.8
Mode of Up & Down Feed	Mech. Chain/ .45	.45	.45	.45	.45	.45
Mode of Rotation	Rotary Table/ .65	.65	.65	.65	.65	.65
Installation of Casing	Drive Option/ .5	.5	.5	Fluid/ 1.0	.5	.5
Mast Raising	Manual/.3	.3	.3	.3	.3	.3

TABLE 18

ESTIMATED PERFORMANCE/WORTH SCORE $(Si)_j$

ARCO S MODEL (cont'd)

CIRCULATION Performance	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
Equipment Leveling	None/.2	.2	.2	.2	.2	.2
Hole Stabilization	Casing/.5	.5	.5	Fluid/1.0	.5	.5
Rotary Speed Range	High-1.0 Low-1.0	H-1.0 L-1.0	H-1.0 L-1.0	H-1.0 L-1.0	H-1.0 L-1.0	H-1.0 L-1.0
Axial Thrust Rating	4000/.5	.5	.5	.5	.5	.5
Torque Rating	900/.75	.75	.75	.75	.75	.75
Hole Diameter Rating	4/.7	.7	.7	.7	.7	.7
Hole Depth Rating	300/1.0	1.0	1.0	1.0	1.0	1.0
Circulation Temperature Sensitivity	Air/1.0	Water/.2	.2	.2	.2	.2
Reliability	Mech./.7	.7	.7	.7	.7	.7

objective, etc., until all the principal objectives were assigned weights by successive paired comparisons. These values were totalled and normalized weights reported for each. A summary of this scheme is reported below:

RANK-ORDERED OBJECTIVE	RELATIVE IMPORTANCE	NORMALIZED WEIGHTING FACTOR
Simplicity of Operation	100%	29%
Equipment Versatility	.97 X 100% = 97%	28%
Transportability	.89 X 97% = 86%	25%
Reliability	.72 X 86% = 62%	18%
TOTAL	345%	100%

Referring to Figure 15, the lower level criteria were apportioned relative weights that each criterion of the next level was judged to influence the higher level criterion with which it is associated. For example, rank-ordered paired-comparisons were made for hole construction, well development and erectibility for simplicity of operation. Then the relative contribution of each toward the apportioned 29% weight of simplicity of operation determined as shown below:

RANK-ORDERED SUBCRITERIA FOR SIMPLICITY OF OPERATION	RELATIVE IMPORTANCE	NORMALIZED WEIGHTS	APPORTIONED % CONTRIBUTION TO OBJECTIVE
Hole Construction	100%	48%	14%
Well Development	.65 X 100% = 65%	31%	9%
Erectibility	.70 X 65% = 46%	21%	6%
TOTALS	211%	100%	29%

The paired-comparison and apportionment of weights is carried out along the entire chain of criteria hierarchy until decomposition is complete at the physical performance levels specified. The complete apportionment of

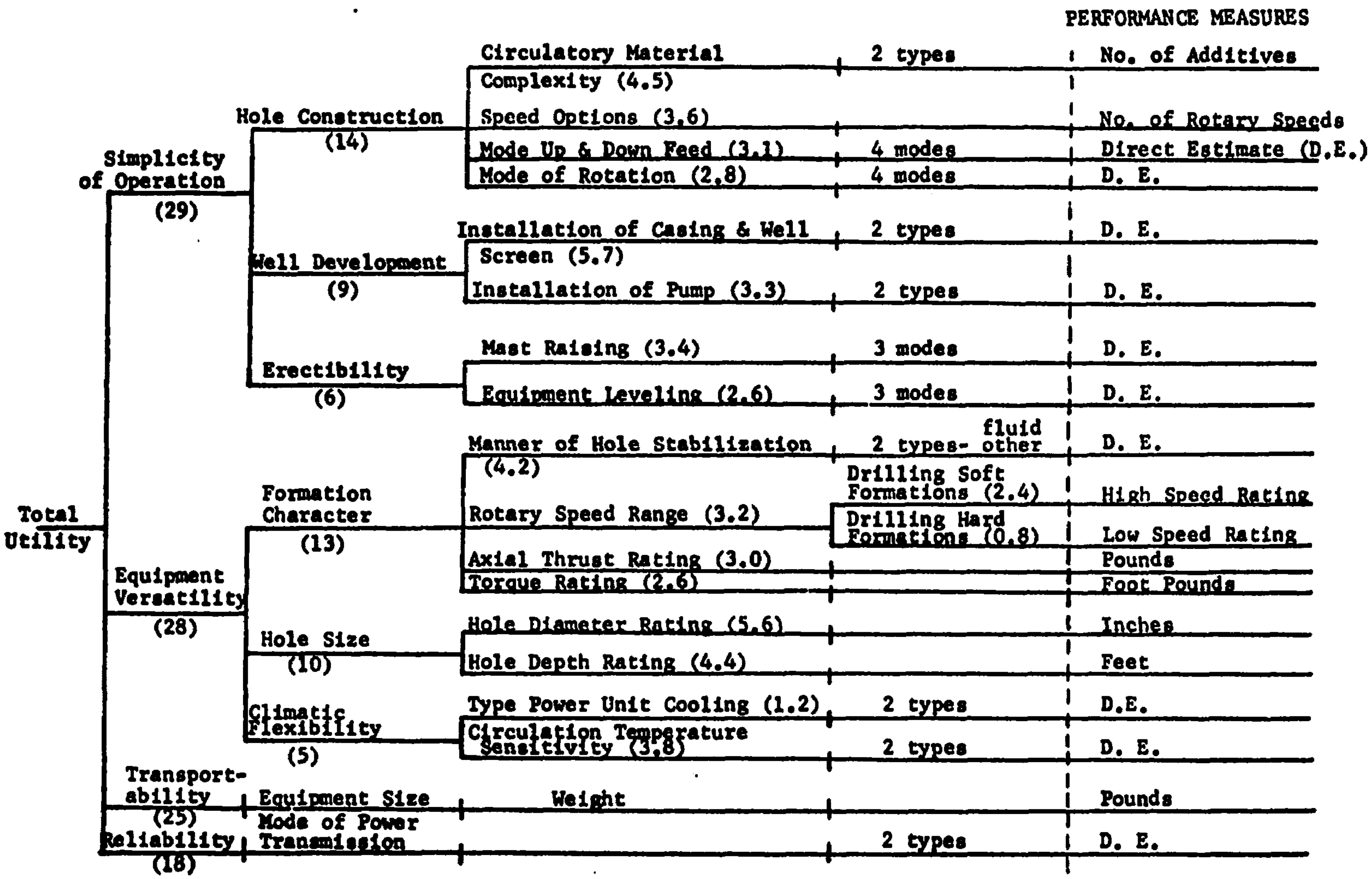


FIGURE 27: HIERARCHY OF EFFECTIVE WEIGHTS

The weighting factors for the lower-level criterion and respective performance measures are now subjected to the rigor of adjustment. As previously noted, the adjusting factor seeks to define, in percentage terms, the effectiveness of the performance measure to interpret the meaning of its associated criterion. For example, the measure of weight is regarded by the writer to be 100% successful in interpreting the meaning of equipment size; whereas, direct worth estimates, such as that associated with reliability may be regarded as somewhat arbitrary and, in such a case, its value to interpret the criterion's meaning should be degraded. The writer chose to attach a 60% level as an adjusting factor for reliability. Each adjusting factor multiplied times the criterion's formally established effective weight for each criterion. The adjusting factors and effective weights again derived by concensus are reported in Table 19.

Total Utility for Alternatives

The final utility scores can now be formulated by combining the worth scores from Table 17 and Table 18 and the adjusted effective weights from Table 19 for each performance measure and totalling the results for each alternative to reflect total utility index. This operation and the total utilities are summarized in Table 20. (Note: The utility scores and total utility index will be expressed in percentage terms and <u>not</u> decimal equivalents.)

The tabularized formulations can be expressed mathematically as follows:

$$TU_j = \sum_{j=1}^{19} (Si)_j W_j, \quad i=1 \text{ to } 6$$

WHERE: TU_j is the total utility for the ith alternative well construc-

TABLE 19

FORMULATION OF ADJUSTED EFFECTIVE WEIGHTS

Performance Criterion	Effective Weights (1)	Adjusting Factor (2)	Product (2) x (3)	Adjusted Effective Weights
Equipment Weight	25.0	.9	22.5	26.0
Pump Installation	3.3	.8	2.6	3.0
Power Unit Coolant	1.2	1.0	1.2	1.4
Circulatory Material Complexity	4.5	1.0	4.5	5.2
Speed Options	3.6	1.0	3.6	4.2
Mode Up & Down Feed	3.1	1.0	3.1	3.6
Mode of Rotation	2.8	1.0	2.8	3.2
Installation of Casing	5.7	.9	5.1	5.9
Mast Raising	3.4	.9	3.1	3.6
Equipment Leveling	2.6	.75	2.0	2.3
Hole Stabilization	4.2	.9	3.8	4.4
High Rotary Speed Range	2.4	.7	.6	.7
Low Rotary Speed Range	.8	.7	.6	.7

TABLE 19

FORMULATION OF ADJUSTED EFFECTIVE WEIGHTS

(cont'd)

Performance Criterion	Effective Weights (1)	Adjusting Factor (2)	Product (2) x (3)	Adjusted Effective Weights
Axial Thrust Rating	3.0	1.0	3.0	3.5
Torque Rating	2.6	.9	2.3	2.7
Hole Diameter Rating	5.6	1.0	5.6	6.5
Hole Depth Rating	4.4	1.0	4.4	5.0
Circulatory Temperature Sensitivity	3.8	1.0	3.8	4.4
Reliability	18.0	.6	10.8	12.4

TABLE 20

TOTAL UTILITY SCORES (TU_j) FOR

BIG INDIAN DESIGN/ARCO S MODEL

Circulation / Performance	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
Equipment Weight	13/13	13/13	13/13	13/13	0/0	0/0
Pump Installation	3/3	3/3	3/3	3/3	3/3	3/3
Power Unit Coolant	.7/.7	.7/.7	.7/.7	.7/.7	.7/.7	.7/.7
Circulatory Material Complexity	5.2/5.2	3.1/3.1	2.1/2.1	3.6/3.6	3.1/3.1	2.1/2.1
Speed Options	2.1/3.4	2.1/3.4	2.1/3.4	2.1/3.4	2.1/3.4	2.1/3.4
Mode of Up & Down Feed	3.6/1.6	3.6/1.6	3.6/1.6	3.6/1.6	3.6/1.6	3.6/1.6
Mode of Rotation	3.2/2.1	3.2/2.1	3.2/2.1	3.2/2.1	3.2/2.1	3.2/2.1
Installation of Casing	3.0/3.0	3.0/3.0	3.0/3.0	5.9/5.9	3.0/3.0	3.0/3.0
Mast Raising	3.6/1.1	3.6/1.1	3.6/1.1	3.6/1.1	3.6/1.1	3.6/1.1
Equipment Leveling	2.3/.5	2.3/.5	2.3/.5	2.3/.5	2.3/.5	2.3/.5
Hole Stabilization	2.2/2.2	2.2/2.2	2.2/2.2	4.4/4.4	2.2/2.2	2.2/2.2

TABLE 20

TOTAL UTILITY SCORES (TU_j) FOR BIG INDIAN

DESIGN/ARCO S MODEL (cont'd)

Performance / Circulation	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
High Rotary Speed Range	2/2	2/2	2/2	2/2	2/2	2/2
Low Rotary Speed Range	.7/.7	.7/.7	.7/.7	.7/.7	.7/.7	.7/.7
Axial Thrust Rating	3.4/1.8	3.4/1.8	3.4/1.8	3.4/1.8	3.5/3.5	3.5/3.5
Torque Rating	2.3/2.0	2.3/2.0	2.3/2.0	2.3/2.0	2.3/2.0	2.3/2.0
Hole Diameter Rating	5.5/5.2	5.5/5.2	5.5/5.2	5.5/5.2	5.5/5.2	5.5/5.2
Hole Depth Rating	5/5	5/5	5/5	5/5	5/5	5/5
Circulatory Temperature Sensitivity	4.4/4.4	.9/.9	.9/.9	.9/.9	.9/.9	.9/.9
Reliability	12.4/8.7	12.4/8.7	12.4/8.7	12.4/8.7	12.4/8.7	12.4/8.7
Total Utility	77.6/65.6	72/60.0	70.9/59.6	77.6/65.6	59.1/48.7	58.1/47.7

tion system subject to the jth criteria weighting functions.

$(Si)_j$ is the scoring function of the ith alternative system for criteria j.

Wj is the weighting function for the jth criteria (adjusted effective weight).

The testing procedure was applied by the writer to the final results, but it failed to induce any changes to the original weights or adjusting factors. The results indicate what must be regarded as negligible difference between the Big Indian Design (Model 300) with air or water circulation. However, one should remember that the use of a water-mud circulatory media necessitates water at the drilling site and air does not. Further, the burden of transporting the water <u>was not</u> included in the total equipment weights. If it had been included the worth score for equipment weight for virtually any drill system and any size of hole with water circulation would be <u>zero</u>.

Cost Effectiveness

Cost effectiveness of the alternatives can be established by a simple extension of total utility by plotting the alternative's cost versus its total utility. Cost, incident to this study, will include only the initial procurement cost for the equipment configuration. Personnel costs will be static since each drilling rig will require at least two operators. Operating costs are also relatively static since the only differential will be the additives associated with the alternative and are insignificant at a drilling depth of 150 feet. Therefore, the costs reported are limited solely to the procurement cost, at present day (1971), list prices quoted by the manufacturer for specific equipment items. No attempt was made to discount the acquisition costs.

Further, it must be recognized that the total equipment cost for an alternative could, and probably will, differ from the actual cost to design and build a prototype around the designated equipment. However, it seems safe to assume that such cost differentials will be relatively uniform across the entire equipment sample since all of the alternatives' configurations are subject to the same aggregation techniques and list prices.

The illustrated example data on the ARCO S Model alternatives will be evaluated to reflect the application of the cost-effectiveness analysis. The relevant data is summarized below and graphed in Figure 28.

	System Alternative	Total Utility	Total Procurement Cost ($)
(1)	ARCO S Model, Air	63.8	11,500
(2)	Air-Foam	58.4	11,000
(3)	Air-Foam-Gel	58.0	9,000
(4)	Water	64.0	9,100
(5)	Air Hammer	47.4	16,700
(6)	Air-Foam Hammer	46.3	16,800

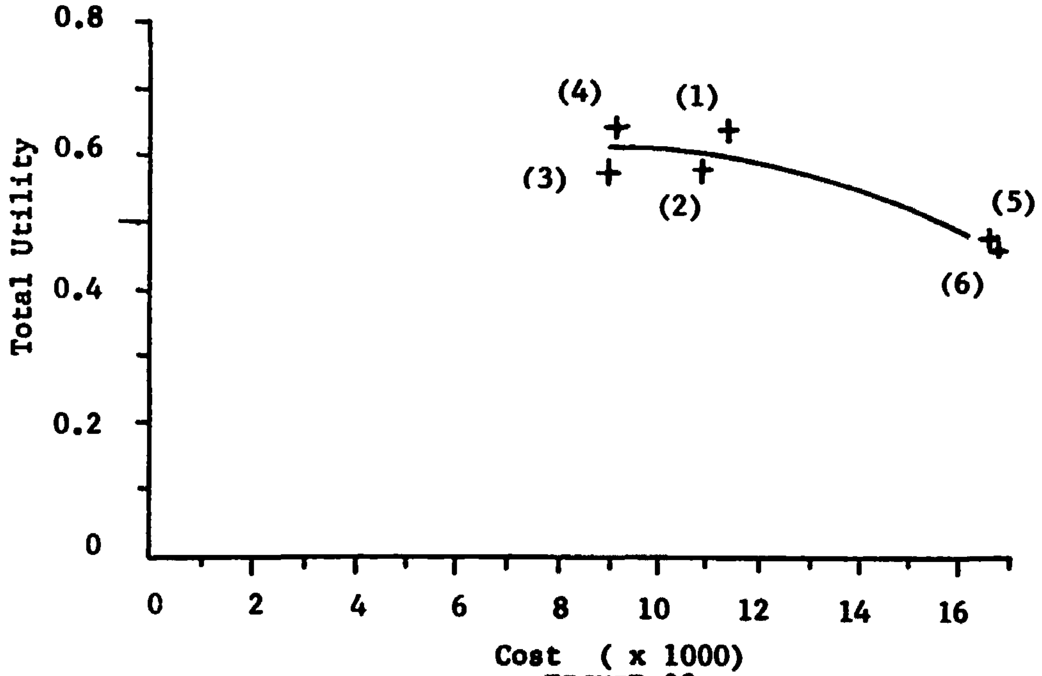


FIGURE 28

EXAMPLE OF COST EFFECTIVENESS

Inspection of Figure 28 indicates alternatives three and four possess the least cost and highest effectiveness. Beyond points three and four, effectiveness decreases linearly, with increased cost. This is logically explained since as cost increases, the weight of the equipment (which possesses a high weighting function, 0.54) increases; thereby negatively influencing effectiveness.

CHAPTER V

PRESENTATION OF FINDINGS

Data collection incident to the equipment being studied and field interviews with personnel involved in drilling operations, were executed over a ten month period (September, 1970 to July, 1971). The data

alternatives subsequently in this chapter. However, it is equally important to convey the findings derived from the numerous field interviews conducted during the course of this study and present an array of various drilling equipment design concepts that emerged.

Field Observations of Water Well Drilling Operations

As previously reported, water well drilling not only consists of drilling a hole in the ground, but also the matter of installing a production pump and well development. The U. S. Army's objective of lightweight equipment particularly influences drilling operations and the equipment's performance. The principal characteristics of a drilling rig affected by weight are the pulldown or axial thrust capability of the drill, the size and type of circulatory system, and the type of supporting material required to sustain the drilling operations.

Rock Penetration and Drill System Characteristics

The matter of axial thrust relative to penetration rates in hard rock has been previously discussed. The significance of penetrating hard rock was consistently discounted by drillers and associated groundwater personnel, in view of the shallow depth (150 feet). The longer mission-time associated with lower penetration rates in hard rock was also felt to be inconsequential by elements of the U. S. Army's Combat Development Command. Further, the axial thrust capability of the drill is maximized by the concept of drilling on the center of gravity of the rig (as in Big Indian Design) and/or providing a means to weight down the system with sand bags or physically anchoring the drill equipment to the ground. The latter is considered less attractive because of the problem of anchoring the equipment in highly variable and unpredictable soil conditions. When queried for a recommendation for the axial thrust needed for the Army's objectives, drillers most often indicated a range of 6000 to 10,000 pounds.

Power Transmission

Power transmission to the drill and circulatory systems has gradually evolved in favor of hydraulic operation as opposed to mechanical. The case for this favoritism was presented in Chapter II. Manufacturers employ either large capacity oil reservoirs or oil coolers to maintain the hydraulic oil at the appropriate temperature. The oil cooler significantly reduces the oil reservoir capacity required for the hydraulic systems with an overall weight savings. The pressure requirements for hydraulically powered systems varies from 2000 to 5000 pounds per square inch. The industry holds partiality for the lower extreme (2000 to 3000 p.s.i.) with all components operated at the same pressure. This provides for a uniform type and size of hydraulic fittings with all the components which will facilitate maintenance. The hydraulically powered systems are generally much lighter than equivalent mechanical components.

Circulatory System(s)

The physical weight of the circulatory equipment must be evaluated in terms of the flexibility it affords in drilling subsurface formations, the weight and complexity of materials associated with its operation. Water or mud circulation is preferred among personnel interviewed as a method to deal with the situation of hole caving. However, many prefer to use air for most drilling operations and maintain a mud pump with their equipment which is used only to cope with drilling caving formations when required. There is also a large number of drillers resorting to use of foam injection with air circulation which permits them to drill larger diameter holes with the same size drill pipe and their existing compressor. A good example of this flexibility is made by referring to Table 11, in Chapter III. Here it can be noted that a compressor of sufficient size to drill a four inch diameter hole with air, can also drill a six inch diameter hole with foam injection. Aftercoolers are also favored with the use of compressors for air circulation to reduce temperatures of the circulation hoses (a safety feature which prevents minor burns to operators), to improve efficiency of bit cooling, and to minimize thawing the sides of the drilled hole in perma-frost subsurfaces. Aftercoolers represent a minimal increase of weight of 50 to 100 pounds. Dry type air filters are also preferred with air compressors, as opposed to the oil type. Frequent cleaning of the dry type air filters was pointed out as the most significant element of compressor preventative maintenance. Air receivers or tanks to equalize the air flow hould be used with compressors that support the downhole percussion tool. However, Big Indian Drilling Company does not use an air receiver with conventional air circulatory drilling operations.

There are two alternatives in deference to using water or mud circulation to replace air in caving formations: driving and then drilling out the casing; or use of expendable drill pipe where the drill pipe becomes the casing upon completion of drilling. The former necessitates carrying a heavier than normal casing (10 lb./ft. versus 5.3 lb./ft. for 3 inch I.D. casing) and pipe driving equipment, whereas, the latter's effectiveness is questionable since it is not known whether the air pressure required to start up drilling circulation after additional drill pipe has been added to the drill string will be sufficient to regain circulation. Further, in using expendable drill pipe the matter of removing the drill bit at the bottom of the hole to allow insertion of the well screen must be considered. A removable bit for such circumstances is manufactured by one firm (26). Drill operators often blow the bit off with a dynamite charge. It should also be possible to configure a bit that could be easily removed in a manner similar to removing a core barrel with a wire-line as in soil sampling. Currently, driving the casing is preferred over the use of expendable drill pipe because of the technical limitations mentioned and considering that including such a capability will permit driving well points when necessary.

Well Development

Personnel in the well development equipment field were consistent in their recommendation of using a single slot sized screen (0.015 inches) and length (10 to 15 feet), regardless of the type of water bearing formation in which it is to be placed. An example of an exception to the use of a universal slot size is the contingency of encountering a water formation in proximity of beaches. In such a case, a 0.010 inch slot screen should be used. Plastic screens are preferred to steel wire wound screens because of the lightweight and resistence to corrosion, although they possess a disadvantage of less strength and ruggedness.

Overpumping the well, if equipped with a submersible pump, was regarded as adequate to develop the well. If a positive or force pump is to be used, developing the well by surging or application of compressed air was recommended (27).

Helicopter Transportability

Big Indian Drilling Company, which has extensive experience in deploying drilling equipment by helicopter for geophysical exploration (seismic), conveyed some valuable insight to various aspects of heliborne drill transport. Pilot error was pointed out as the single major cause of damage to the drilling equipment in transport. High carbon structural steel, as the principal structural members of the rig, is therefore preferred to structural aluminum for physical weight reduction of the equipment. The length of the sling, with which the equipment is attached and carried by the helicopter, should be kept to a minimum, to prevent the equipment from oscillating when suspended. Flying with sling loads in mountains, where updrafts can be severe, is a significant limitation in deployment of the Helidrill. Normal load levels per lift for a 60 nautical mile round trip, with one pilot and one crew member, is 3500 pounds with the Bell Helicopter, Model 204B. During a hot day (approximately 100 degrees F.), sea level, situation, the load level is reduced to 2500 pounds for the same mission profile. This compares to the Army's recommended load level (which was reported earlier) of 3450 pounds for a standard day and 2250 pounds for a hot day (95 degrees F.) at 2000 feet pressure altitude.

Analysis

Macroanalysis

Formulating the illustrated example in Chapter IV in context of the problem addressed by this study has also provided a basis for macro-screening of the alternatives to discern the feasibilities of subjecting them to closer scrutiny.

Gross screening of the alternatives will be directed toward evaluating the alternative hole sizes and drill pipe combinations and the circulatory alternatives (Ref. Figure 8). The total physical weights for various alternatives have been tabulated and are reported in Appendix 4. They were formulated from the weights reported in Chapter III and do not include the weight of water to support drilling operations where water injection is required. Justification for not including these weights in the analysis can be made by referring to Table 21. Here the weight of support materials, including and excluding drive pipe/or water, is reported for drilling a four inch diameter hole with 2 3/8 inch drill pipe (the lightest weight alternative). Obviously, if water is included in the transport weight of the system alternative, all circulations, except air, are unacceptable from the physical weight standpoint. This is a very important point to bear in mind throughout the analysis.

TABLE 21

COMPARATIVE PHYSICAL WEIGHTS OF SUPPORT MATERIALS

WITH AND WITHOUT DRIVE PIPE OR WATER*

DESCRIPTION	CIRCULATION					
	Air	Air Foam	Air Foam Gel	Water	Air w/ Downhole Hammer	Air-Foam with Downhole Hammer
Weight (lbs.) without drive pipe or water weight (lbs.)	1560	2065	2120	1830	1920	2175
Weight (lbs.) with drive pipe or water weight (lbs.)	2020	3775	3345	6230	12,380	12,635

*for a 4 inch hole and 2 3/8 inch drill pipe

A representative circulation of air was chosen to evaluate the feasibility of various hole and drill pipe size combinations. The physical weights for three hole sizes and air circulation for each drill system were plotted in Figure 29. The drill system number designations follow those reflected with the data on drills in Chapter III.

Note that <u>all</u> well construction systems sized for the 6 inch hole and 4 1/2 inch drill pipe alternative exceed the capacity of being lifted in two sorties by the current Model UH1 helicopter. Consequently, alternatives associated with this hole and drill pipe size will not be studied. The alternatives of drilling a 6 inch hole with 2 3/8 inch drill pipe will be included to relate the distinction of drilling three different sized holes.

Now the potential of the various circulations for closer study will be assessed. Again, air will be taken as the representative circulation, and the physical weights of five typical drill systems will be plotted for the six circulatory alternatives (see Figure 30).

Here it can be seen that <u>none</u> of the representative drills displayed can be carried on two lifts with the UH1 helicopter if they are equipped with the downhole percussion tool. Even if the weight constraint is relaxed to include two sling loads for a total transport weight of 6000 pounds, only one drill would be within the allowable weight margin. Therefore, alternatives with air and air-foam circulation with a downhole percussion tool will not be further scrutinized. Further, the significance of including a capability to improve penetration rates in hard rock was negated as reported in the section on field observations.

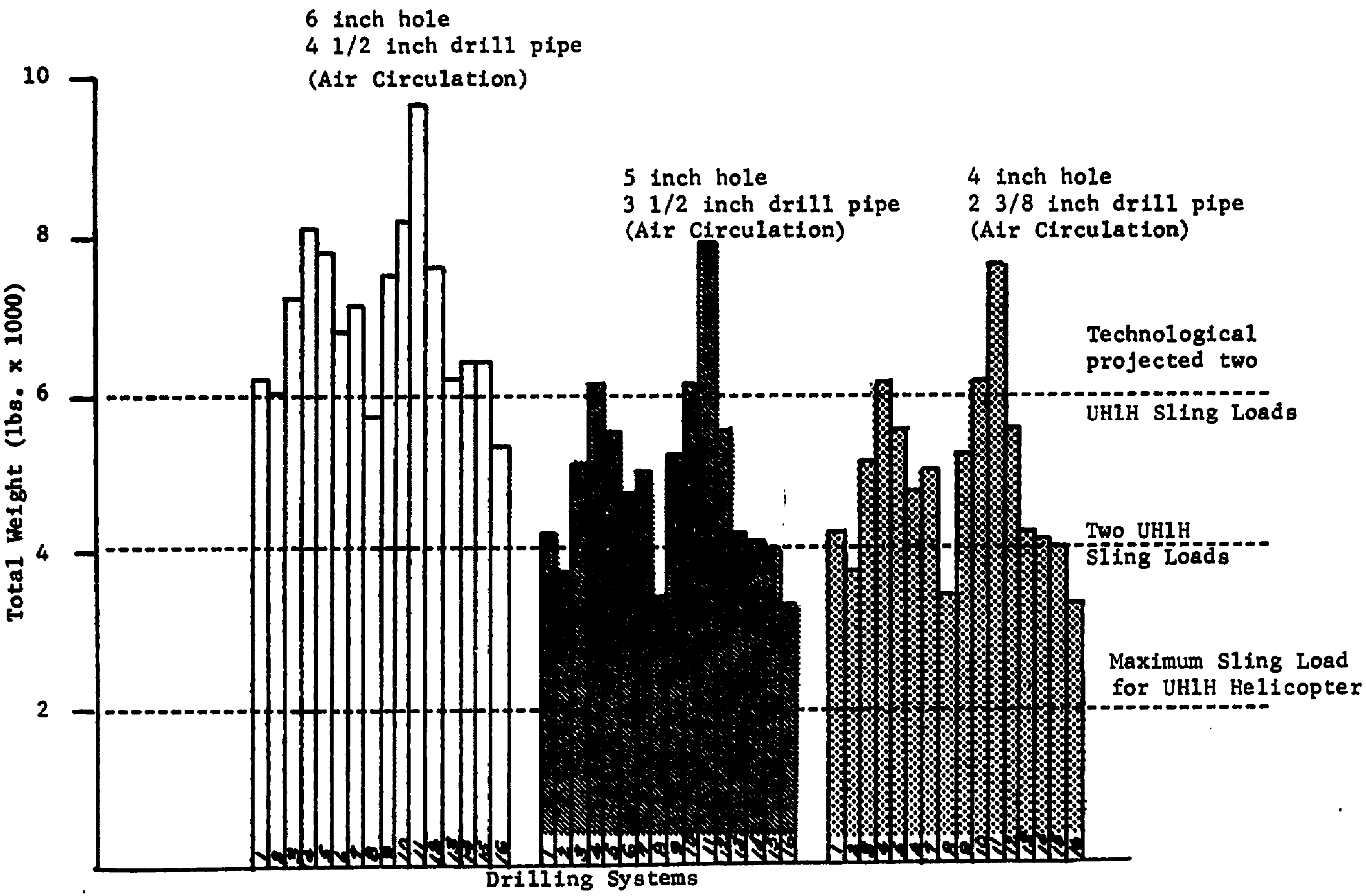


FIGURE 29: TOTAL WELL CONSTRUCTION SYSTEM'S WEIGHT RELATIONSHIP w/HOLE & DRILL PIPE SIZE

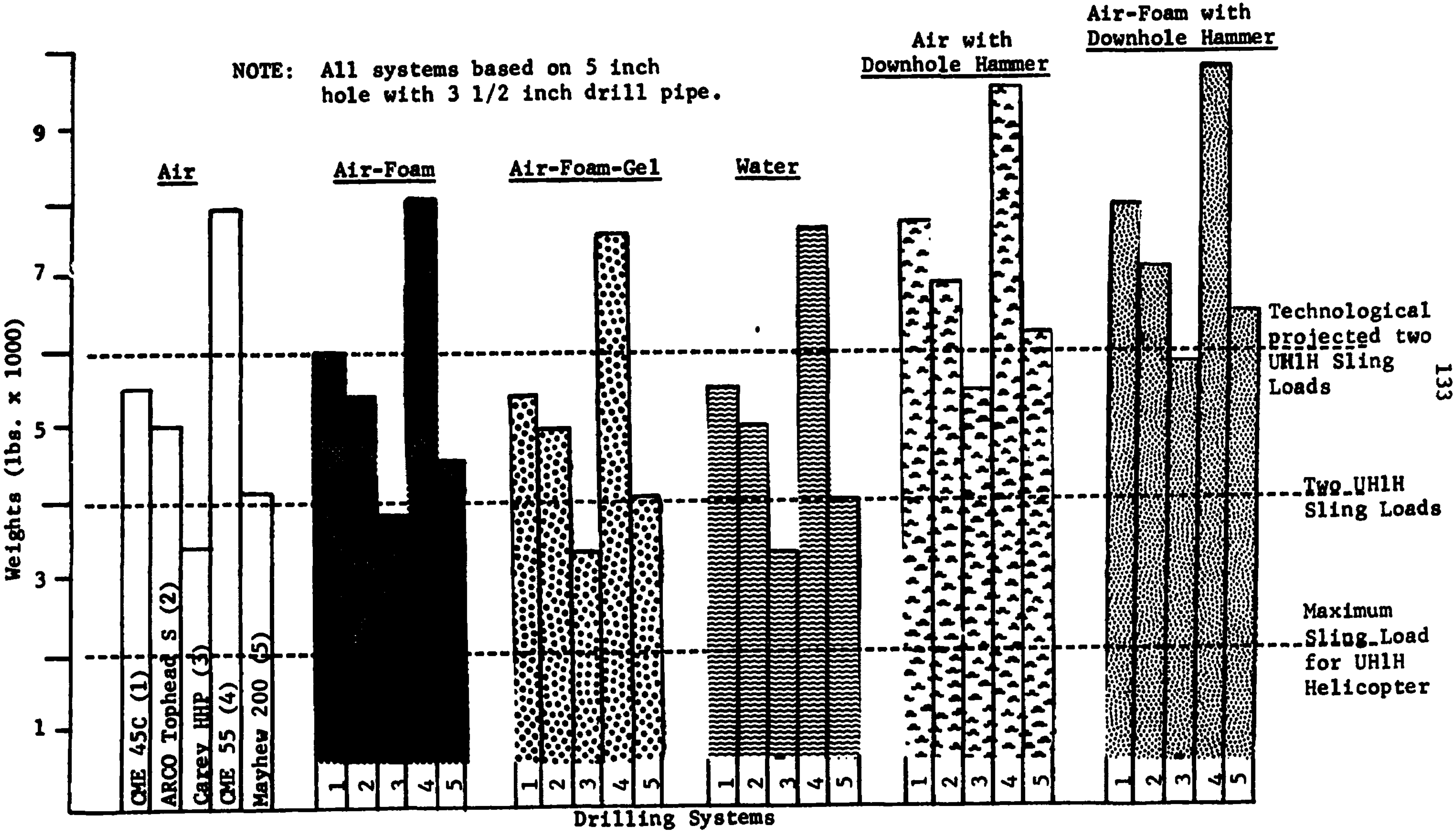


FIGURE 30
TOTAL WELL CONSTRUCTION SYSTEM'S WEIGHT RELATION TO MODE OF CIRCULATION

Microanalysis

The remaining alternatives after the gross screening process are summarized in Figure 31. This represents the decision alternatives that will be closely analyzed in the same manner as the illustrated example in Chapter IV.

The decision model was formulated using the identical scoring and weighting functions developed in Chapter IV. The model was computerized for rapid formulation of the total utilities. The flow diagram for the computer model and the computer program written in Fortran IV and programmed for execution on the IBM 1130 computer are displayed in Figures 32 and 33, respectively. The nomenclature associated with the variables is detailed below:

NWT-number of weighting functions (19 in this case).

NSYS-number of systems alternatives, or for each hole size the number of circulation modes, to be evaluated (i.e., four; air, air-foam, air-foam-gel, and water-mud).

SCORF-scoring function values for each alternative and criterion, of which there are nineteen.

WEIGF-weighting function for each criterion.

TU(I)-total utility for each circulatory and drill system alternative for a specific hole diameter and drill pipe size.

SW(I,J)-the product of scoring function of each alternative criterion times its weighting factor for each specific criterion.

CIRNM and SYSNM-simply designations to print out the names of the circulation, drill system, and hole and drill pipe size for each alternative.

The results of computing the total utilities for the alternatives delineated in Figure 31 and following the scoring functions and weighting functions detailed in Chapter IV are reported in Table 22.

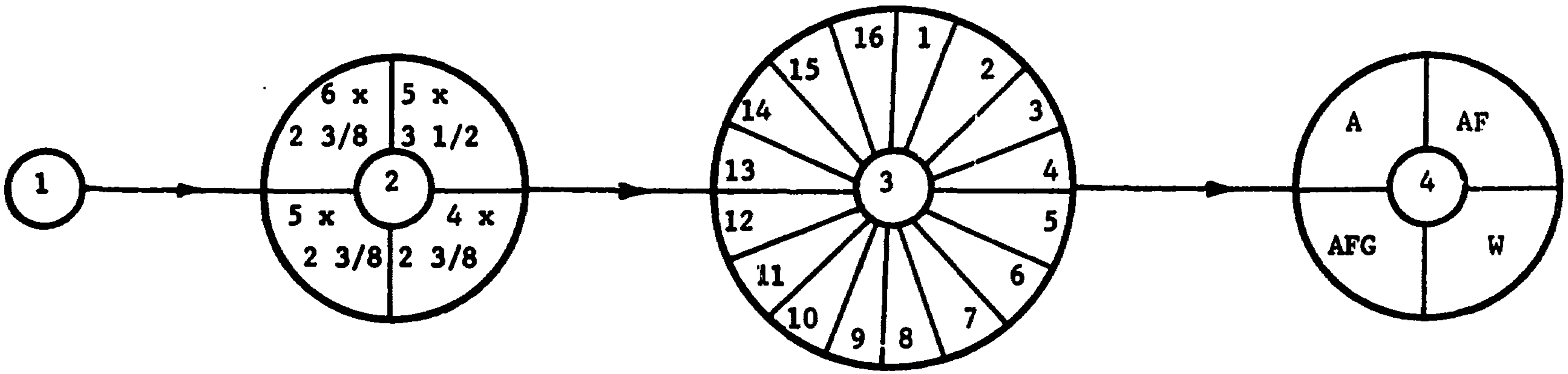


FIGURE 31

DECISION OPTIONS FOR SELECTED WELL CONSTRUCTION ALTERNATIVES

LEGEND: Node 1. Complete well construction system.
Node 2. Options for hole size (in.) X drill pipe size (in.).
Node 3. Alternative drill systems (see Table 9 for drill designations).
Node 4. Circulatory system alternatives: A is air; AF is air-foam; AFG is air-foam-gel; W is water.

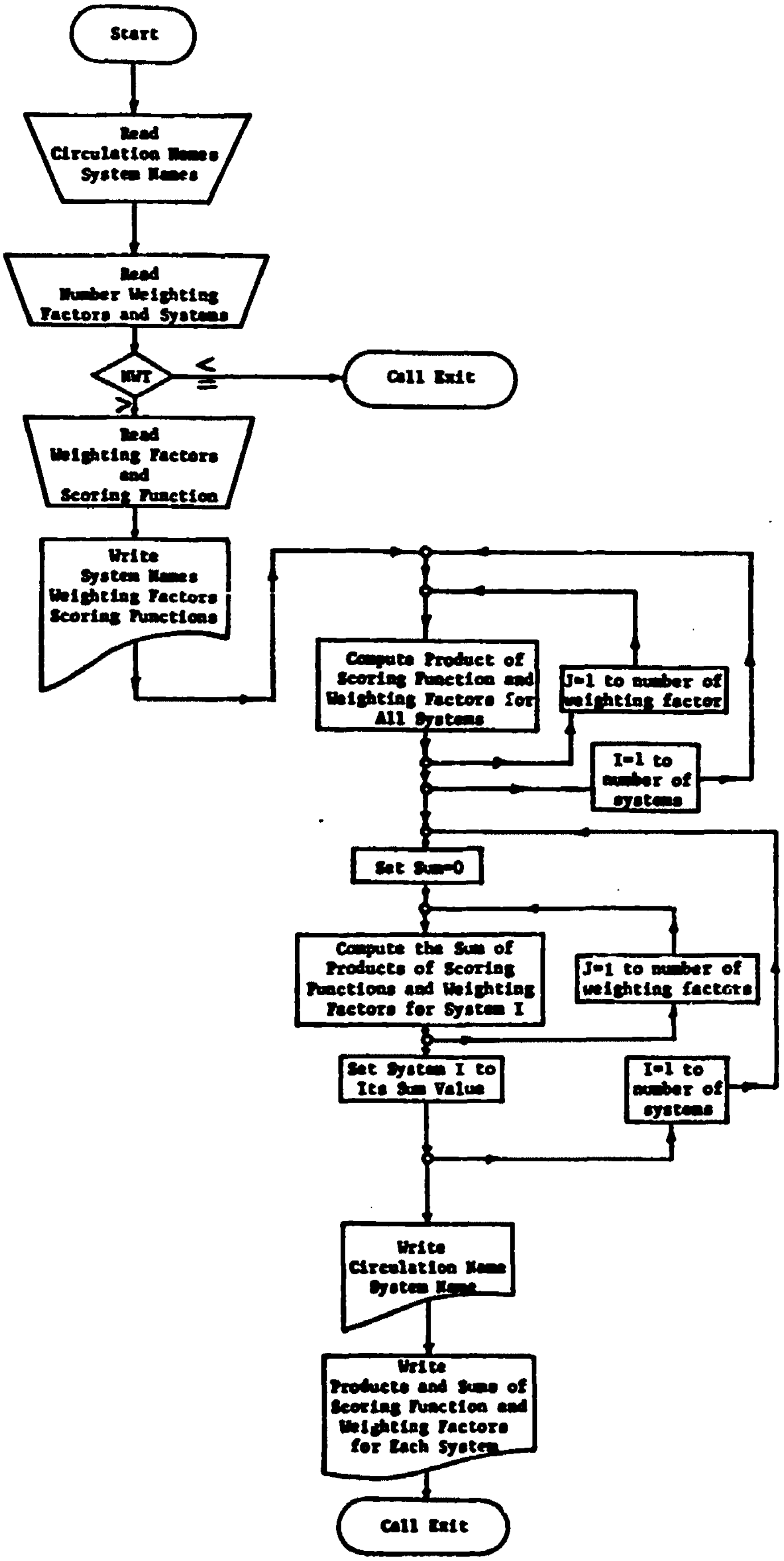


FIGURE 32: FLOW DIAGRAM FOR COMPUTER PROGRAM

FIGURE 33

COMPUTER PROGRAM FOR TOTAL UTILITY

COMPUTATION OF ALTERNATIVES

```
      DIMENSION SCORF(20,20),WEIGF(20),SW(20,20),TU(12),SYSNM(40),
     1CIRNM(10)
C              INPUT SECTION OF PROGRAM
C              READ IN SCORING FUNCTIONS AND WEIGHT FUNCTIONS
C        READ IN CIRCULATION NAMES, ONE PER CARD
      READ(2,1114)(CIRNM(I),I=1,4)
1114  FORMAT(A4)
1000  READ(2,1111)(SYSNM(I),I=1,40)
1111  FORMAT(40A1)
      READ(2,8) NWT,NSYS
8     FORMAT(2I2)
      IF (NWT)999,999,12
12    READ(2,10)(WEIGF(J),J=1,NWT)
10    FORMAT(20F4.0)
       DO 101  I=1,NSYS
      READ(2,10)(SCORF(I,J),J=1,NWT)
101   CONTINUE
C              OUTPUT DATA FOR VISUAL CHECK
      WRITE(5,112)
112   FORMAT(1H1)
      WRITE(5,1112)(SYSNM(I),I=1,40)
1112  FORMAT(//40X,40A1,///)
      WRITE(5,11)(WEIGF(J),J=1,NWT)
       DO 102 I=1,NSYS
      WRITE(5,11)(SCORF(I,J),J=1,NWT)
11    FORMAT(19F6.2/)
102   CONTINUE
C              END OF INPUT SECTION
C              COMPUTATION OF INDIVIDUAL UTILITIES
       DO 103 I=1,NSYS
       DO 103 J=1,NWT
       SW(I,J)= SCORF(I,J)*WEIGF(J)
103   CONTINUE
C              COMPUTE TOTAL UTILITY
       DO 104 I=1,NSYS
       SUMSW=0.0
       DO 104 J=1,NWT
105   SUMSW=SUMSW+SW(I,J)
       TU(I)= SUMSW
104   CONTINUE
C              END OF COMPUTATION LOOPS
C              OUTPUT STEPS
      WRITE(5,98)
       DO 107 I=1,NSYS
107   WRITE(5,814) I,CIRNM(I),(SW(I,J),J=1,9)
814   FORMAT(5X,I4,1X,A4,9F9.4/)
      WRITE(5,98)
       DO 106 I=1,NSYS
     WRITE(5,84) I,CIRNM(I),(SW(I,J),J=10,NWT),TU(I)
84    FORMAT(5X,I4,1X,A4,10F9.4,F6.2/)
106   CONTINUE
98    FORMAT(1H ////)
       GO TO 1000
999   CALL EXIT
     END
```

TABLE 22

TOTAL UTILITY (TU_j) FOR WELL CONSTRUCTION ALTERNATIVES

Hole-Drill Pipe Size and Circulation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
6"- 2 3/8"																
AIR	77.6	71.8	62.4	62.4	64.8	57.8	59.0	62.4	55.0	56.5	62.0	61.0	74.7	68.6	65.3	56.7
AIR-FOAM	72.0	62.2	69.8	56.8	59.2	65.2	66.4	56.8	62.4	50.9	56.4	55.4	69.1	63.0	59.7	51.1
AIR-FOAM-GEL	70.9	65.9	68.8	55.7	71.9	64.2	65.4	56.4	62.1	49.8	55.4	67.3	68.0	62.7	59.3	50.8
WATER-MUD	77.6	71.9	75.5	62.4	77.9	70.9	72.1	62.4	68.1	56.2	62.1	73.0	61.8	68.7	65.3	56.8
5"-3 1/2"																
AIR	77.6	71.8	75.4	62.4	77.8	70.8	72.0	62.4	68.0	69.5	62.0	74.0	74.7	68.6	65.3	56.7
AIR-FOAM	72.0	66.2	69.8	56.8	59.2	65.2	66.4	56.8	62.4	63.9	56.4	55.4	69.1	63.0	59.7	51.1
AIR-FOAM-GEL	70.9	65.9	68.8	55.7	71.9	64.2	65.4	56.4	62.1	62.8	55.4	67.3	68.0	62.7	59.3	50.8
WATER-MUD	77.6	71.9	75.5	62.4	77.9	70.9	72.1	62.4	68.1	69.5	62.1	74.0	74.8	68.7	65.3	56.8
5"-2 3/8"																
AIR	77.6	71.8	62.4	62.4	64.8	70.8	72.0	62.4	55.0	56.5	62.0	61.0	74.7	68.6	65.3	56.7
AIR-FOAM	72.0	66.2	69.8	56.8	72.2	65.2	66.4	56.8	62.4	50.9	56.4	68.4	69.1	63.0	59.7	51.1
AIR-FOAM-GEL	70.9	65.9	68.8	68.7	71.9	64.2	65.4	56.4	62.1	62.8	55.4	67.3	68.0	62.7	59.3	61.2
WATER-MUD	77.6	71.9	75.5	75.4	77.9	70.9	72.1	72.8	68.1	69.5	62.1	74.0	74.8	68.7	65.3	67.2
4"-2 3/8"																
AIR	76.7	70.9	74.5	61.5	76.9	69.9	71.1	61.5	67.1	55.6	61.1	73.1	73.8	67.7	64.4	55.8
AIR-FOAM	71.1	66.0	68.9	55.9	72.0	64.3	65.5	56.6	62.2	50.0	55.5	67.5	68.2	62.8	59.5	50.9
AIR-FOAM-GEL	70.2	65.0	67.9	54.8	71.0	63.3	64.5	55.5	61.2	48.9	54.5	66.4	67.1	61.8	58.4	49.9
WATER-MUD	77.4	71.7	75.3	75.2	77.7	70.7	71.9	72.6	67.9	69.3	61.9	73.8	74.6	68.5	65.1	67.0

The maximum total utility formulated was 77.9 for the Schramm drill with various circulatory and hole size alternatives. Since there is a large group of alternatives with at least 70% total utility, all systems with this value or greater total utility were segregated and are reported in Table 23 so that they may be more closely examined.

For each category of hole and drill pipe size, the mean values of total utility of each group reported in Table 23 are: 73.7 for the 6 inch-2 3/8 inch size; 73.9 for the 5 inch-3 1/2 inch size; 73.5 for the 5 inch-2 3/8 inch size; and 73.3 for the 4 inch-2 3/8 inch size. Further, since both the 5 inch hole diameter with 3 1/2 inch or 2 3/8 inch drill pipe contain the maximum total utility value for any of the drill systems, it appears that these are the optimum hole and drill pipe combinations.

The same observation can be made of the circulatory alternatives; i.e., air and water-mud circulation contain the greatest density of maximum total utility scores for the drill systems reported. Again, it is emphasized that the physical weight of water and drive pipe were not included in this analysis.

The alternatives have been narrowed to either of two hole and drill pipe sizes and a choice of two circulations. Now the impact of relaxing several criteria should be considered, specifically reliability, the mode of mast raising and means of equipment leveling. The former criterion has been qualified as highly subjective and the latter two are criteria that may easily be incorporated in a drill system design at relatively little cost, both monetarily or in terms of additional physical weight. Therefore, each of ten drills in the 70% total utility

TABLE 23

TOTAL UTILITIES GREATER THAN 70% FOR WELL CONSTRUCTION ALTERNATIVES

Hole-Drill Pipe Size and Circulation	1	2	3	4	5	6	7	8	12	13						
6"- 2 3/8"																
AIR	77.6	71.8								74.7						
AIR-FOAM	72.0															
AIR-FOAM-GEL	70.9				71.9											
WATER-MUD	77.6	71.9	75.5		77.9	70.9	72.1		73.0							
5"-3 1/2"																
AIR	77.6	71.8	75.4		77.8	70.8	72.0		74.0	74.7						
AIR-FOAM	72.0															
AIR-FOAM-GEL	70.9				71.9											
WATER-MUD	77.6	71.9	75.5		77.9	70.9	72.1		74.0	74.8						
5"-2 3/8"																
AIR	77.6	71.8				70.8	72.0			74.7						
AIR-FOAM	72.0				72.2											
AIR-FOAM-GEL	70.9				71.9											
WATER-MUD	77.6	71.9	75.5	75.4	77.9	70.9	72.1	72.8	74.0	74.8						
4"-2 3/8"																
AIR	76.7	70.9	74.5		76.9	69.9	71.1		73.1	73.8						
AIR-FOAM	71.1				72.0											
AIR-FOAM-GEL	70.2				71.0											
WATER-MUD	77.4	71.7	75.3	75.2	77.7	70.7	71.9	72.6	73.8	74.6						

range, for the 5 inch hole and either size drill pipe, and for both air and water-mud circulation will be given a maximum score for these criteria and the results examined. These alternatives will also be evaluated by reconfiguring the scoring function for physical equipment weight to allow for technological improvement in the helicopter's lift capability for two lifts as well as one lift as was done with initial physical weight scoring function presented in Figure 25, Chapter IV. The new scoring function is shown in Figure 34.

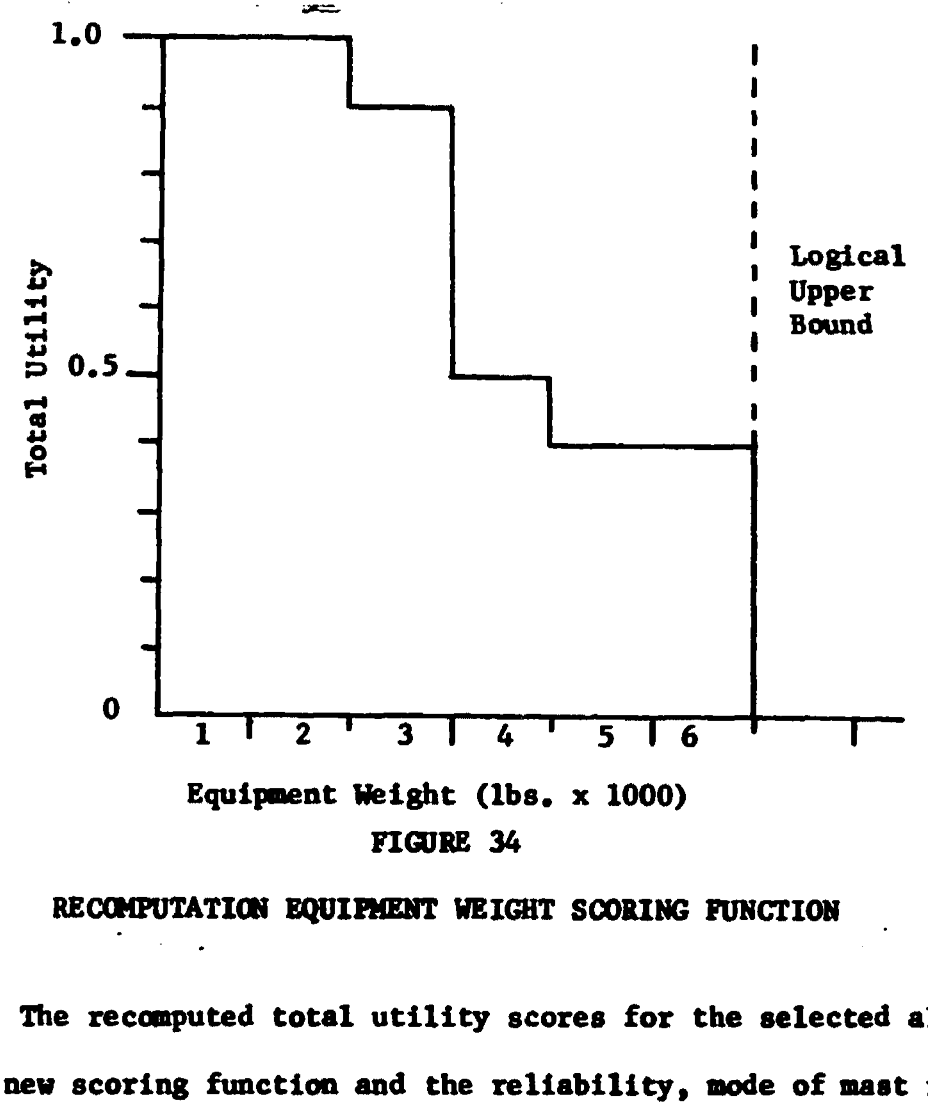


FIGURE 34

RECOMPUTATION EQUIPMENT WEIGHT SCORING FUNCTION

The recomputed total utility scores for the selected alternatives with a new scoring function and the reliability, mode of mast raising and means of leveling the equipment relaxed to their maximum weight values, are reported in Table 24. Those system alternatives which

TABLE 24

RECOMPUTED TOTAL UTILITY FOR SELECTED ALTERNATIVES

	1	2	3	4	5	6	7	8	12	13						
5"-3 1/2" AIR	75.0	76.2	74.7	64.2	75.2	71.1	71.2	66.7	75.1	76.4						
WATER-MUD	75.0	76.2	74.7	64.3	75.3	71.2	71.3	66.8	75.2	76.5						
5"-2 3/8" AIR	75.0	73.6	64.3	64.2	64.8	71.1	71.2	64.1	64.7	76.4						
WATER-MUD	77.6	76.2	74.7	74.7	75.3	71.2	71.3	66.8	75.2	76.5						

would not be considered as changing significantly in equipment weight criteria to accommodate the additional capability of mast raising and equipment leveling did not achieve a gain in total utility in this recomputation. However, those on the extreme of a physical weight range lost considerable utility by changing into a new physical weight range (i.e., Carey HHP, designation 8, 5 inch hole, 2 3/8 inch drill pipe with water-mud circulation changed from 72.8 to 66.8 in total utility).

The total utility indexes reported in Table 24 reflect the highest values for air circulation with the 5 inch hole and 3 1/2 inch drill pipe combination; whereas, the highest aggregate indexes for water-mud circulation are seen in the 5 inch hole and 2 3/8 inch drill pipe combination. Consequently, it seems warranted at this point to make some distinction between these alternative hole-drill pipe size combinations and circulations. Further, it is logical that this distinction take the form of evaluating the alternatives for the contingency of including the weight of water or drive pipe in the transportation weight. This, in effect, will discern which, if any, of the alternatives allow sufficient weight latitude to accommodate the necessity of including such materials if required at the drilling site.

The physical weight added to the system to include drive pipe materials will in essence be the same for the air circulatory mode with either drill pipe sizes and a 5 inch hole. Except with the 5 inch, 3 1/2 inch alternative, the drive pipe materials <u>must</u> include <u>2 3/8 inch drill pipe</u> to drill out the materials inside the driven casing <u>as a substitute</u> for 3 1/2 inch drill pipe that normally accompanies the rig. As a

TABLE 25

COMPARABLE PHYSICAL WEIGHTS OF SUPPORT MATERIAL WITH AND WITHOUT

DRIVE PIPE OR WATER FOR A 5 INCH HOLE

	AIR	WATER-MUD
Weight (lbs.) without drive pipe or water weight	1535	1805
Weight (lbs.) with drive pipe or water weight	2900	6205
Total increase in weight for drive pipe or water	1365	4400

result, the additional weight incurred for the 5 inch hole and either drill pipe combination will be the same. Further, the drive pipe may be used as the drill pipe in conventional drilling operations where unstable formations present no problem. The key distinction lies in sizing the entire system around the 3 1/2 inch drill pipe alternative which was configured for delivery of the optimum quantity of air at the least power requirements. This is verified by reviewing the equipment weights of the selected alternatives (i.e., drill systems 1,2,3,4,5,6,7,8,12 and 13) in Appendix 4. Here it is seen that the alternatives for a 5 inch hole, 2 3/8 inch drill pipe are 900-1000 pounds heavier than those with the same hole size and 3 1/2 inch drill pipe.

The physical weight incurred by the necessity of transporting water with water-mud circulation will also be the same for the 5 inch hole and either drill pipe alternative (see Table 14). Also, the equipment configurations for either drill pipe size reflect an insignificant weight differential (approximately 350 lbs.) as opposed to the physical weight of water to be transported (4400 lbs.).

Therefore, the remainder of the analysis will be directed toward discrimination of air and water-mud circulation for the 5 inch hole, 3 1/2 inch drill pipe alternative. The additional weight incident to including the drive pipe or water with this alternative is summarized in Table 25.

Obviously, an alternative that may have to assimulate an addition of 1365 pounds for drive pipe materials, and only in certain drilling conditions, is much more attractive than having to lift an additional 4400 pounds when water is not available at the drill site. The equipment weights and costs of the ten selected drills will now be arrayed for air circulation and the 5 inch hole, 3 1/2 inch drill pipe size to discern which of the alternatives is capable of assimulating the additional weight for drive pipe materials (1365 pounds) and remain under the total weight of 6000 pounds. These costs and weights are reported in Table 26.

There are only four alternatives reported in Table 26 that do not exceed a maximum weight of 6000 pounds, namely the Big Indian 300, Cyclone Drillette, Carey HHP and the Longyear Design. The cost effectiveness of these systems can be assessed by plotting their associated recomputed total utility scores against their cost. This graph is reported in Figure 35.

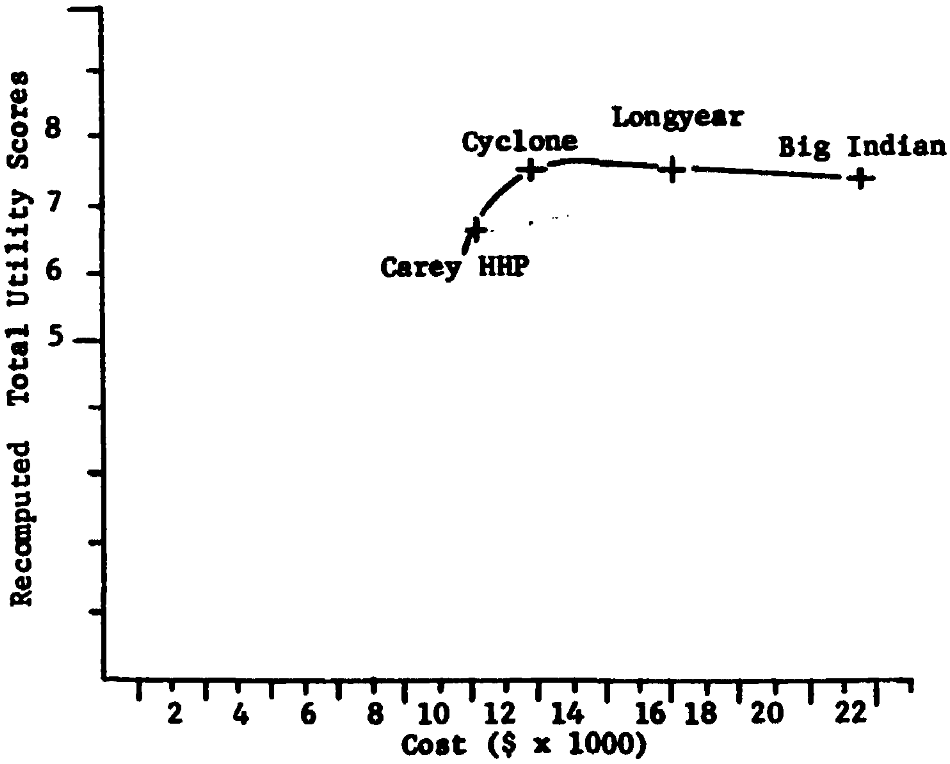


FIGURE 35

COST EFFECTIVENESS OF SELECTED ALTERNATIVES

TABLE 26

EQUIPMENT WEIGHT AND COST FOR SELECTED ALTERNATIVES

INCLUDING DRIVE PIPE MATERIALS

NO.	DRILL SYSTEM* ALTERNATIVE	WEIGHT WITHOUT DRIVE PIPE MATERIALS (lbs.)	WEIGHT WITH DRIVE PIPE MATERIALS (lbs.)	COST** ($)
1.	Big Indian, 300	4160	5525	22,745
2.	Cyclone Drillette	3660	5025	13,030
3.	WABCO FA100	5110	6475	13,130
4.	Mobile B30S	6080	7445	11,750
5.	SCHRAMM	5480	6845	15,500
6.	Carey HLT4	4685	6050	13,025
7.	ARCO Tophead S	4990	6355	12,330
8.	Carey HHP	3360	4725	11,150
12.	CME 45C	5490	6855	12,250
14.	Longyear Design	4155	5520	17,128

*All for Air Circulation, 5 inch Hole, 3 1/2 inch Drill Pipe
**Costs do not include drive pipe materials

The curve has two distinct ranges, one below and one of above the Cyclone Drillette alternative. The lesser slope above the Cyclone Drillette reflects negligible gain in efficiency (i.e., total utility) with increased cost. However, one should be wary of the cost associated with this graph. Longyear and Big Indian costs are probably more accurate since they essentially include costs from drawing board to construction of the prototype. Whereas, the other two alternatives' cost was assessed by aggregating costs of the various equipment components. Further, if the Big Indian Model 300 is to be considered for production in the U. S. A., the patent rights costs must be included. (These costs are quoted by the company: for use in one country-Cdn. $25,000; worldwide rights-Cdn. $75,000.) For these reasons the significance of the cost-effectiveness relationships is mitigated as reported in Figure 35. The cost-effectiveness aspect can assume a principal role when actual bids are solicited to construct the prototype. Then, rather than accept the lowest bid and <u>assume</u> it's the best, the total utility versus cost relations can be used to assess which system truly possesses the most favorable total utility/cost ratio.

CHAPTER VI

DISCUSSION AND CONCLUSIONS

Discussion

The transition in evaluating the total utility of the alternatives based on the physical weight of the equipment without the weight of drive pipe or water and then including these materials requires elaboration. All of the alternatives were initially analyzed unencumbered by the additional weight of drive pipe or water to insure that no reasonable alternative was overlooked in the analysis. When the resulting total utilities were tabulated, it was obvious, because of large numbers of cogent alternatives remaining, that some distinction between the matter of including the weight of drive pipe or water was clearly warranted. Further, since the design features of equipment leveling and mast raising by either mechanical or hydraulic means can be easily incorporated in the overall system design, these performance criteria were relaxed. This resulted in improving the total utility for both the Longyear Design and the Cyclone Drillette alternative. Whereas, the Big Indian Design (Model 300) was not influenced. The Carey HHP alternative was negatively affected, since the addition of these capabilities incurred lesser gain in total utility than was necessary to compensate for the total utility lost as a result of anticipating an increase in the physical weight for this alternative.

It should also be noted that the use of the air circulatory mode possessed equivalent utility as water circulation in the total utilities reported for all system alternatives. Since it is impossible to predict the probability of the availability of water at a randomly selected drill site it was not feasible to include a probability factor with the water circulation alternative. However, the necessity of limiting all drilling sites to only those that possess a water source to support drilling operations must be regarded as highly unpalatable. The only recourse in such a situation is to air lift the water to support the drilling operations, which was shown to be impractical.

Selecting the optimum hole diameter, drill pipe size combination is not only associated with the inherent physical weight of an equipment alternative, but also the flexibility afforded in the anticipated well yield and in drilling larger diameter holes when desired. Clearly, the hole diameter, drill pipe size combinations of 5 inch-3 1/2 inch and 5 inch-2 3/8 inch demonstrated the most favorable total utilities for nearly all the equipment alternatives. Those alternatives related to the 5 inch diameter hole and 3 1/2 inch drill pipe possess the more attractive physical weights which will allow sufficient latitude to include drive pipe, include a provision to use the drill pipe as casing if feasible, or using conventional lightweight plastic casing.

Without relaxing the parameters, the Big Indian Design had the highest utility. This is to be expected since this drill system is configured to include almost the exact qualities desired by the U. S. Army. However, by relaxing performance factors which could be incorporated in a prototype design (See Table 24), both the Cyclone Drillette and Longyear Design exhibit competitive total utilities. Big Indian Company's physical location in Canada presents possible procurement difficulties. And, to reiterate, the cost effectiveness of these alternatives is of limited value since the design-to-production costs are not uniform for each alternative. This leads to another disadvantage of the Big Indian design; the necessity of purchasing patent rights. However, for planning purposes, the cost of the drilling rig, for design-to-production of the prototype drill, appears to be in the range quoted by the Longyear and Big Indian designs; approximately $18,000. This only includes the cost of the drill system and not the other well construction elements.

It is doubtful that any kind of subjective process could have equalled the thoroughness of the methodology used to assess the complex alternatives incident to this study. Certainly none come to mind that allow quantification of such a complicated criterion as simplicity of operation which is frequently only given lip service.

In using the methodology, one must be cautioned in the complete delineation of the criteria and each criterion's thorough decomposition. In addition, the mode of soliciting informed opinion as to the scoring and weighting functions is critical to the validity of the model. Initially, the writer formulated a decomposed set of 9 subcriteria and then solicited informed opinion as to the scoring and weighting functions for each. These criteria proved to be too broad in definition and necessitated a much more finite disaggregation, ultimately to a set of 19 subcriteria. Further, selection of weights and scores singularly by individuals, and then aggregation of these individuals to arbitrate inconsistencies proved to be the most fruitful in formulating the overall criteria listing, scoring and weighting functions. Fundamentally, one must be sure that the opinions solicited are truly those from informed persons.

Further, the validity of testing the algorism is somewhat nullified in evaluating a large number of alternatives such as those in this study. It is just not logical to take such large numbers of alternatives and perceive any clear rank-order listing to compare the results with the calculated total utilities. Consequently, one must exercise a great deal of caution in the assessment of the criteria to insure consistency.

Conclusions

Method of Analysis

The model applied in this study provided a realistic mechanism to structure the decision alternatives available, then evaluate these alternatives in a manner that reflected not just a few perceived distinctions between the equipment alternatives, but an entire spectrum of desired characteristics that could not have been aggregated in the mind of the decision maker to select a final alternative. Further, the methodology's potential goes much beyond the application reported here. The model can easily be extended to any other comparisons of commercial equipment, or for that matter, existing military equipment to reflect the distinctions in their performance. Most importantly, the model provides a means to actually allow judgement on simplicity of operation to be qualified and contribute measurable worth to an equipment alternative.

Finally, it should be emphasized that the model was formulated and applied to selection of drilling equipment based solely on the U. S. Army objectives. Drilling equipment is specifically designed for a particular drilling operation (e.g., augering or coring) and, therefore, has designed characteristics to operate effectively in its specific application. Consequently, the presence or absence of a specific manufacturer's equipment in the final alternative should not be construed to be either an endorsement for or negation of any of the equipment incident to this study.

Equipment Design

The optimum design considerations for the U. S. Army objectives to drill water wells in remote tactical areas should encompass the alternatives described below.

Hole Diameter and Drill Pipe Size

5 inch hole, 3 1/2 inch drill pipe is the optimum.

Circulation Mode

Principally the optimum is air with drive pipe; a mud pump (centrifugal) should be included with the prototype equipment design to validate the projections made incident to simplicity of operation inherent in this study. The air compressor should be equipped by dry-type filters and an aftercooler. No air receiver is required. A positive displacement air compressor should be specified with a free air capacity of 210 c.f.m. at 30 p.s.i. continuous pressure at a speed of 1750 r.p.m.

Mode of Power Transmission

All components should be configured for hydraulic operation and control. An oil-cooler should be included in the specifications.

Hydraulic pressures should be specified at a single uniform value in the range of 2000 to 3000 p.s.i.

Drill System

The drill system should encompass the tophead drive, rack and pinon up and down feed inherent to the Cyclone Drillette. A base section should be specifically designed to support the drill system, circulation equipment and power unit; provide for three point hydraulic cylinder leveling; and the drill positioned such that it will drill on the center of gravity of the base. Torque and pulldown ratings for the drill should conform with those inherent to the Cyclone Drillette. The drill should be equipped to raise and lower the mast with a hydraulic cylinder. Structural materials for the entire drill system should be specified as high tensile carbon steel.

Supporting Materials

The support materials should conform with those specified for a 5 inch diameter hole, 3 1/2 inch drill pipe, in Table 14.

Power Unit

A water cooled, gasoline driven power unit should be specified of sufficient capacity to support both the drill and circulatory systems concurrently.

Prototype Testing

The testing program for the prototype should provide for vindication of the procedures outlined below.

Expendable Drill Pipe

Assess the feasibility of employing the drill pipe as the casing after completing drilling operations. To include the manner of removing the bit and installing a well screen; and regaining air circulation in loose or caving formations.

Simplicity of Operation

Distinguish between complexity of operation of air or water-mud circulation; discern the advantages and disadvantages associated with hydraulically controlled rotation speed; appraise the limitations associated with utilizing drive pipe in caving formations.

Penetration Rates

The prototype should be tested on rock formations of variable degrees of hardness to evaluate the limitations as to the formations which the system will efficiently penetrate. Associated with the matter of penetration rates is the appraisal of the most efficient manner of anchoring the system to achieve its optimum axial thrust. This involves determining the effectiveness of sand bags to weight the system or use of ground anchors. The limitations of the equipment in drilling caving formations as related to the use of expendable drill pipe or driven casings, as mentioned above, must also be correlated with the characteristics of the drill and its performance.

REFERENCES

1. Anonymous, U. S. Army Water Supply Equipment, U. S. Army Engineer Research and Development Laboratories, December, 1966, Fort Belvoir, Virginia.

2. Michael, E. D., "Problems of Military Water Supply in the Republic of Vietnam", Military Assistance Command Science Advisor Report, August, 1970, U. S. Military Assistance Command Vietnam, APO San Francisco, California 96222.

3. Michael, E. D., "Ground Water Resources and Military Well Construction in the Republic of Vietnam", Military Assistance Command Vietnam, APO San Francisco, California 96222.

4. Anonymous, Water Encyclopedia, Water Information Center, Inc., 1968, Port Washington, New York.

5. Anonymous, "Mechanical Drilling Methods for Groundwater Utilization", U. S. Army Mobility Equipment Research and Development Command, April, 1970, Fort Belvoir, Virginia.

6. Anonymous, Life Cycle Management Model for Army Systems, Department of the Army Pamphlet No. 11-25, October, 1968, Headquarters, Department of the Army, Washington, D. C.

7. Rudavsky, A. B., Ground Water Utilization: Study of Methods with Engineering Analysis, U. S. Army Mobility Equipment Research and Development Command, April, 1970, Fort Belvoir, Virginia.

8. Williams, T. N., et al, Scientific and Technical Applications Forecast-1964-Excavation, Office of Chief of Research and Development, 1964, Headquarters, Department of the Army, Washington, D. C.

9. Anonymous, Well Drilling Operations, Department of the Army Technical Manual 5-297, September, 1965, Headquarters, Department of the Army, Washington, D. C.

10. Micro-Grapix Editors, Master Library of Water Well Equipment and Maintenance Data, The National Water Well Association, 1971, Columbus, Ohio.

11. Anonymous, General Water Catalog for Submergible Pumps, Reda Pump Division of TRW, Inc., Bartlesville, Oklahoma.

12. Todd, David K., Ground Water Hydrology, John Wiley and Sons, 1963, New York, New York.

13. Paone, James, et al, Rock Drillability for Military Applications, U. S. Department of the Interior, Bureau of Mines, April, 1968, Minneapolis, Minnesota.

14. White, C. G., "A Rock Drillability Index", Quarterly of the Colorado School of Mines, Vol. 64, No. 2, April, 1969, Golden, Colorado.

15. Miller, J. R., Professional Decision Making, Praeger Publishers, 1970, New York, New York.

16. Riel, R. H., "Reliability, Maintainability, Human Factors and Safety Requirements in QMR's and SDR's", U. S. Army Combat Development Command Maintenance Agency, August, 1968, Aberdeen Proving Grounds, Maryland.

17. Anonymous, "Detail Specifications for UH1H for FY69 Procurement", Bell Helicopter Report 205947080, November 16, 1967, Headquarters, Army Aviation Systems Command, Saint Louis, Missouri.

18. Anonymous, Operator's Manual for UH1H Helicopter, Department of the Army Technical Manual 55-1520-210-10, May, 1969, Headquarters, Department of the Army, Washington, D. C.

19. Brantly, J. E., Rotary Drilling Handbook, Palmer Publications, 1961, New York, New York.

20. Anonymous, "Bulletin RF-69(4-69)5M, Rotofoam", Schramm, Inc., 1969, West Chester, Pennsylvania.

21. Anonymous, Well Drilling Manual, Koehring Speedstar Division, undated, Enid, Oklahoma.

22. Gray, G. R., "Mud Know-how Helps Exploration Drilling", Mining in Canada, May and June, 1970, Calgary, Canada.

23. Anonymous, "Revert Cuts Costs and Makes Better Wells", UOP Johnson Drillers Journal, September-October, 1965, Saint Paul, Minnesota.

24. Drobny, N. L., et al, "Cost Effectiveness Analysis of Waste Management Systems", Journal of Environmental Systems, Vol. 1(2), June, 1971, Baywood Publishing Company, Farmingdale, New York.

25. Eckenrode, R. T., "Weighing Multiple Criteria", Journal of Management Science, Vol. 12, No. 3, November, 1965.

26. Anonymous, "Aardvark for Horizonal Drilling and Installation of Horizonal Drains", Technical Bulletin of Soil Sampling Service, Inc., undated, Puyallup, Washington.

27. Anonymous, "The Principles and Practical Methods of Developing Water Wells", Bulletin Number 1033, June, 1968, UOP Johnson Division, Saint Paul, Minnesota.

APPENDIX

APPENDIX 1

GLOSSARY OF TERMS

AQUIFER- Water bearing subsurface formation.

ANNULAR VELOCITY-Upward velocity of the circulatory media in the annulus.

ANNULUS-Area between the sides of the drilled hole and the drill pipe.

BIT-Tool at the end of the drill string which performs the cutting or drilling at the bottom of the hole.

BUCKET AUGER-A drill method which forces an auger into the ground and is then raised to the surface to be cleaned when filled with hole cuttings.

CABLE-TOOL OR PERCUSSIVE DRILLING-Drilling is carried out by alternately raising and dropping a heavy string of drilling tools in the bored hole.

CASING-Circular pipe used during drilling operations to prevent the hole from caving, prevent intrusion of undesirable water into the well, and prevent surface water contamination of the acquifer.

CIRCULATION SYSTEM-All rigs are equipped with an air compressor or mud pump, or both. The circulatory media is passed through transmission lines and drill pipe to the bottom of the hole from which it carries cuttings to the surface.

CORE DRILLING-A drilling method used principally to obtain rock or earth samples in subsurface exploration.

DOWNHOLE DRILLING-A drilling technique where the power source that supports the drilling operation is placed just above the bit.

DRAW WORKS-Power driven winch(es), normally equipped with a clutch and brake, for hoisting and lowering a drill string.

DRILL STEM OR STRING-A group of components; including subs, adaptors, drill pipe, drill collar and bit, which are joined together to form a drill string for drilling a hole.

DROP PIPE-Pipe suspended within the casing, which is connected to a plunger pump cylinder or submersible pump located at the bottom of a well. The drop pipe serves to hold the pump assembly in place and acts as the discharge line from the pump.

HOISTING EQUIPMENT-Normally a draw works with cable or the pulldown device used in reverse.

HOLLOW SPIRAL AUGERING-A continuous spiral auger with a hollow center shaft, used to bore into subsurface formations. The cuttings are conveyed to the surface following the spiral.

KELLY-Formed or machined section of hollow drill steel connected directly to the water swivel at the top and to the drill pipe at the bottom. Flats or spines of the kelly engage with the rotary table so that rotation is imparted to the kelly, transmitted to the drill pipe and bit.

MAST-Framework used to support wire-line sheaves, tophead drives, pull-down chains and hoisting lines. Also referred to as derrick or tower.

MULTIPURPOSE RIG-Drilling rig that can employ two or more drilling processes (e.g., rotary, augering).

NOVEL DRILLING TECHNIQUES-Methods inherent to this report which drill the subsurface formations with non-solid tool bits or solid bits which are not rigidly connected to a surface power unit.

PACKER CYLINDER-Positive displacement pump cylinder that fits closely against the sides of the casing which eliminates the necessity of a drop pipe inside the casing to convey the water to the surface.

PRODUCTION PUMPS-Pumps employed after completion of drilling operations to bring the water to the surface.

PULLDOWN EQUIPMENT-The mechanism used to apply axial thrust to the bit or provide hoisting power.

RIG-A drilling machine complete with all accessory equipment.

REVERSE CIRCULATION DRILLING-Rotary drilling where flow of drilling fluid is reversed as compared with conventional rotary methods (i.e., drilling fluid forced down the annulus and returns to the surface through the drill pipe).

ROTARY RIGS-Equipment that carries out drilling operations with two energy types; rotation and pressure to the drilling bit against the formation.

ROTATIONAL TORQUE-Torque is the effectiveness of a force to produce rotation from the line of action of the force to the center about which rotation occurs.

SUB-A short section of hollow shafting (normally pipe) used to connect one type of thread or connector to another.

SUBMERSIBLE PUMP-A well production pump which is placed inside the well and below the well's static water level, as opposed to placing the power unit at the ground surface above the well.

TURBO DRILL-Drilling equipment which places the prime mover (a multi-stage turbine) directly over the bit at the bottom of the hole to impart rotation.

WATER SWIVEL-A device which allows passing the circulatory fluid (air or water) from a stationary hose to a rotating kelly or drill pipe.

WELL DEVELOPMENT-Methods to improve the well's production after drilling is completed.

WELL SCREEN-An intake structure at the bottom of the well casing which prevents sand from entering the well with the water from the acquifer.

APPENDIX 2

DATA SHEET

No.__________

MFG____________________,Model____________________ Date______________

1. Overall Drill System: Hole Size______________

Weight (#)	Cost ($)	Depth Capability (ft.)	Overall Operating Height (feet)

2. Drill Head:

Depth Capability (ft.)	Cost ($)	Weight (#)	System Hyd.	Mech.	Pneu.

   a. Drill pipe; size_________, material_________, weight/ft._______

   b. Mast and Winch; height__________, lift capacity (#)____________

   c. Pulldown system; hydraulic______, mechanical______, or pneumatic_________

   d. Bits; types____________________, weight______________________

   e. Capable of Mix?

3. Prime Mover:

Capable of mix (yes/no)	Weight(#)	Cost($)	Dower(HP)	Fuel	Cooling

4. Circulatory System: a. Compressor

Capable of Mix (yes/no)	Weight(#)	Cost($)	STD Operating Pres(psi)	Vol(cfm)	Material for Support #Water	#Oil

b. Mud Pump

Capable of Mix (yes/no)	Weight(#)	Cost($)	Type & Rating (gpm)	Material for Support #Water #Additive	Supporting Power (HP) Required

c. Air and Mud capability?

Supporting Power Required (HP)

5. Auxiliary Equipment: a. Down Hole Capability

Capable of Mix (yes/no)	Weight(#)	Cost($)	Power (HP) Required for Support	Operating Pres(psi)	Vol (cfm)

b. Sand Bailer;

c. Hydraulic Motor;

d. Type Power Transfer;

APPENDIX 3

ORGANIZATIONS AND PERSONNEL CONTACTED

FIRM	FIRM REPRESENTATIVE
Ground Water Consultants	
1. Groundwater Associates Norman, Oklahoma	Mr. Tim Holden
2. Engineering Enterprises, Inc. Norman, Oklahoma	Mr. John Marsh
3. Hydro Research Science Sunnyvale, California	Dr. A. B. Rudavsky
U. S. Government Agencies	
1. Department of the Army, Mobility Equipment Command Maintenance and Reliability Branch, St. Louis, Missouri	Mr. Charles Patterson
2. Department of the Army, Combat Development Command, Engineer Agency, Fort Belvoir, Virginia	Mr. C. S. Grazier Maj. M. S. Higgins
3. Department of the Army, Artillery Test and Evaluation Command, Fort Sill, Oklahoma	
4. U. S. Geological Survey (USGS), Groundwater Branch, Oklahoma City, Oklahoma	Mr. J. H. Irwin
5. USGS, Groundwater Branch, Denver, Colorado	Mr. Gene Schuter
6. USGS, Groundwater Branch, Albuquerque, New Mexico	Mr. F. C. Koopman
7. HQ, U. S. Army Aviation Systems Command, St. Louis, Missouri	Mr. Fred Kurshaw
Water Well Drillers	
1. Ray Meyer Drilling Company Norman, Oklahoma	Mr. Ray Meyer

FIRM	FIRM REPRESENTATIVE
2. Poindexter Drilling Company Oklahoma City, Oklahoma	Mr. Poindexter
3. Erkenbrock Drilling Company Anadarko, Oklahoma	Mr. Glen Erkenbrock
4. Lee Murphy Drilling Company Midland, Texas	Mr. Lee Murphy
5. Puckitt Drilling and Supply Company San Angelo, Texas	Mr. Puckitt

Drill Equipment Manufacturers

1. Jess and Lowell Well Casing Co. Oklahoma City, Oklahoma (plastic casing manufacturer)	Mr. Poindexter
2. Gardner-Denver Company Dallas, Texas (drill equipment manufacturer)	Mr. Don Hill
3. WABCO, Drilling Equipment Div. Enid, Oklahoma (drill equipment manufacturer)	Mr. Bill Ball
4. Walker-Neer Company Wichita Falls, Texas (drill equipment manufacturer)	Mr. Dave Campbell
5. Koehring Speedstar Division Enid, Oklahoma (drill equipment manufacturer)	Mr. Jack Allen
6. Acker Drill Company Scranton, Pennsylvania (drill equipment manufacturer)	Mr. F. W. Davenhall
7. Spraque and Henwood, Inc. Scranton, Pennsylvania (drill equipment manufacturer)	Mr. Bob Davis
8. Mobile Drill Equipment Company Indianapolis, Indiana (drill equipment manufacturer)	Mr. Jim Stokes
9. Central Mine Equipment Company St. Louis, Missouri (drill equipment manufacturer)	Mr. John Flint

FIRM	FIRM REPRESENTATIVE
10. American Rig Company Houston, Texas (drill equipment manufacturer)	Mr. Paul Hampton
11. Geo Space Corporation, Houston, Texas (previously Carey Machine & Supply) (drill equipment manufacturer)	Mr. Tim Holden
12. Sanderson Cyclone Drill Company Orville, Ohio (drill equipment manufacturer)	Mr. Carl Back
13. Longyear Company Minneapolis, Minnesota (drill equipment manufacturer)	Mr. W. Eastman Mr. W. W. Svensen
14. Big Indian Drilling Company Calgary, Alberta, Canada (drill equipment manufacturer)	Mr. Giles Wilderman
15. Drilling Accessories Manufacturing Dallas, Texas (drill equipment manufacturer)	Mr. Butler
16. Schramm, Incorporated West Chester, Pennsylvania (drill equipment and compressor manufacturer)	Mr. C. Metzger
17. Eastman Industries Houston, Texas (turbo drill manufacturer)	Mr. Marvin Schindler
18. Mission Manufacturing Company Houston, Texas (downhole percussion tool manufacturer)	Mr. Steve Berube
19. Cook Well Strainer Company Cincinnati, Ohio (well screen manufacturer)	Mr. M. R. Fox
20. U.O.P. Johnson Division St. Paul, Minnesota (well development material manufacturer)	Mr. R. L. Schreurs
21. TRW, Reda Pump, Incorporated Bartlesville, Oklahoma (submersible pump manufacturer)	Mr. O'Rourke

FIRM	FIRM REPRESENTATIVE
22. Jensen Bros. Manufacturing Co, Inc. Coffeyville, Kansas (water well pumping equipment manufacturer)	Mr. C. H. Marler
23. WABCO, Pneumatic Equipment Division Quincy, Illinois (air compressor manufacturer)	Local Distributor: Nix Compressors Oklahoma City, Okla.
24. Quincy Compressors, Incorporated Quincy, Illinois (air compressor manufacturer)	Mr. G. Simons
25. Ingersoll-Rand Company (air compressor and drill equipment manufacturer)	Local Representative: Oklahoma City, Okla.
26. Berkley Pump Company (submersible pump manufacturer)	Local Representative: Oklahoma City, Okla.
27. Deming Pump Company (submersible pump manufacturer)	Local Representative: Oklahoma City, Okla.
28. Jaccuzzi Pump Company (submersible pump manufacturer)	Local Representative: Oklahoma City, Okla.
29. Hughes Tool Company Houston, Texas (drilling tools manufacturer)	Mr. T. E. Parrish

APPENDIX 4

COMPUTATION OF EQUIPMENT WEIGHT FOR VARIOUS ALTERNATIVES

Equipment weights for the various well construction alternatives were calculated by configuring tabular arrays of circulatory equipment, power units and support materials based on the alternative hole and drill pipe size combinations and circulatory mode alternatives.

Table 27 is the array of circulatory equipment alternatives. Note that the designation of the circulatory equipment follows Table 12 which listed various circulatory equipment characteristics. Included with the circulatory equipment's designation is its weight and the required power to support its operation. The power units designated in Table 28 are then selected based on the total power required to support both the circulatory equipment and the drill system being considered. Again, the power unit designations follow those in Table 13, Chapter III. The numbers parenthetically enclosed following the power unit's designation are the ranges of power available, <u>in excess</u> of the power required for circulation equipment corresponding to the same hole and drill pipe size combinations and circulatory mode (i.e., Table 27), to support the drill system. For example, an alternative associated with a 6 inch hole, 4 1/2 inch drill pipe, air circulatory mode: the power unit number 5 would support both the circulatory equipment designated C5a and drill systems which required 40 to 26 brake horsepower. Those alternatives which require two power units to support the circulatory equipment and drill system can be identified where a power unit is designated and a plus (+) symbol follows with power unit designation and power ranges.

The support material(s) weight incident to an alternative are arrayed in Table 29. These total weights include materials aggregated in Tables 14 and 15, and encompass the following: drill pipe, casing, bits, well screen, well production pump, drop pipe, power unit for production pump, miscellaneous tools, and any additives or feeders for the additives (EXCLUDING WATER) associated with the circulation.

The total system weights are then computed by summing the weights reported in the three arrays (Table 27, 28 and 29) plus the drill system's weight reported in Chapter III, Table 9. The total system(s) weight are reported in Table 30. An example of one computation for the Big Indian (Model 300), 6 inch hole, 4 1/2 inch drill pipe, air circulation is: from Table 12 and 27, the designated circulatory equipment weight is 1070 pounds; from Table 13, the associated weight with the power unit (number 5), which will support both the compressor 5a and the drill system (35 b.h.p.) is 1200 pounds; the support materials' weight from Table 29 for this alternative is 2997 pounds; these weights plus the weight of the drill system from Table 9 (953 lbs.), total to 6220 pounds for the weight of this well construction alternative.

TABLE 27

ALTERNATIVE WELL CONSTRUCTION COMPRESSOR DESIGNATIONS

Drill System and Hole Size	Mode of Circulation					
	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
6"-4 1/2"	C5a 1070[a] (51)[b]	C7	C14 191 (7.5)	C1 190 (34)	C17 2900 (75)	C17
6"-2 3/8"	C5b 1070 (85)	C7	C10	C1	C18 3200 (100)	C17
5"-3 1/2"	C7 475 (34)	C7	C14	C1	C16 2000 (50)	C16
5"-2 3/8"	C5b 1070 (85)	C7	C14	C1	C17	C16
4"-2 3/8"	C7 475 (34)	C10 312 (15)	C14	C2 62 (9)	C11 1775 (0)	C9 925 (25)

a. Weight of compressor (lbs.)

b. Brake horsepower required (bhp)

NOTE: Compressor numbers coincide with designations in Table 12.

TABLE 28

ALTERNATIVE WELL CONSTRUCTION POWER UNIT DESIGNATIONS

Drill System and Hole Size	Mode of Circulation					
	Air	Air-Foam	Air-Foam-Gel	Water	Air Hammer	Air-Foam Hammer
6"-4 1/2"	PU5(40-26)* PU4(25-11) PU3(10 or less)	PU4(40-26) PU3(25 or less)	PU3(40-31) PU9(30-10) PU7(10 or less)	PU4(40-26) PU3(25 or less)	PU4 + PU9(40-21) PU8(20-15) PU7(16 or less)	PU4 + PU9(40-21) PU8(20-15) PU7(16 or less)
6"-2 3/8"	PU5 + PU9(40-21) PU8(20-15) PU7(16 or less)	PU4(40-26) PU3(25 or less)	PU3(40-26) PU9(25 or less)	PU4(40-26) PU3(25 or less)	PU6 + PU9(40-21) PU8(20-15) PU7(16 or less)	PU4 + PU9(40-21) PU8(20-15) PU7(16 or less)
5"-3 1/2"	PU4(40-26) PU3(25 or less)	PU4(40-26) PU3(25 or less)	PU3(40-31) PU9(30-10) PU7(10 or less)	PU4(40-26) PU3(25 or less)	PU5(40-26) PU4(25-11) PU3(10 or less)	PU5(40-26) PU4(25-11) PU3(10 or less)
5"-2 3/8"	PU5 + PU9(40-21) PU8(20-15) PU7(16 or less)	PU4(40-26) PU3(25 or less)	PU3(40-31) PU9(30-10) PU7(10 or less)	PU4(40-26) PU3(25 or less)	PU4 + PU9(40-21) PU8(20-15) PU7(16 or less)	PU5(40-26) PU4(25-11) PU3(10 or less)
4"-2 3/8"	PU4(40-26) PU3(25 or less)	PU3(40-26) PU9(25 or less)	PU3(40-31) PU9(30-10) PU7(10 or less)	PU9(40-21) PU8(20-15) PU7(16 or less)	PU9(40-21) PU8(20-15) PU7(16 or less)	PU4(40-36) PU3(35-20) PU9(19 or less)

NOTE: Power Unit numbers (PU) coincide with designations in Table 13.

* Numbers parenthetically enclosed are the brake horsepower of the drill system that can be supported (including power to support the circulatory system) for the designated power unit.

TABLE 29

ALTERNATIVE WELL CONSTRUCTION SUPPORT MATERIAL WEIGHTS

Drill System and Hole Size	Mode of Circulation					
	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
6"-4 1/2"	2997	3503	3559	3287	3356	3612
6"-2 3/8"	1807	2313	2369	2077	2166	2422
5"-3 1/2"	1533	2039	2095	1803	1892	2148
5"-2 3/8"	1181	1687	1743	1451	1540	1796
4"-2 3/8"	1559	2065	2121	1829	1918	2174

NOTE: Weights do not include drive pipe or water.

TABLE 30

ALTERNATIVE SYSTEMS TOTAL WEIGHTS

Drill System and Hole Size	Mode of Circulation					
	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
Big Indian (953)* 6"-4 1/2"	6220	6131	5603	5630	9361	9617
6"-2 3/8"	5680	4939	4534	4420	8169	8425
5"-3 1/2"	4161	4721	4139	4146	6018	6274
5"-2 3/8"	5054	4315	3787	3794	7543	5949
4"-2 3/8"	4187	4330	4165	3744	5300	4952
Cyclone Drillette(750) 6"-4 1/2"	6017	5628	5140	5127	9156	9412
6"-2 3/8"	5477	4438	4081	3917	7966	8222
5"-3 1/2"	3658	4218	3686	3643	5842	6092
5"-2 3/8"	4851	3812	3334	3291	7340	5746
4"-2 3/8"	3684	3822	3712	3291	5096	4749

*Weight of drill system (lbs.).

TABLE 30

Continued

Drill System and Hole Size	Mode of Circulation					
	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
WABCO FA100 (1900) 6"-4 1/2"	7167	7078	6550	6577	10,306	10,562
6"-2 3/8"	6627	5888	5481	5367	9116	9372
5"-3 1/2"	5108	5668	5086	5093	6992	7248
5"-2 3/8"	6001	5262	4734	4741	8490	6896
4"-2 3/8"	5134	5277	5112	4691	6247	5899
Mobile B30S (2870) 6"-4 1/2"	8137	8048	7520	7547	11,276	11,532
6"-2 3/8"	7597	6858	6451	6337	10,086	10,342
5"-3 1/2"	6078	6638	6056	6063	7962	8218
5"-2 3/8"	6971	6232	5604	5711	9460	7866
4"-2 3/8"	6104	6247	6082	5663	6217	6869

TABLE 30

Continued

Drill System and Hole Size	Mode of Circulation					
	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
Schramm Design (2572) 6"-4 1/2"	7839	7450	6962	6949	10,623	10,879
6"-2 3/8"	7059	6260	5903	5739	9448	9499
5"-3 1/2"	5480	6040	5508	5465	7664	7920
5"-2 3/8"	6433	5634	5156	5113	8622	7568
4"-2 3/8"	5506	5644	5534	5113	6679	6321
Carey HLT4 (1477) 6"-4 1/2"	6764	6655	6127	6154	9883	10,139
6"-2 3/8"	6204	5465	5058	4944	8693	8949
5"-3 1/2"	4685	5235	4663	4670	6569	6825
5"-2 3/8"	5578	4839	4311	4318	8067	6473
4"-2 3/8"	4711	4854	4689	4267	5823	5476

TABLE 30

Continued

Drill System and Hole Size	Mode of Circulation					
	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
ARCO Tophead S (1780) 6"-4 1/2"	7067	6958	6430	6457	10,186	10,442
6"-2 3/8"	6507	5768	5361	5247	8996	9252
5"-3 1/2"	4988	5538	4966	4973	6872	7128
5"-2 3/8"	5881	5142	4614	4631	8370	6776
4"-2 3/8"	5014	5157	4992	4570	6127	5779
Carey HHP (449) 6"-4 1/2"	5716	5327	4839	4826	8531	8756
6"-2 3/8"	5936	5137	3880	3616	7325	7376
5"-3 1/2"	3357	3917	3385	3342	5541	5717
5"-2 3/8"	4310	3511	3033	2990	6499	5445
4"-2 3/8"	3383	3521	3411	2990	4556	4198

TABLE 30

Continued

Drill System and Hole Size	Mode of Circulation					
	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
Sprague & Henwood 40C (2275) 6"-4 1/2"	7542	7153	6665	6552	10,326	10,582
6"-2 3/8"	6947	5953	5606	5432	9336	9387
5"-3 1/2"	5183	5743	5211	5168	7367	7623
5"-2 3/8"	6321	5337	4859	4816	8510	7271
4"-2 3/8"	5209	5347	5237	4816	6567	6274
Acker Hillbilly M3 (2900) 6"-4 1/2"	8167	8078	7550	7577	11,306	11,562
6"-2 3/8"	7627	6888	6481	6367	10,116	10,372
5"-3 1/2"	6108	6668	6086	6097	7982	8248
5"-2 3/8"	7001	6262	5634	5741	9490	7896
4"-2 3/8"	6134	6277	6112	5693	7247	7199

TABLE 30

Continued

Drill System and Hole Size	Mode of Circulation					
	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
CME 55 (4380) 6"-4 1/2"	9647	9558	9030	9057	12,786	13,042
6"-2 3/8"	9107	8368	8001	7487	11,596	11,852
5"-3 1/2"	7888	8148	7566	7573	9472	9728
5"-2 3/8"	8481	7742	7114	7221	10,970	9376
4"-2 3/8"	7614	7757	6592	7173	8723	8679
CME 45C (2270) 6"-4 1/2"	7571	7462	6660	6947	10,697	10,946
6"-2 3/8"	7011	6272	5865	5767	9527	9527
5"-3 1/2"	5492	6043	5206	5477	7376	7632
5"-2 3/8"	6385	5646	4854	5125	8874	7280
4"-2 3/8"	5518	5661	5232	4811	6631	6269

TABLE 30

Continued

Drill System and Hole Size	Mode of Circulation					
	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
Longyear Design (945) 6"-4 1/2"	6232	6123	5559	5622	9351	9607
6"-2 3/8"	5672	4933	4526	4412	8161	8419
5"-3 1/2"	4153	4703	4131	4138	6037	6293
5"-2 3/8"	5046	4307	3779	3786	7535	5941
4"-2 3/8"	4179	4322	4157	3745	5292	4944
Mayhew 200 (1150) 6"-4 1/2"	6417	6028	5540	5527	9201	9457
6"-2 3/8"	5822	4838	4481	4317	8211	8262
5"-3 1/2"	4058	4618	4086	4043	6242	6498
5"-2 3/8"	5196	4212	3734	3691	7385	6146
4"-2 3/8"	4084	4222	4112	3691	5442	5149

TABLE 30

Continued

Drill System and Hole Size	Mode of Circulation					
	Air	Air-Foam	Air-Foam Gel	Water	Air Hammer	Air-Foam Hammer
ARCO Model S (1100) 6"-4 1/2"	6367	5978	5490	5477	9151	9407
6"-2 3/8"	5772	4788	4431	4267	7976	8027
5"-3 1/2"	4008	4568	4036	3993	6192	6448
5"-2 3/8"	4961	4162	3684	3621	7150	6096
4"-2 3/8"	4034	4172	4062	3641	5207	4849
ARCO 100 AR-C (350) 6"-4 1/2"	5317	5228	4510	4727	8216	8472
6"-2 3/8"	4837	4038	3681	3517	7226	7277
5"-3 1/2"	3258	3818	3046	3243	5142	5398
5"-2 3/8"	4211	3412	2694	2891	6400	5046
4"-2 3/8"	3282	3422	3072	2651	4457	4099